Can computational models of reading aloud account for how individuals who are deaf and hard of hearing read?

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Abstract

Can computational models of reading aloud account for how individuals who are d/Deaf and hard of hearing read?

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Purpose: This paper proposes modifications to two current computational models of reading aloud - the Dual Route Cascaded (DRC) Model and the Connectionist Dual Process (CDP++) Model, that are specific to individuals who are d/Deaf and hard-of-hearing (d/Deaf/HoH).

Methods: A brief summary of the of the DRC and the CDP++ models are first provided. Differences in how individuals who are d/Deaf/HoH read based on past literature are then reviewed in the context of the two models. Finally, adaptations to the existing models are proposed and new d/Deaf/HoH-specific versions of both models are discussed.

Results: Several different strategies of reading instruction for individuals who are d/Deaf/HoH are identified from the proposed model modifications. These involve decreasing emphasis on auditory phonological processing instruction, adding multi-sensory phonological processing instruction, and increasing semantic knowledge instruction.

Conclusions: Current computational models based on normal hearing data do not accurately account for how individuals who are d/Deaf/HoH read. Although the proposed modifications to the computational models should be tested, they hold potential to guide new reading instruction strategies that would help individuals who are d/Deaf/HoH achieve literacy levels comparable to their normal hearing peers.

Keywords: Dual-route Theory, Deaf, hard-of-hearing, computational models, reading

Introduction

How children who are deaf and hard-of-hearing (d/Deaf/HoH)[1] learn to read and what intervention approaches would help them achieve literacy levels comparable to their normal hearing peers remains an important clinical question (Lederberg et al., 2013; Moeller et al., 2007). Children who are deaf have been shown to have lower overall literacy skills than their normal hearing peers (Harris et al., 2017). One study administered the Stanford Achievement Test to 4808 children from the ages of 8 to 18 who had a hearing difference that varied from mild to profound. The Stanford Achievement Test breaks up readers into 4 categories: below basic, basic, proficient, and advanced. This study found that the majority of these d/Deaf/HoH consistently scored “below basic” in their reading level across grades (Traxler, 2000). The use of the Stanford Achievement Test as a valid measurement of the reading skill level of children who are d/Deaf/HoH has been more recently validated by Qi and Mitchell (2012) (Qi & Mitchell, 2012). This is of concern because not only have higher levels of literacy been associated with better overall educational outcomes, language abilities, and math skills, individuals with better literacy skills have been shown to have higher income and quality of life outcomes (C. J. Johnson et al., 2010; Kelly & Gaustad, 2007; Lederberg et al., 2013). Individuals who are d/Deaf/HoH face a large amount of discrimination throughout their lives. Because literacy has ties to so many quality of life outcomes, increasing literacy outcomes for individuals who are d/Deaf/HoH could greatly reduce the disparity between individuals who are typically hearing

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[1] In this paper, d/Deaf is used to refer to individuals with profound unaided hearing loss who may or may not identify with being culturally Deaf, while HoH is used to describe individuals with mild to moderate hearing loss early in life i.e., not age-induced. We acknowledge that the experiences of these three groups are significantly different and do not presume that hearing loss is an intrinsic deficit.

and those who are d/Deaf/HoH. Despite the large body of research that has demonstrated reading challenges in children who are d/Deaf/HoH and the implementation of different approaches of teaching reading, children who are d/Deaf/HoH have not achieved literacy levels comparable to their normal hearing peers (Harris & Terlektsi, 2011; Lederberg et al., 2013; Marschark et al., 2015; Pimperton et al., 2016; Wauters et al., 2006).

Computational models of reading aloud are computer programs that specify the main stages of the reading process and implement the computations that are necessary to transform the visual word input into the spoken word read aloud. Once a model is established it can be used to simulate real reading performance regarding how accurate an individual is at reading a given word as well as how long it takes to read the word. The use of computational models to describe the complex behavior of how an individual reads aloud is a powerful approach which allows investigators to collect data on human reading performance and test their models of the reading process. Critically, being able to test a model means that if a model's output does not match human reading performance, then the model can be revised. Once a model is relatively consistent with human data, model simulations provides a method of studying impaired reading such as observed in individuals with dyslexia or individuals who are d/Deaf/HoH (Ziegler et al., 2014, 2020). One such study even developed personalized computational models for children with dyslexia and then based intervention strategies off of predictions from the individual's model (Ziegler et al., 2020). The inherent flaw of these models is that they cannot fully capture the complexities of human cognition and thus are always an over-simplification of how humans read. Moreover, even if the output of the model completely matches human data, it does not necessarily mean that the model is identical to the human processes. Nevertheless, utilizing this approach for the d/Deaf/HoH population could hold promise for designing effective reading interventions for individuals who are d/Deaf/HoH.

This paper reviews reading performance data from individuals who are d/Deaf/HoH in the context of two computational models of reading aloud. By comparing data from individuals who are d/Deaf/HoH to these established models of reading, we aim to postulate how adaptations of these models could more accurately reflect how individuals who are d/Deaf/HoH read. We first examine the Dual-Route Cascaded (DRC) model in the context of d/Deaf/HoH data and identify aspects of the d/Deaf/HoH data that cannot be accounted for within this model. Although the DRC model is an older model, it is better able to match human data of reading aloud than newer models. However, one of its greatest limitations is that the DRC model requires a set of human-programmed rules, which limits how well it can be trained. We then introduce a second computational model, the Connectionist Dual-Process (CDP++) model, which introduces learning to solve the limitation of the DRC model. In the CDP++ model, new rules are generated with each dataset that determine what pronunciations are selected for in the model. This paper then suggests modifications to both the DRC and CDP++ model that would better account for data from individuals who are d/Deaf/HoH. Finally, implications of these modifications and their clinical relevance are discussed.

The Dual-Route Theory and Computational Models of Reading

The two computational models of reading aloud that are examined in this paper, the DRC and the CDP++ model, are both based on the Dual-Route Theory of reading aloud. In fact, the CDP++ model was designed to overcome the shortcomings of the DRC model but, as of yet, is unable to match the DRC in terms of performance with human data (Pritchard et al., 2012;

Robidoux & Pritchard, 2014). The accuracy of these two models have been determined by validating model pronunciation output against a large set of human reading data to determine whether the output of the models match the pronunciation of humans reading aloud (Coltheart & Rastle, 1994; Mousikou et al., 2017).

The input into the two models, or starting point of word reading, is always the printed word. The encoded print is then broken into visual features and then into the letters that make up the word, and subsequently to phonemes. Phonemes are the individual units of sound that comprise a word which distinguish one word from another. The output of the models always goes from the final stage of a phonemic representation of the word to the produced speech, or the word read aloud.

The Dual-Route Theory posits that there are two main pathways involved in reading aloud, often referred to as lexical and orthographic pathways. Lexical means relating to the words or vocabulary of a language whereas orthographic refers to the letters and spelling. The orthographic pathway can be thought of as how a beginning reader such as a kindergartner would read. For example, if the word "CAT" is the word being read aloud, the early reader would rely on sounding out individual graphemes (letters) and pronouncing them in order (e.g., /k/ /a/ /t/). This method of reading via the orthographic pathway takes more time and is not accurate for words that do not have a set letter-to-sound relationship. For example, the words "wave" and "have" have the same coda (ending "ave") but are pronounced in two different ways that cannot be predicted from how they are spelled. Thus, skilled readers rely more heavily on the lexical pathway to read these words.

The lexical pathway, on the other hand, is how literate individuals most often read. Instead of sounding out individual phonemes, groups of letters are recognized and pronounced based on prior knowledge. This occurs with more experienced readers who have read a specific word enough times to develop a representation of it that can be accessed e.g., the reader has encountered the word “cat” enough that instead of sounding out each individual letter, the reader recognizes the words as a whole. This is a more efficient and accurate way to read in the case of words like “wave” and “have”, which require past experience to be pronounced correctly. The lexical pathway is also thought to contain an input for semantic knowledge, word meaning, which can provide additional assistance in selecting for the correct word to read aloud. Semantic information is particularly critical for heteronyms such as “lead,” meaning heavy metal, and “lead,” meaning to guide; these words are pronounced differently but are spelled exactly the same. For heteronyms, there is no visual indicator of the different pronunciations and thus, a skilled reader would rely on semantic knowledge to guide their selection of what word to pronounce.

While the two pathways are separate and may serve different purposes, according to the Dual Route Theory, both pathways are activated simultaneously. The way that the correct pronunciation is selected is through comparison of activation levels; thus, the word that receives the highest level of activation via either route is selected and subsequently pronounced. Sometimes the speed of the lexical route sacrifices the accuracy of the nonlexical route, which can be seen often in beginning readers. When reading a word such as “became” they will recognize the first few letters “bec” and could activate the word “because” due to its higher frequency in their mental lexicon.

The DRC Model

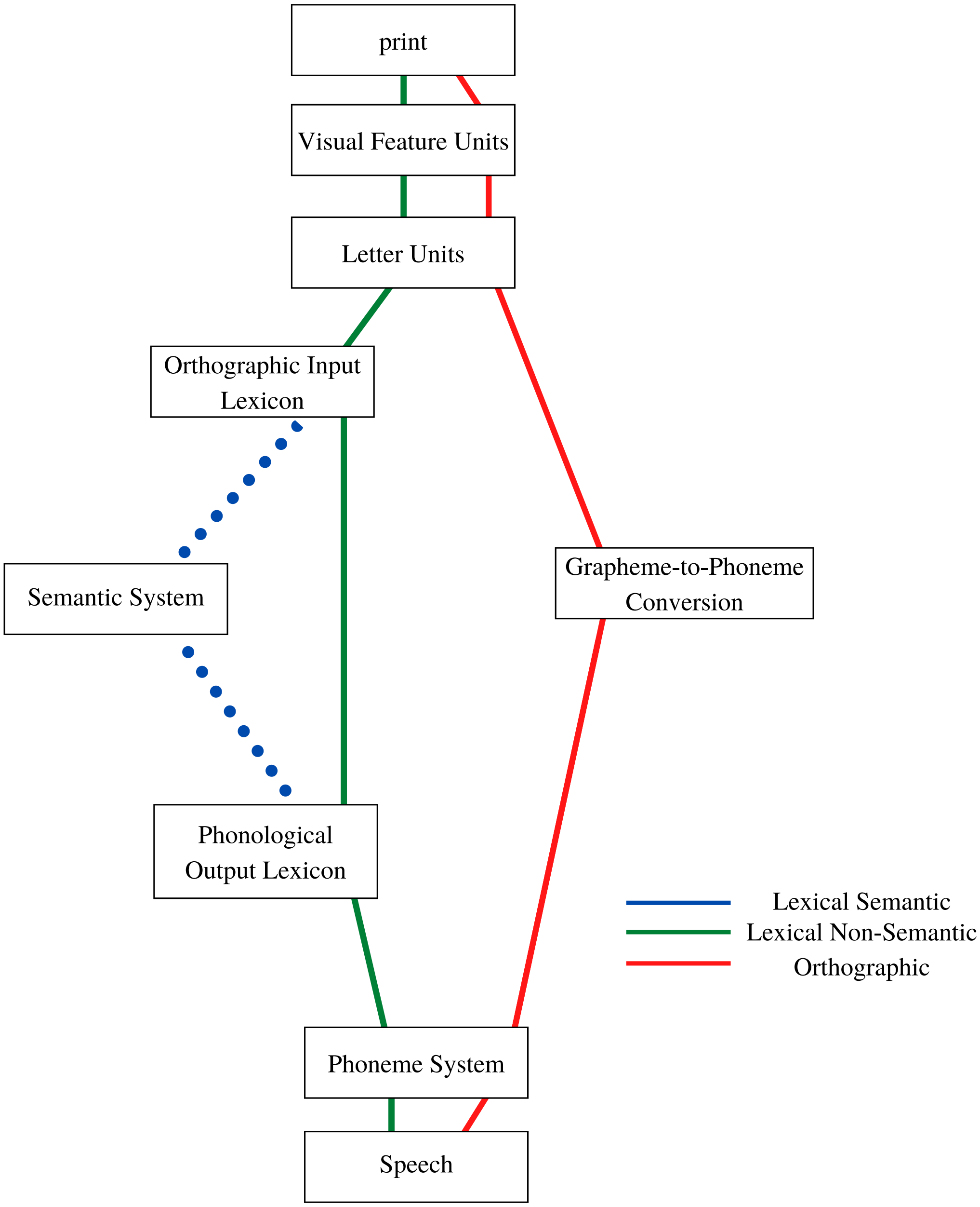

Figure 1: Schematic diagram of the DRC model. Dashed blue lines - The Lexical Semantic pathway is not implemented in the current iteration of the DRC model, but is a critical pathway in the Dual-Route Theory of Reading

The DRC is a computational model (Fig. 1) that implements the Dual-Route Theory (DRT) of reading aloud. The DRC has two primary pathways - lexical and orthographic. Both pathways begin with an individual seeing visual input and analyzing it for features (Visual Feature Units) and then coding units as letters (Letter Units) (Coltheart et al., 2001). The lexical pathway of the DRC activates word pronunciations based upon recognizing either the whole word or phonemes within the word. The orthographic pathway, on the other hand, relies on sounding out words letter by letter then converting to phonemes according to a set of lexical “rules” that are pre-programmed in the model (Perry et al., 2007).

An important point to note, is that according to the Dual-Route Theory of reading there is in fact, a third pathway because the lexical pathway is divided into two: the lexical semantic pathway includes contribution of the semantic system (Fig. 1, dashed blue line) while the lexical non-semantic pathway does not (Fig. 1, green line). The influence of the semantic system is important in differentiating words with the same spelling but different meanings and pronunciations; it is through semantic information that the appropriate pronunciation is activated. The DRC computational model deviates from the Dual-Route Theory because the lexical semantic pathway is not implemented in the model, leaving only the lexical non-semantic pathway (Fig. 1, green line). The lexical semantic pathway plays an important role in the accurate description of how individuals who are d/Deaf/HoH read and is thus, included in Fig. 1.

In the Dual-Route Theory, the lexical non-semantic pathway and lexical semantic pathway are equally weighted, meaning that they share equal importance. Each pathway represents a different approach to reading. When a reader sees a word, they can recognize the word as a whole, and access the representation through the meaning of the word. This would be activation of the lexical semantic pathway because the word form activates meaning, which selects the pronunciation (Fig. 1, blue pathway). An example of this would be a reader seeing the word “cat” and then activating the representation of a four-legged fluffy animal, which then activates the pronunciation /kat/. The lexical non-semantic pathway is an alternate approach which would be a reader seeing the letters of the word “cat”, and then activating the phonological representation of the letters, which then activates the pronunciation. Using this pathway, the pronunciation is activated by the knowledge that those letters make the sound /kat/ and the semantic representation of cat is not involved.

D/Deaf/HoH Reading Differences in the Context of the DRC Model

Past research suggests that there are a number of ways that individuals who are d/Deaf/HoH read differently than normal hearing individuals. The five differences that are focused on in this paper are that d/Deaf/HoH readers are more likely to: 1) Rely on word meaning (semantic information), 2) sound out words, 3) use visemes (multi-sensory information), 4) encounter difficulty with low-frequency (uncommon) words, and 5) have more difficulty reading words in complex sentences. In the next section, this paper will review each of these differences and then propose modifications to the DRC that would account for them.

Table 1: A description of the differences between readers who are d/Deaf/HoH and normal hearing readers.

Reading Skill	D/Deaf/HoH Readers	normal hearing Readers
Semantic Information	Individuals who are d/Deaf/HoH rely more upon the meaning of words to read rather than phonological knowledge. This is perhaps due to a less robust phonological system	normal hearing individuals rely more upon phonological knowledge to read. They have a fully developed phonological system and so are able to activate words quickly through it.
Sounding Out Words	Individuals who are d/Deaf/HoH rely most heavily on sounding out words over other routes of activation.	Due to the loss of efficiency and speed, normal hearing readers usually only rely on sounding out words only when encountering a novel word.
Visemes (Multi-Sensory Input)	Individuals who are d/Deaf/HoH use other senses to increase their phonological knowledge. Visemes are used as a supplement to auditory phonological knowledge.	normal hearing individuals rely on auditory phonological cues.
Reading Uncommon Words	Individuals who are d/Deaf/HoH show decreased speed and accuracy when reading low-frequency words and words that follow irregular pronunciation rules.	normal hearing individuals maintain their speed and accuracy when reading low-frequency words and words that follow irregular pronunciation rules.
Complex Syntax	Individuals who are d/Deaf/HoH demonstrate more difficulty reading a word when it is written in a complex sentence.	normal hearing individuals show no noticeable effects due to syntactic complexity.

Semantic Information

Individuals who are d/Deaf/HoH rely more upon the meaning of words to read rather than phonological knowledge. Peleg et al. (2020) asked highly proficient readers who were deaf to decide whether a word was real or not. Each word was either a homonym word (a word that is spelled the same but has multiple meanings), an unambiguous word (a word with one meaning and pronunciation), or a homograph (a word with one spelling but multiple pronunciations). Individuals who were deaf made the decision more slowly than hearing individuals when the word was a homonym, indicating that semantic processing was significant and slowed down their response time (Peleg et al., 2020).

This shows that they were relying on semantic information, which is represented by the lexical semantic pathway in the DRC. However, normal hearing individuals made the decision significantly slower when the word was a homograph, showing that they were relying on phonological information (the lexical non-semantic pathway).

In terms of model modifications, this difference can be accounted for by applying greater weight to the lexical-semantic pathway than the lexical non-semantic pathway. This re-weighting would result in stronger and thus, faster activation of word pronunciations via semantic processing than the other two pathways. An important point to note is that individuals who are d/Deaf/HoH do indeed have access to a phonological system, but that access is likely reduced. This is demonstrated by the fact that individuals who are d/Deaf/HoH are able to judge whether words rhyme, indicating that their phonological systems are active (Sterne & Goswami, 2000). Moreover, using rhyme to teach reading has been shown to be an effective strategy for d/Deaf/HoH children (Gietz et al., 2020).

Sounding Out Words

Readers who are d/Deaf/HoH show an increased reliance on sounding out words (Hirsh-Pasek & Freyd, 1983). This has also been demonstrated in past neuroimaging studies, with individuals who are d/Deaf/HoH showing increased neural activation in the regions of the brain associated with sounding out words in comparison to normal hearing readers (Aparicio et al., 2007). One modification to the DRC model that can account for this difference is by re-weighting the orthographic pathway to have higher priority over the two lexical pathways when modelling how individuals who are d/Deaf/HoH read.

Visemes

Readers who are d/Deaf/HoH use visemes as a supplement to auditory phonemes. Visemes are a visual representation of a speech sound, or phoneme, which can be useful for lip reading. A specific example of a viseme in English would be the image of a person’s lips closed and slightly pursed to represent the sound /p/. One way to think of visemes is phonological processing through a different sensory modality (vision). Thierfelder et al. used an error disruption paradigm with eye-tracking to examine orthographic vs. viseme activation in readers who were d/Deaf/HoH. When reading, a person’s eye focuses on a specific word, this is called the “foveal area.” They are also using their peripheral vision, the “parafoveal area” to subconsciously read future words. Thierfelder asked normal hearing subjects and subjects who were d/Deaf/HoH to read sentences and judge whether they made sense or not, however all of these sentences contained an incorrect word. These all had a relationship to the correct word in the testing condition, they were either: a homophone (word that is pronounced the same but spelled differently), orthographically related, or homovisemic (words that would look the same using visemes e.g. mom/bomb). They then used eye gaze to track what words readers were reading and therefore where their foveal/parafoveal areas were. When the errored word reached the foveal area, it was changed to the correct word. If readers fixated on the substituted word for a different time amount than the control condition, the prime was judged to have affected the word processing. Readers who were d/Deaf/HoH were found to have a similar effect from homophonic and homovisemic errors. This demonstrates that individuals who are d/Deaf/HoH might use visemes as a part of their phonological processing. (Thierfelder et al., 2020). A modification to the DRC model to account for this would be to input visemes (multi-sensory information) into the lexical non-semantic pathway. In fact, one such study has demonstrated efficacy of this approach by implementing a set of German visemes into the existing DRC model. They found that the revised model more accurately matched reading data from individuals who were d/Deaf/HoH (Elliott et al., 2012). This shows that modifying the DRC model to include viseme processing in the lexical non-semantic pathway would make the model more consistent with human data.

Read Uncommon/Irregular Words Differently

Readers who are d/Deaf/HoH theoretically use different lexical “rules” that guide pronunciation in their orthographic pathway than normal hearing readers. Individuals who are d/Deaf/HoH show decreased speed and accuracy when reading low-frequency words and words that follow irregular pronunciation rules. People who are d/Deaf/HoH receive degraded language input heard through hearing aids or cochlear implants (Moeller et al., 2007). While these devices restore the perception of sound to some degree, there is still a common deficit in hearing high-frequency sounds such as /s/ or individuals who have higher-pitched voices such as women or children (Stelmachowicz et al., 2004). Different reading speed and accuracy in individuals who are d/Deaf/HoH could be due to this diminished language input. Amenta et al. (2020) found that deaf individuals who use a cochlear implant (CI) and were implanted before 3 years of age took a longer time to read aloud low-frequency words and words with a high proportion of consonants than normal hearing individuals (Amenta et al., 2020). This is interpreted to mean that these words are processed differently in individuals who are d/Deaf/HoH versus normal hearing individuals. Past research has found that individuals with moderate hearing loss acquire morphemes (an individual unit of language that carries meaning, such as /s/ indicating possession or “ing” showing present progressive action) and show different correct morpheme production at different times that normal hearing individuals (McGuckian & Henry, 2007). A review paper found various studies that also supported this morphological difference (Moeller et al., 2007). This is significant because it suggests that individuals who are d/Deaf/HoH use different morphological rules than normal hearing individuals. Overall, these processing differences suggest that different language input in individuals who are d/Deaf/HoH creates different rules in the orthographic pathway. The current DRC model’s orthographic pathway is programmed with a static set of rules that describe how it should pronounce words based upon grapheme combinations. These rules are currently the same for all readers, regardless of hearing ability.

The programming in of a set of lexical rules is inherently a weakness of the DRC model, described as an “absence of learning,” because it does not generate its own lexical rules from a set of data like the CDP++ model. Instead it is programmed in with lexical rules, introducing an area of human bias as experimenters pick what rules to add. Additionally, the DRC model does not utilize a learning algorithm and so is unable to model selecting for multiple regular pronunciations. For example, the phonological group “ave” can be pronounced in multiple ways e.g. “wave” as opposed to “have,” but the current DRC model, the most common regular pronunciation is always selected. This is referred to as “all-or-none” processing, because there is no room for multiple correct pronunciations. These weaknesses are addressed in the CDP++ model through the addition of statistical learning both in the orthographic and lexical pathways.

Syntactic complexity related to language access and overall language skills

Difficulty reading complex syntax has been demonstrated to be an underlying deficit of individuals who are d/Deaf/HoH (Guo & Spencer, 2017; Stelmachowicz et al., 2001). Individuals who are deaf demonstrate more difficulty understanding the meaning of a sentence as the syntactic complexity of a sentence increases than seen in normal hearing individuals (Quigley et al., 1974). Individuals who are d/Deaf/HoH also take longer to read sentences containing more complex syntax than their normal hearing peers (Traxler et al., 2014). These results suggest that the sentence structure that contains a word affects how that word is activated. For example, the word “dog” when reading a simple sentence, “I walked the dog.” is activated differently than when reading a more complex sentence, “If he goes to the store then I will walk the dog.” Individuals who are d/Deaf/HoH would take longer to activate “dog” in the second sentence because it has more complex syntax. The current DRC model is unable to account for syntactic differences because it only models single words. In fact, the maximum input length is a 8 letters. One modification to the DRC that could account for syntax, would be to model the reading of multiple words. The CDP++ model discussed in the next section, implements this modification.

Connections between Pathways

Higher literacy skills in individuals who are d/Deaf/HoH are associated with stronger neural connections between lexical-semantic and orthographic routes of processing (Gutierrez-Sigut et al., 2019). Guetierrez-Sigut et al. (2019) asked readers who were deaf to judge whether a stimuli was a word or not. However, before the stimulus was presented, they presented a masked prime that was either matched-case (ALTAR-ALTAR) or mismatched case (altar-ALTAR). They then measured how long it took the readers to judge the word. The matched-case stimuli served as a baseline measurement of response time, while the mismatched case was meant to measure the influence of lexical semantic activation on orthographic activation. Theoretically, a reader who has stronger connections between the lexical semantic and orthographic pathways will take less time to judge the mismatched case because meaning of the prime (lexical semantic knowledge) activates the orthographic representation. They found that more highly-skilled readers took less time to judge the mismatched case word than less skilled readers (Gutierrez-Sigut et al., 2019). This suggests that more highly skilled deaf readers have stronger connections between their lexical semantic and orthographic pathways. This effect has also been found in normal hearing and developing readers using the same masked prime paradigm (Jacobs et al., 1995; Perea et al., 2015). As seen in fig. 1, the current DRC model does not include pathways for cross-activation of lexical/orthographic routes, as would be predicted by this data. One modification to the DRC that could account for this data would be to add connections between the orthographic and lexical pathways that would allow for cross-activation.

DRC Model Changes summary

Based on the differences between how individuals who are d/Deaf/HoH and normal hearing individuals read, several modifications are proposed to generate a d/Deaf/HoH specific DRC model. First, the DRC model needs to add semantic processing. Second, differential weighting of the three pathways would occur to more accurately reflect how d/Deaf/HoH access word pronunciations. The highest weighting would be applied to the orthographic (red) pathway, which can be thought of as sounding words out. The second highest weighting would be applied to the lexical semantic (blue) pathway, which can be thought of as whole word reading via word meaning. Finally, the lowest weight would be assigned to the lexical non-semantic (green) pathway, which can be thought of accessing pronunciations via phonemes and the phonological system.

Third, visemes and the representation of multi-modal information needs to be included in the modeling of the lexical pathway. This will account for the fact that phonological knowledge is accessed by visual information as well as auditory information in readers who are d/Deaf/HoH.

Fourth, the d/Deaf/HoH model’s orthographic pathway should be programmed with lexical rules that are specific to individuals who are d/Deaf/HoH. These could include reduced ability to segment and analyze morphological units (Gaustad et al., 2002) and decreased knowledge of transitive and intransitive verbs-especially lower frequency verbs (Berent et al., 2013).

Finally, both the d/Deaf/HoH specific model and the normal hearing model should be altered to include cross-activation routes between the lexical and orthographic pathways. These will account for the fact that there is cross-activation between these two routes when reading aloud.

Both the proposed d/Deaf/HoH DRC model and the existing DRC model have several key weaknesses that the CDP++ model was designed to overcome. These are the fact that the DRC requires pre-programmed lexical rules in its orthographic pathway and cannot model challenges with reading complex syntax seen in d/Deaf/HoH readers. The CDP++ model addresses these issues by introducing statistical learning of lexical rules and by increasing input capacity into the model. The next section will discuss the CDP++ model, the established differences in reading aloud in individuals who are d/Deaf/HoH from the context of the CDP++ framework.

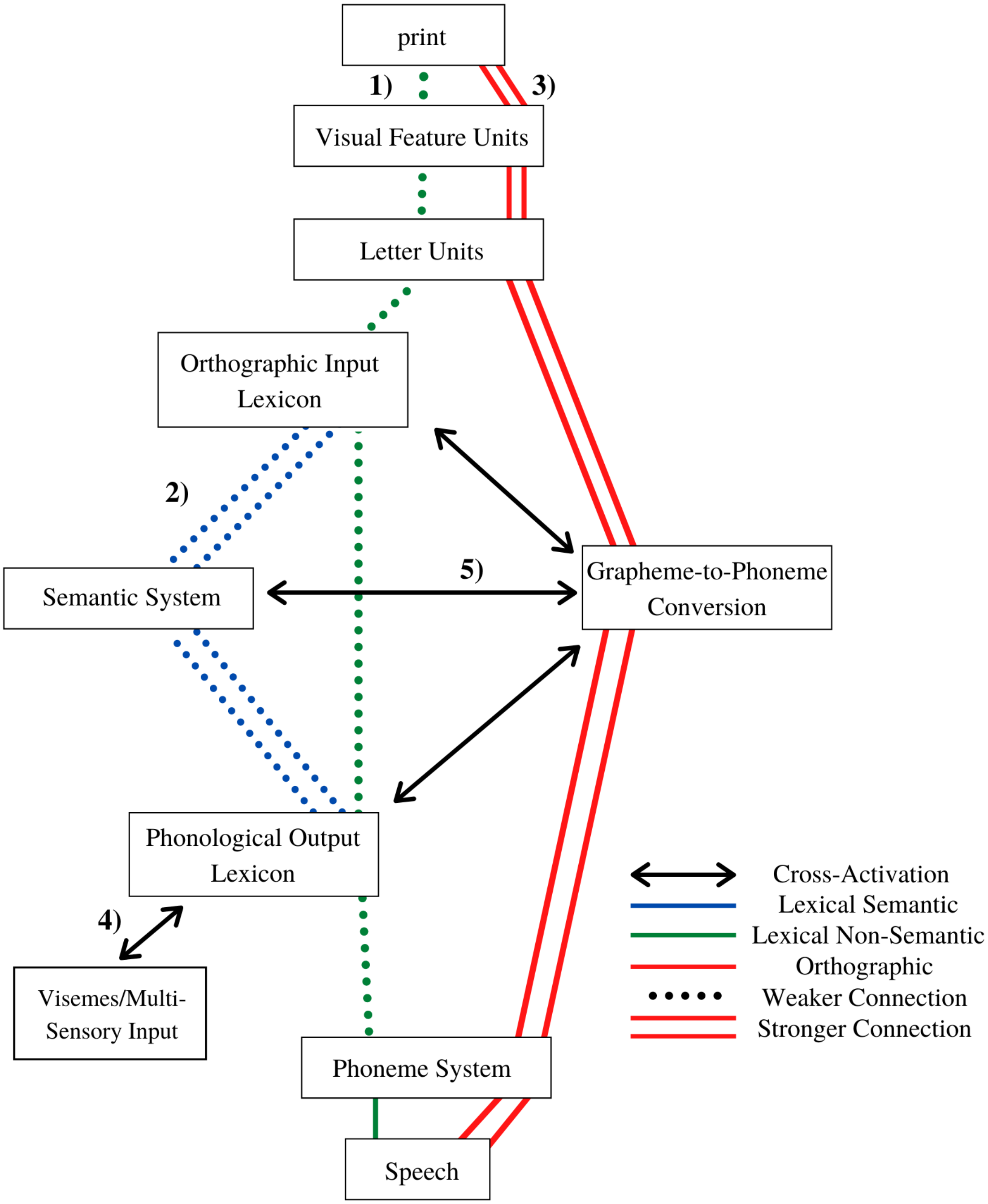

Figure 2: The DRC model for individuals who are d/Deaf/HoH. Proposed changes are highlighted by numbers.

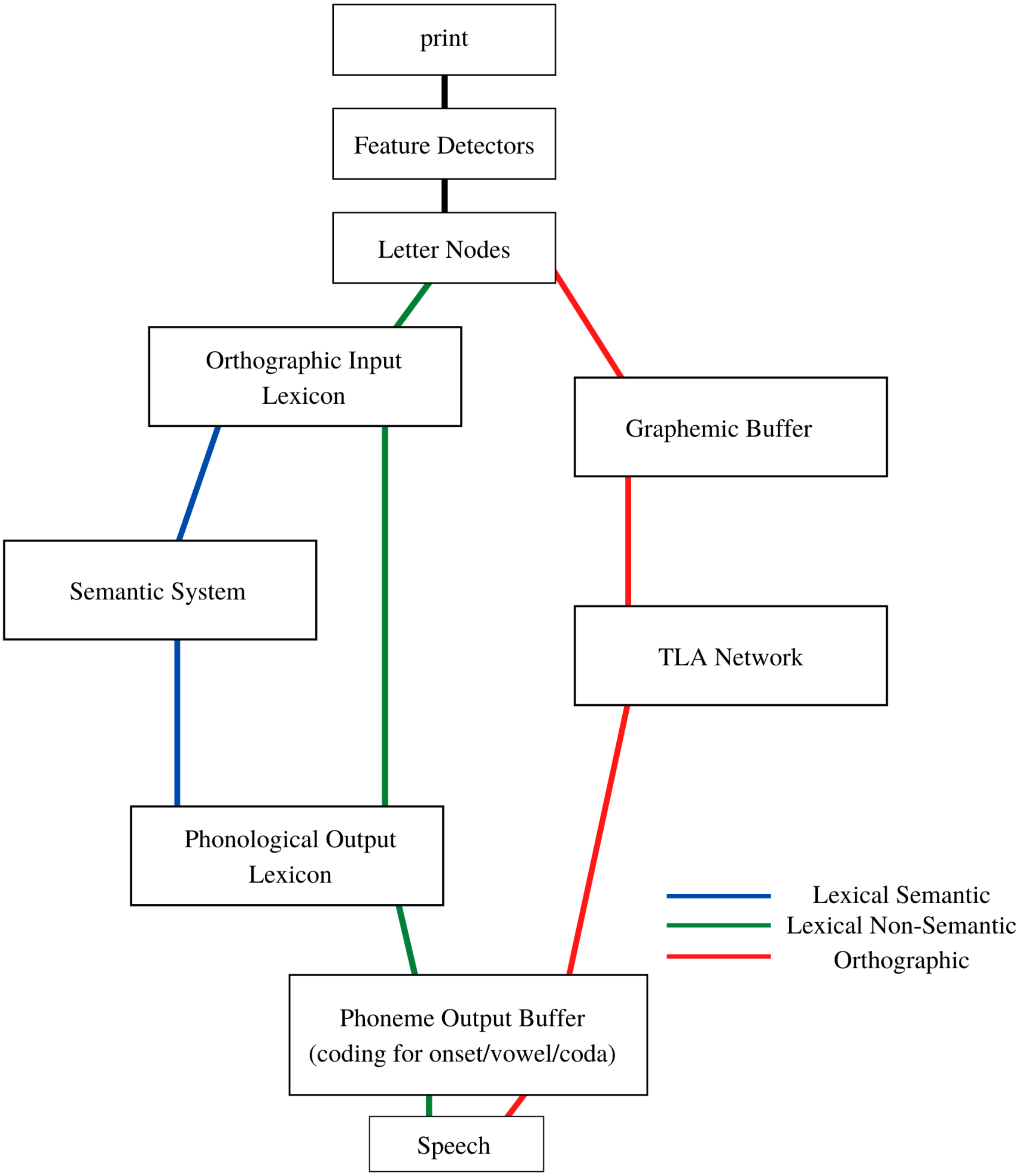

Figure 3: The CDP++ model.

Connectionist Dual Process ++

The Connectionist Dual Process model (CDP++) (schematic diagram in Fig. 3) is another computational model that is based on the principles of the DRC model, but is designed to improve upon shortcomings such as the “absence of learning” and “all-or-none processing” demonstrated in the orthographic route of the DRC (Perry et al., 2007). Because it was designed as an improved version of the DRC, the CDP++ model has similar routes to the DRC model; a lexical route (with a semantic processing component) and an orthographic route.

Both the orthographic and the lexical route begin exactly the same way as the DRC model, except that the CDP++ has 27 slots for letters as opposed to the DRC’s 8. This allows for modeling of multiple words. Once a word is input, the visual features are analyzed in the feature detector, then letters are activated based on those visual features.

The lexical route of the CDP++ is almost identical to the DRC model except for the addition of statistical learning. This is because the lexical route of the DRC simulates human data well but relies on rules that are hand-programmed in by researchers. The CDP++ overcomes this issue by using statistical learning from a dataset so that the items in the orthographic lexicon and phonological lexicon were “learned” in a way that resembles how normal hearing children learn language. Once the entries are “learned,” the lexical pathway runs identically to the DRC until the phonemes are selected in the Phoneme Output Buffer, which will be discussed later.

The orthographic route of the CDP++ model is quite different from the DRC model. After the letters and features are analyzed, the letters are converted into graphemes, which are units of letters that produce one sound e.g. “t” “tch” or “ng”. These graphemes are then input into a processing center, the TLA network, that activates phonemes according to a set of statistically learned rules. The highest activated phonemes then are sent to the Phoneme Output Buffer, where they are compared with the activated phonemes from the lexical route and then the phonemes with the highest activation are selected and pronounced.

The Phoneme Output Buffer step is also a change from the DRC route. In this step in the CDP++ model, all of the phonemes are coded as either onset if they before a vowel, vowel if they are a vowel, and coda if they come after a vowel at the end of the word. Then the highest activated phonemes are pronounced.

Changes from the DRC Model to the CDP++ Model

The changes from the DRC model are meant to make the CDP++ model more representative of the human process of reading aloud. The key differences that are relevant to this paper are: 1) the addition of statistical learning for generation of rules in the orthographic and phonological lexicons, as well as the orthographic route, 2) The increase from an 8 letter maximum input to a 27 letter maximum input, and 3) the coding of all phonemes before pronunciation as either onset/vowel/coda.

Statistical Learning

The addition of statistically learned rules from a dataset to the CDP++ model means that the dataset can be personalized to the d/Deaf/HoH population. Because the dataset can be changed, a dataset that more accurately fits the d/Deaf/HoH population could be run and then the generated rules would be more representative of what individuals who are d/Deaf/HoH use. Because the CDP++ model uses statistical learning in the lexical route in the orthographic and phonemic lexicons as well as in the orthographic route, these rules are now able to be generated as specific to individuals who are d/Deaf/HoH. normal hearing individuals and individuals who are d/Deaf/HoH have been demonstrated to use different lexical rules (Amenta et al., 2020). Therefore, changing the lexical rules in the model to better fit what is used by individuals who are d/Deaf/HoH would improve the model.

A limitation to this, however, is that language input throughout the d/Deaf/HoH population is very heterogeneous. There is a wide spectrum of access from someone who is profoundly deaf and does not use amplification to someone who has a mild hearing loss and who uses hearing aids. This means that it would be hard to create a general dataset to represent the entire population. However, a study from Ziegler (2020) used individual data from people who have dyslexia in order to generate personalized computational models, which could be an option for individuals who are d/Deaf/HoH (Ziegler et al., 2020).

Increase of Input Length

The CDP++ model can model an input of up to 27 letters, which means that syntactical effects can be modeled. As previously stated, individuals who are d/Deaf/HoH process words differently when they are contained in a more complex syntax (Quigley et al., 1974; Traxler et al., 2014) The DRC model is unable to model the syntactical effects because it only allows input of up to 8 letters. However, because the CDP++ allows for up to 27 letters, multiple words are able to be input. The CDP++ model has been found to be able to predict minor across-word effects. Study participants read aloud lists of words that were either grouped by difficulty (one list of easy words then one list of hard words) or randomly intermixed. There was a change in the amount of time that it took the individuals to read the words aloud, and the CDP++ model was able to able to predict some of this variance (Cortese et al., 2017). This across-word effect is relatively simple and small in this study, but it shows that the CDP++ model has the potential to model syntactical effects seen in the d/Deaf/HoH population.

Onset/Vowel/Coda Encoding

The automatic phonological coding of phonemes as onset/vowel/coda within the CDP++ does not fit with human data from deaf individuals. Overall, individuals who are d/Deaf/HoH demonstrate a lower level of phonological awareness/processing that does not fit with a model in which every pronunciation is coded based upon phonological characteristics. While it has been demonstrated that automatic phonological processing occurs in hearing readers, a study using event-related potentials found that deaf readers did not automatically activate phonological processing, as would be predicted by the CDP++ model (Gutierrez-Sigut et al., 2017). Another study found that while hearing readers strongly rely upon orthographic-phonological codes, deaf readers rely more strongly upon orthographic-semantic codes (Peleg et al., 2020). Furthermore, a study found that phonological coding was not spontaneously activated in deaf readers when a language with a transparent orthography (a language wherein one letter consistently refers to one single phoneme) was used (Díaz, 2017). A review paper found that while phonological processing is usually a weakness in individuals who are d/Deaf/HoH, lower phonological processing abilities were not necessarily correlated with lower reading ability (Moeller et al., 2007). Another study found that across multiple studies of phonological processing abilities and reading, phonological processing was not the determining factor of reading ability (Mayberry et al., 2011). These study findings support the conclusion that deaf readers do not use phonological knowledge as much as the CDP++ model would predict, because based upon the current model, reading any word would automatically activate the phonological system because it would have to be encoded for onset/vowel/coda before being pronounced.

CDP++ Model Changes Summary

Because the CDP++ model is based on the DRC model, several changes that were suggested for the DRC model are also recommended to make a CDP++ model that is specific to individuals who are d/Deaf/HoH. These changes are the addition of multi-sensory input such as visemes (see change in Fig 4, number 1), adding pathways for cross-activation between routes (see change in Fig 4, number 2), as well as re-weighting the pathways to prioritize the orthographic, then semantic, then lexical pathway.

There are several other changes that are specific to the CDP++ model. The first of these would be to remove phonological tagging of onset/vowel/coda from the orthographic route and from the semantic route and limit it to the lexical route.(see change in Fig 4, number 3) Because the CDP++ model ties the semantic and lexical route together, this requires removing the semantic processor from the lexical route and creating a purely semantic route see change in Fig 4, number 4). However, this better fits with the data that semantic/orthographic connections are stronger than semantic/phonological connections in individuals who are d/Deaf/HoH (Cripps et al., 2005). This is because in the d/Deaf/HoH CDP++ model, the lexical network does not have to be activated in order to activate semantics due to the fact that semantic knowledge has its own pathway. This change also fits with data that the phonological system does not need to be activated in individuals who are d/Deaf/HoH in order for them to be a skilled reader (Gutierrez-Sigut et al., 2019). Since the orthographic and semantic routes now do not require phonological coding, there are ways for individuals who are d/Deaf/HoH to read without phonological knowledge. Adding these changes creates a CDP++ model that better fits with the existing d/Deaf/HoH data and has the potential to be used in future research or even intervention.

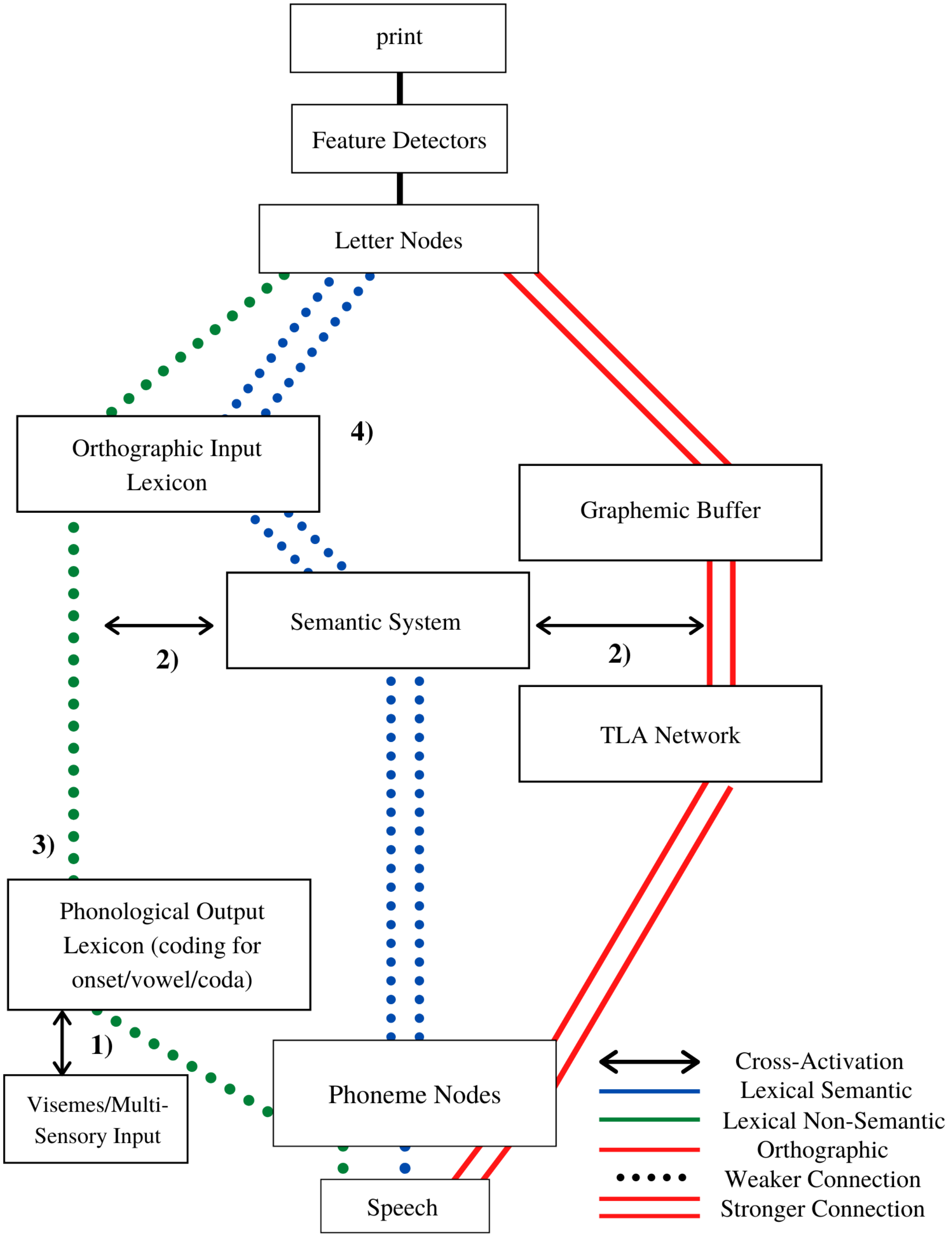

Figure 4: The CDP++ model for individuals who are d/Deaf/HoH. Changes from the existing model are highlighted by numbers.

Comparison of DRC and CDP++/Future Research

Future research on the d/Deaf/HoH specific models should include testing them to see if they match human data in order to determine how viable they are. This paper has suggested theoretical changes, but the next step should be validating them by seeing how closely they are able to match data from individuals who are d/Deaf/HoH.

Both models have their strengths but while the DRC model currently more accurately fits human data, the CDP++ has a higher potential to account for differences in d/Deaf/HoH readers due to its ability to learn. The ability to input a set of data and have the model derive lexical rules eliminates an area of human bias and allows for a more adaptable model. Thus, the CDP++ model is able to be adapted for different amounts of hearing loss or even completely different reading impairments depending upon the data that is input.

An important limitation to note however, is that neither model is able to accurately test how semantic information is encoded. The d/Deaf/HoH models both include a theoretical route of semantic processing but because of the lack of clarity on how semantic information is encoded within the brain, neither one has a computational formula to model semantic processing. This is a significant limitation because semantic knowledge is a fundamental step in the process of reading. This is demonstrated by the fact that having a larger vocabulary is correlated with greater reading skill and vice versa (Davis, 1944; C. Johnson & Goswami, 2010).

Overall, the two models have different strengths when explaining how deaf and HoH individuals read. The DRC model has the advantage of better fitting normal hearing human reading data. However, the CDP++ model has the advantage of having stronger theoretical underpinnings and the potential to better account for the spectrum of language input that individuals who are d/Deaf/HoH receive. This paper will now discuss additional theories that may contribute to understanding the process of how individuals who are d/Deaf/HoH read aloud.

Additional Theories

There are other theories that are not computational models but have demonstrated strong effects upon the ability of deaf individuals to read. They are included in this paper as they have strong potential for influencing clinical interventions. The first of these is the orthographic depth theory, which states that how transparent a language's orthography is will affect the method of how the language is read (Seidenberg, 1992). This theory has demonstrated validity within a transparent language such as Spanish, in which readers did not activate the same levels of phonological coding as seen in an English, a relatively opaque language (Díaz, 2017). This has clinical implications because it demonstrates that phonological knowledge is not necessarily needed to be a skilled reader. Many clinical reading interventions for individuals who are d/Deaf/HoH focus on facilitating phonological connections, but this research suggests that methods that focus on other avenues could be effective.

Another theory to consider is the early language access theory, which states that regardless of other interventions or method of access, children with hearing loss do the best when they have full access to a complete language-be it spoken or signed (Kushalnagar et al., 2010). This theory is well-validated with human data and is also supported by the concept of neural pruning, that there is a window of time for neurons to make rapid and widespread connections before neurons that are not being used are re-purposed for other brain areas. This theory is seen within children who receive their cochlear implant after 3 years of age versus those who receive their cochlear implant before the age of 3. The strongest predictor of how good these cochlear implant users will be is the age of implantation (Dijk et al., 1999; Moeller, 2000a). This language ability is important, because how well a child uses spoken language is directly correlated with how well they learn to read (Moeller, 2000). The clinical implication here is that early access to a full language, whether it be through early amplification/implantation or the use of a complete sign language is key to developing neural language connections that will be important when learning to read.

Clinical Implications

Rich language input

The CDP++ model emphasizes the importance of receiving a full and complete language input, due to the fact that this early input creates rules for not only understanding spoken language but also for reading. Strategies such as universal hearing screenings to promote early identification and early implantation and/or hearing aid fitting or ASL usage within the home are all intervention strategies that will increase a child’s access to language and help them develop their lexical rules. Both proposed models support the idea that phonological awareness strategies are not necessarily the most effective, due to the fact that that the phonological system does not need to be inherently activated. Instead, strategies could focus on strengthening semantic representations of words through more holistic learning methods such as sensory integration or explicit vocabulary instruction in order to foster a broader semantic network. These methods bypass the phonological barrier by strengthening other routes such as the semantic or orthographic in order to foster more fluent reading.

Enhancing semantic representation

Some teaching strategies exist that focus on enhancing semantic representation, such as the *Foundations for Literacy* curriculum, which is effective in teaching reading to d/Deaf/HoH children. This curriculum is not only focused on phonological knowledge, but has half of its focus dedicated to increasing semantic representations of words (Lederberg et al., 2014). This approach was found to increase the outcomes of d/Deaf/HoH children when used consistently for an entire school year (Lederberg et al., 2014). Semantic approaches are largely under-utilized when teaching reading to deaf individuals. However, individuals who are d/Deaf/HoH have full access to their semantic network, while by definition they have impaired access to phonological knowledge due to a lack of access to auditory information. Since languages with transparent orthographies demonstrate that phonological knowledge is not necessary to become a skilled reader, focusing on strengthening the semantic route instead the impaired phonological route should be a consideration for clinicians and/or teachers of the deaf.

In fact, one study found that bottom-up strategies could actually hinder d/Deaf/HoH reading development (Strassman, 1997). Activities such as developing phonological knowledge and not emphasizing reading for its intended purpose of gaining meaningful knowledge may give d/Deaf/HoH children the idea that reading is an activity strictly for the school setting and academic purposes. Additionally, there is evidence that once a child has learned language, better phonological knowledge does not inherently predict a better reader (Lazard & Giraud, 2017).

Strengthening bottom-up processing

The approaches that exist for enhancing phonological processing are numerous and show variable success. Factors that influence success beyond facilitating phonological processing, is that interventions are initiated at an early age, have multi-sensory inputs, and instruction is delivered consistently (Runnion & Gray, 2019). There are a few approaches that involve visual phonics, but none so far that directly target visemes, which is how the mouth looks when producing sounds (Trezek et al., 2007). A teaching approach that targets visemes would be supported by viseme data and could add value to phonological approaches.

Conclusion

Individuals who are d/Deaf/HoH do not achieve equitable literacy outcomes as their hearing peers. Literacy is closely tied to various quality-of-life outcomes, and so addressing literacy is a powerful way to target the overall discrimination that individuals who are d/Deaf/HoH face. sComputational modelling is a useful clinical tool, as has been demonstrated through research areas such as dyslexia, where it has made valuable contributions to clinical knowledge. Using these models as a way to advance therapies for individuals who are d/Deaf/HoH is a promising field and should be strongly and thoughtfully considered by both researchers and clinicians. Novel teaching approaches such as semantic-based instruction or experience-based reading strategies, hold potential to improve reading outcomes in children who are d/Deaf/HoH.

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