

A Dual-Route Cascaded Model of Reading by Deaf Adults: Evidence for Grapheme to Viseme Conversion

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There is an ongoing debate whether deaf individuals access phonology when reading, and if so, what impact the ability to access phonology might have on reading achievement. However, the debate so far has been theoretically unspecific on two accounts: (a) the phonological units deaf individuals may have of oral language have not been specified and (b) there seem to be no explicit cognitive models specifying how phonology and other factors operate in reading by deaf individuals. We propose that deaf individuals have representations of the sublexical structure of oral–aural language which are based on mouth shapes and that these sublexical units are activated during reading by deaf individuals. We specify the sublexical units of deaf German readers as 11 “visemes” and incorporate the viseme set into a working model of single-word reading by deaf adults based on the dual-route cascaded model of reading aloud by Coltheart, Rastle, Perry, Langdon, and Ziegler (2001, *DRC: A dual route cascaded model of visual word recognition and reading aloud*. *Psychological Review*, 108, 204–256. doi: 10.1037//0033-295x.108.1.204). We assessed the indirect route of this model by investigating the “pseudo-homoviseme” effect using a lexical decision task in deaf German reading adults. We found a main effect of pseudo-homovisemy, suggesting that at least some deaf individuals do automatically access sublexical structure during single-word reading.

It is well documented that deaf individuals lag behind the hearing in reading age (Traxler, 2000; Wauters, Van Bon, & Tellings, 2006). In an attempt to understand why deaf readers lag behind their peers, much research in the field has focused on identifying the potential underlying skills that contribute to deaf reading competence. Various skills, such as Sign Language competence, phonological awareness, speechreading

skill, and vocabulary, have been correlated with reading achievement, but there is disagreement regarding which of the implicated skills are crucial for high reading achievement by deaf individuals and why. In contrast to research on word recognition in hearing persons, the current debates concerning reading by deaf individuals do not offer proposals that describe and model the specific cognitive processes involved when deaf individuals read.

Even though reading ability of deaf individuals is probably a too complex behavior to be explained by one factor alone, the literature still reflects a tendency to emphasize one skill over another, without making specific and detailed models attempting to explain exactly how all the factors, or one supposedly crucial factor, operate together in the act of reading.

Paul and Lee (2010, p. 459) for example, state, “Reading is a complex cognitive activity, and no single factor can account for the complete range of difficulties that impede the reading development of individuals.” In their “qualitative similarity hypothesis,” they claim that deaf readers develop reading skill in a qualitatively similar fashion to their hearing peers, only quantitatively delayed. However, without describing exactly how the hearing read, this hypothesis remains too general to allow experimental tests. As there is still an intensive ongoing debate regarding the relative contributions of orthography and phonology in hearing readers and dyslexics (Alvarez, Carreiras, & Perea, 2004; Frost, 1998; Stenneken, Conrad, Hutzler, Braun, & Jacobs, 2005), the “qualitative similarity hypothesis” seems to be a limited research tool, unless its authors

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specify which of the competing computational models of hearing reading they find most convincing (Coltheart, Rastle, Perry, Langdon, and Ziegler, 2001; Grainger & Jacobs, 1996; Perry, Ziegler, & Zorzi, 2007; Zorzi, 2010). Second, there needs to be an explanation of the mechanism that delays deaf individual's reading competence in comparison to hearing readers. Also, an explanation is required of the fact that some deaf readers are not simply delayed in reading development; rather, they never actually do reach hearing levels of reading as reflected in the reading quotients of the adult participants in our experiment, provided in the results section below.

Hermans, Knoors, Ormel, and Vcrhoeven (2008a) also point out the lack of specific models of reading by deaf individuals. They develop a model which specifies how bilingually educated deaf children acquire written language vocabulary. Their model describes three stages through which an orthographic lexical entry is incorporated into a child's mental lexicon. In the first stage, an association between a Sign word and the written cognate is established. At this point, the lexical entry contains only orthographic information but no morphological, syntactic, or semantic specifications. In the second stage, the semantic and syntactic specifications of the Sign lemma are copied into the lexical representation of the orthographic word. At this stage, the Sign Language system is not necessarily involved in the recognition of the written word. In the last stage, the morphological specifications for the orthographic word are filled in and the connection to the conceptual system is independent of the Sign Language system. The authors also provide experimental evidence for the activation of the Sign cognates during reading (see also Morford, Wilkinson, Villwock, Piñar, and Kroll [2011] for evidence of American Sign Language activation during English reading). This model provides a specific description of how written language vocabulary can be acquired by deaf children in a particular setting, and it offers an account of the correlations that will be mentioned below between Sign Language skills, productive vocabulary, and reading skill. However, the model is not informative regarding the possible contribution of phonological awareness, recoding, and speechreading to deaf individuals' reading skill.

Below, we present some of the skills that are thought to have a major impact on deaf individuals'

reading competence, focusing mainly on phonological skills and speechreading, as these are relevant to our experiment. However, this does not constitute a comprehensive review of all the research on all related skills. We then address terminological issues, and finally, we present our working model of word recognition in deaf readers.

Skills Related to Reading Comprehension Among Deaf Individuals

One of the most debated issues in the deaf reading literature is whether deaf individuals have phonological representations of oral-aural languages, and if so, whether they automatically make use of these representations when reading. Based on deaf participant's performance on rhyme judgments, Dodd and Hermelin (1977) suggested that deaf individuals have representations of the sublexical structure of English based on speechreading. The studies that followed since, assessing whether or not deaf individuals have phonological representations of written words, have produced mixed results. A meta-analysis of studies on phonological coding and awareness (PCA) among deaf readers by Mayberry, Giudice, and Lieberman (2011) found that of the studies meeting their inclusion criteria, 16 reported evidence of PCA, 20 reported no evidence of PCA, and 11 reported evidence of PCA for a subgroup. In general, their results showed that PCA predicts 11% of reading proficiency variance in the deaf population. For additional reviews of PCA in deaf readers, see Paul, Wang, Trezek, and Luckner (2009), Perfetti and Sandak (2000), and Wang, Trezek, Luckner, and Paul (2008). A longitudinal study by Colin, Magnan, Ecalle, and Leybaert (2007) seemed to show that phonological awareness is predictive of reading skill for deaf individuals. They found that phonological awareness, measured using a rhyme decision and rhyme generation task, in 21 deaf and hearing pre-readers predicted written word recognition scores 1 year later. However, a longitudinal study by Kyle and Harris (2010) showed a more complex pattern of findings, as described below.

Rhyme judgment data suggest that at least some deaf individuals can activate some form of phonological code for written words when required to do so.

However, the ability to make correct rhyme judgments when asked to do so does not provide strong evidence that phonological codes are automatically accessed during reading. A stronger case could possibly be made, if a pseudo-homophone effect—a valid marker of well-functioning phonological recoding in hearing readers as measured by the lexical decision task (LDT; Braun, Hutzler, Ziegler, Dambacher, & Jacobs, 2009; Ziegler, Jacobs, & Kluppel, 2001)—could be demonstrated in deaf readers, suggesting that they automatically access phonological codes while reading. The reason is that in order to perform a visual lexical decision the activation of phonological codes in principle is not required. It is actually a hindrance to performance, as far as pseudo-homophones (BRANE, FOCKS) are concerned. Beech and Harris (1997) used a card sorting LDT with deaf children. They did not find significant regularity or homophony effects. Transler and Reitsma (2005) replicated the Beech and Harris study with better controlled stimuli and did find a pseudo-homophone effect for deaf children. Note that both these studies only measured error rates. Ormel, Hermans, Knoors, Hendriks, and Verhoeven (2010) used a picture–word verification task with deaf children but did not find a significant effect of pseudo-homophony.

In summary, there is some evidence for phonological awareness and recoding in at least some deaf individuals. However, whether phonological codes are automatically accessed during reading and how PCA is related to reading achievement is not clear. Furthermore, to the best of our knowledge, no study has specified the possible phonological units activated by deaf individuals, beyond the assertion that they may be derived from speechreading.

Harris and Moreno (2006) aimed to identify the skills of good deaf readers. They directly compared good and poor reading groups. They measured phonological coding in deaf individuals by counting the percentage of phonetic errors in spelling and in counting syllables. They also looked at orthographic awareness, speech intelligibility, and accuracy in speechreading. From their results, they concluded that speechreading ability was probably the underlying skill used by good readers. Within the Good Reader group were individuals both with good and poor phonological skills; however, they all had good speechreading skills. They also suggested that

speechreading alone is not enough. Other factors such as vocabulary size may also determine reading ability. Kyle and Harris (2006) also found productive vocabulary and speechreading skill to be the significant predictors of reading for deaf individuals.

Kyle and Harris (2010) conducted one of the few longitudinal studies on deaf reading skill. Their results suggest that speechreading skill is predictive of later reading skill. The authors assessed the role of phonological awareness, productive vocabulary, speechreading, and short-term memory, over a 3-year period, for a group of 29 deaf children, to assess what impact each skill had on reading outcome. They found that earlier vocabulary and speechreading skills predicted longitudinal growth in reading achievement, while earlier reading ability was related to later phonological awareness. Speechreading was a significant predictor of word reading ability for the first time period, whereas vocabulary was consistently predictive across all measured time periods. The authors interpret this finding as a possible indication that phonological skill is acquired through reading instruction for deaf individuals, and not the other way round, and that speechreading provides the basis from which deaf individuals create their phonological codes of oral–aural language. Findings in Kyle and Harris (2011) showed that speechreading was also a longitudinal correlate of reading and spelling for hearing children as well as deaf children. Further support for the idea that speechreading is the source from which deaf individuals derive phonological units can be found in Hanson and Fowler (1987), Leybaert (2000), and Mohammed, Campbell, Macsweeney, Barry, and Coleman (2006). We propose that the next step in this line of research is to put forward a specific set of phonological units that are derivable from speechreading, to offer a model of how these units are used to read, and to test this model. This is what we attempt to do in our experiment, as described below.

Most of the studies mentioned above did not control for the Sign Language skills of the participants. Chamberlain and Mayberry (2008) found that ASL skill correlates with English-reading skill. Hermans, Knoors, Ormel, and Verhoeven (2008b) also report a strong correlation between Dutch Sign Language vocabulary skills and written Dutch skill. They propose

a model of how competence in a Sign Language can contribute to competence in a written oral–aural language (Hermans et al., 2008a).

Miller (2010) found that phonological awareness was not predictive of reading comprehension skill. Rather, he found that knowledge of the syntactic structure of written Hebrew underlies reading comprehension skill. He discusses deaf individuals' reading skill in terms of two reading strategies, a semantic strategy and a syntactic strategy. He proposes that developing syntactic knowledge of poor readers would be a better educational policy than focusing on phonological awareness.

Visemes—The “Phonemes” of Deaf Readers?

In order to better understand the mixed findings on phonological recoding by deaf individuals during reading, we propose a specific hypothesis on what the phonological codes of deaf individuals are and how they are acquired. We incorporate this code into a tentative working model of single-word reading for deaf individuals.

First, we wish to make one point regarding terminology. The term “phonology” is often used in a different sense in the literature on deaf reading skills than it is used in the Sign Language literature. In the former, it usually refers to sublexical structure that is acoustically manifested, that is, abstract representations of concrete sounds. This is etymologically correct because “phone” means “sound.” In this regard, it makes sense to say that deaf individuals have impoverished phonology as in the example below:

1. “[...] a major source of difficulty for many deaf readers is *impoverished phonological knowledge*.” [italics mine] (Beech & Harris, 1997, p. 106)

However, “phonology” has taken on a broader meaning since the first linguistic studies of American Sign Language in the 1960s (Stokoe, 1960) and has come to mean the abstract representations of sublexical units of any modality, visual or acoustic. Sign linguists generally use the term in its broader sense. In this sense, the quote above is inaccurate because deaf children exposed to Sign from an early age on acquire normal phonological knowledge of their own language, and this is not hindered by auditory deprivation. What they perhaps lack are full representations of the phonologies of German or English or whichever language is used by the

hearing community within which they live. We will use the term “sublexical structure” hereinafter to refer to the phonologies of languages both of hearing and deaf individuals as this is a modality-independent term.

By definition, phonemes are abstract mental units, for this reason, it is stated in Paul et al. (2009, p. 348) that they do not necessarily need to be heard; “Actually we refer to phonemes as abstract entities that do not necessarily need to be heard or spoken (in isolation or as part of blending or segmenting).” This notion is problematic for the following reason; phonemes are abstract, but they are acquired through exposure to concrete sensory input. To develop the full phonemic repertoire of any language, one needs to be exposed to that specific language, preferably at a young age. McQuarrie and Parrila (2009) present evidence that deaf individuals do not have sublexical representations of English that are equivalent to that of the hearing. They conclude that sublexical structure cannot play an important role in deaf reading skills. In contrast, we propose that deaf individuals do have abstract representations of the sublexical units of Spoken Languages. However, these units are not identical to the sublexical units of their hearing peers because they are derived from the visual sensory input alone. We call these units visemes (“visual phonemes”) following Fisher (1968).

McQuarrie and Parrila (2009) note that positive findings of sublexical effects in deaf individuals are mostly from two-choice discrimination experiments, in which the choice could have been made on the basis of “tactile or visual similarity.” They state that what have been reported as phonological effects may have been caused by not controlling for tactile and visual similarity between phonologically similar words. As stated before, we do not claim that deaf individuals have a phonological repertoire that is identical to their hearing peers, but that based on the very visual or tactile stimuli (McQuarrie and Parrila, 2009) present as a confound of phonological similarity, they can develop a repertoire of visemes which may be activated when they read.

Construction of the German Viseme Set of Deaf Readers

Auer (2009) carried out a four-step process in deriving the visemes for English in his studies of speechreading that is very similar to the one we carried out for deriving the

visemes of German. The steps are (a) development of segmental retranscription rules to represent only visually perceptible segments. He does not use the term viseme; instead, he uses the term phoneme equivalence class (PEC); (b) application of retranscription rules to all words in a phonemically transcribed word database; (c) sorting of words into lexical equivalence classes, which I call homovisemes; and (d) use of quantitative measures on information in the retranscribed word database. Auer used 12 PECs for English, compared with the 11 visemes we define for German. For highly skilled speech readers Auer uses 19 PECs. However, Auer does not apply his work to the issue of reading skill.

In our attempt to define the viseme set of deaf readers of German, we analyzed videos of mouthings taken from the German Sign Language (“Deutsche Gebärdensprache” [DGS]) dictionary (Kestner & Hollmann, 2009) as the realization of mouthings by deaf people. We chose to derive our viseme set from mouthings produced by deaf individuals in the context of DGS, instead of from German speechreading for the reasons below.

Mouthings (not to be confused with mouth gestures) in DGS lexical items are identical to the mouthing caused by articulating the German equivalent. Mouthings occur frequently in DGS (Ebbinghaus & Hessmann, 2001) and can serve to disambiguate signs that have the same manual component (such as *SISTER* and *BROTHER*). Although the linguistic status of mouthings in Sign Languages is under debate (Boyes Braem & Sutton-Spence, 2001), in DGS at least they are used and perceived frequently. We reason that it may be better to use visemes that are actually produced by

deaf people, as a deaf person must have a representation of that viseme in order to produce it. Had we just used what deaf individuals see, rather than produce, we would have a weaker basis to claim that these units are mentally stored. For example, a foreign language learner can be exposed to new phonemes, but if she cannot produce them, it is harder, though not impossible, to judge whether she can distinguish these new phonemes when perceiving them.

We went through a list of German phonemes, given in Table 1 below in CELEX notation (Baayen, Piepenbrock, & Gulikers, 1995), and looked for examples of their mouthing in the DGS dictionary. We thus could distinguish 11 different mouth shapes shown in Table 1.

Starting with the bilabial stops, we searched for German words in which /p/, for example, appears word initial and before the vowel /a/, as in the word “Paste.” We looked at word initial position as this provided a clear point of onset. We chose pre-/a/ position on the rationale that the maximal opening of the mouth for this phoneme would also give us an as clear as possible visible point of reference for the termination of /p/. We then took a snapshot of the mouthing and compared it with /p/’s occurring in other environments, such as word medial or word final, and before different vowels. In such environments, the mouthing was coarticulated: for example, there was lip rounding in pre-/o/ position. We assigned the symbol /P/ to this mouthing, and described it as the “lips compressed” viseme /P/. Finally, we compared the viseme /P/ in our first snapshot with its realization by two other speakers of DGS, to filter out individual differences in articulation.

Table 1 Visemic inventory of DGS

Phoneme (CELEX notation)	Viseme	Description
b m p	P	Lips compressed
d n s t z	T	Lips slightly apart with tongue in contact with teeth
@ N g h k r x	-	Relaxed medium opening of mouth
l	L	Open mouth, tongue contacts alveolar ridge, and drops
f v	F	Upper teeth contact lower lip
S	S	Pouting of the lips while teeth stay together
I i j	I	Spreading of lips slightly open
E e	E	Medium opening of spread lips
a	A	Wide opening of mouth
& O Q o	O	Rounding of lips
U Y u y	U	Pouting of lips

In the next stage, we followed the same steps for the German phoneme /b/. According to our analysis, it is visemically identical to /P/, as is /m/. So the three German phonemes /p, b, m/ map onto the viseme /P/. We then repeated this procedure for all German phonemes. We searched for vowels in word initial and pre-/P/ position as the compression of the lips for /P/ gives a clear indication of the vowels termination. Using this procedure, 11 visemes could be clearly identified.

The neutral viseme /-/ is an interesting case that deserves careful future study. In word initial position, we did not always find any visible evidence of its existence. In the entry for "Gala," there is clearly a neutral mouthing before the /A/ viseme, but in "Kabel," this is less clear. The same applies for its occurrences in other positions. In word final position, however, where a reduced vowel would be in German, it is usually clearly seen. Although /-/ appears to be particularly prone to coarticulation, one can speculate that it may have significance as a timing slot and therefore should be represented in a visemic transcription of mouthings. For this reason, we chose the dash as its symbol to indicate that it holds a space in time but has only minimal visual features.

We then converted the CELEX German database into visemic transcription and calculated the frequencies of the 11 visemes as shown in Table 2.

We then assessed how many lexical entries in our visemic lexicon were homovisemic (analogous to homophonic). Out of 51,728 entries in the CELEX database,

87% (45,101) are unique (not homovisemic with any other entry). Out of the total high-frequency words (more than 20 occurrences per million), 83% are unique entries (2,920 of 3,535).

Taking into account the amount of exposure deaf individuals have to mouthings, and Auer's (2009) findings of frequency and neighborhood effects for speech-read words, it is plausible that deaf individuals do indeed naturally acquire a set of visemes. Deaf individuals are exposed to mouthings in several different contexts: As described in Ebbinghaus and Hessmann (2001), speech-reading is used in communication between deaf and hearing individuals, although it is described as being inefficient. Manually coded German, which is frequently used in educational settings for deaf individuals, is also a context in which mouthed German words are accompanied with manual signs. Last, in DGS, mouthings that match the German cognates of signed words occur together with a manual component. Within DGS, mouthing occurs at roughly one mouthed word to every two manual signs. Furthermore, the findings of a correlation between speechreading skill and reading skill in deaf children (Harris & Moreno, 2006; Kyle & Harris, 2006, 2010, 2011) described above would also indicate that a naturally acquired viseme set from speechreading could be utilized in the process of reading by deaf individuals. Our viseme set and dual-route cascaded (DRC) model of reading by deaf adults described below is a specific proposal of how exactly speechreading could provide the basis from which deaf individuals create their sublexical codes of spoken languages.

Despite the fact that DGS mouthings are identical to the mouthing caused by articulating the German cognate, we nevertheless compare our set derived from deaf mouthings to a viseme set taken from the realization of German mouthings by hearing German speakers. Aschenberger and Weiss (2005) constructed a viseme set for German that consists of 15 units. They, for example, assigned /p,b/ a common viseme, but /m/ was assigned a separate viseme because the lip compression lasted longer than for /p/ and /b/. It is important to note that had we adopted the Aschenberger and Weiss set, this would not have altered the architecture of the DRC model nor would it have altered our predictions or the manner in which we designed our experiment as we explain below. It is also

Table 2 Type frequency values of the 11 German visemes

Viseme	Number of occurrences in CELEX (type)	% Occurrences per total occurrences
-	119,728	25.66
T	113,810	24.39
A	40,022	8.57
I	38,161	8.18
P	31,695	6.79
U	24,794	5.31
E	23,559	5.05
L	23,222	4.97
F	21,456	4.59
O	17,894	3.83
S	12,167	2.60
Total occurrences	466,508	

possible that each deaf person has a slightly different number of sublexical units depending on the amount of residual hearing they have—which may give them access to acoustic distinctions in addition to visual distinctions—or simply because some deaf individuals may be more skilled at differentiating the visual features. For example, it is possible that some deaf people distinguish /m/ as visemically different to /p,b/ as reflected in Aschenberner and Weiss' set. Essentially, the more sublexical units one proposes deaf individuals have access to, the closer reading by deaf individuals should approximate hearing reading levels, but the architecture of the system that processes the units remains the same for both deaf and hearing people.

The Dual-Route Cascaded Model of Reading by Deaf Adults

Dual-route models of reading have been referred to in the deaf reading literature (Beech & Harris, 1997), but so far no hypothesis as to exactly what kind of dual-route system would accurately model reading by deaf individuals has been offered. Also, no specific sublexical units have been defined for the indirect route, beyond stating that it is possible that deaf individuals have sublexical representations based on speechreading. Compared to the detailed and empirically well-backed models of hearing reading (Jacobs & Grainger, 1994), the deaf reading literature still requires theoretical development and model building. As explained in Coltheart et al. (2001), the benefit of implementing a theory as a computational model is that computational modeling requires full specification of a process as a computer program will not run unless fully specified. This forces theorists to make very precise theoretical commitments. When a model does not work, it leads either to adjustments of the model or to a rejection of it. Furthermore, computational models also predict behavior on certain tasks, which can then be experimentally verified on humans. If the prediction is not supported, the model must then be modified to account for the new data. They do of course caution that even though a computational model may function and account for all existing empirical data, this does not rule out the possibility that another model with a very different architecture could be developed that can do the same tasks. Should two competing models exist, they can be tested against each

other by devising a new task that would elicit different behaviors from each model given their architecture. Whichever model more accurately mirrors human behavior on this new task would then have to be accepted as the better model. Below I describe in some detail how and why Coltheart and colleagues developed the DRC model of visual word recognition and reading aloud, and how and why we adopt this architecture to describe reading by deaf individuals. For an in depth understanding of the model, the DRC is available as a freely downloadable program at: <http://www.maccs.mq.edu.au/~ssaunder/DRC/>.

The DRC model describes how one syllable words of up to eight letters that are visually perceived as print are converted to a string of phonemes that allows the system to respond on an LDT or to read the phoneme string aloud. The architecture of the model is hand wired rather than learnt through an algorithm. The reason for this being that the developers of the model preferred relying on an architecture that is motivated by empirical findings on human behavior rather than backpropagation because backpropagation can generate architectures that may not reflect what research indicates to be true of the actual architecture of the human cognitive system for reading. The following are some of the architectural choices made by the developers of the DRC model: Processing is cascaded not thresholded. That is, activation spreads from one layer to another automatically without the requirement that activation in the layer reach a certain threshold before flowing down. They also use local rather than distributed representations for words. Sublexical processing takes place at the phoneme level. That is, graphemes (a single letter or a group of letters, such as a, b, gh, ph) associate with a single phoneme. Furthermore, they follow the GRIN principle of computational modeling, which means activation is graded instead of all-or-none, it is random, it is interactive (information flows bidirectionally), and it is nonlinear. For a detailed account of the empirical evidence from humans that motivates each of these choices, see Coltheart et al. (2001) and references therein (Figure 1).

The DRC model converts print to phonemes in the following manner: The first two units in the model reflect early visual perception. On encountering

printed words, visual features that are activated in the visual feature unit layer activate or inhibit individual letters in the letter unit layer. For example, seeing the letter (t) would activate all letter units that share the visual feature of a cross, such as (f) and inhibit all letters that lack this feature such as (l). In this manner many nontarget letters receive activation, but after a sufficient amount of cycles, the target letter (t) will have the greatest amount of activation. From the letter units downward, the task is to convert the letter string into a phoneme string that is available for a response by the system such as reading or deciding if the string is a word or not. The letter units send activation down three routes to the final destination of the phoneme system; the semantic route, the lexical route, and the sublexical route. As this is a cascaded process, activation spreads down all three routes simultaneously and all three routes interact with each other and affect the behavior of the system. Despite having three routes, the DRC model is called a dual-route model because

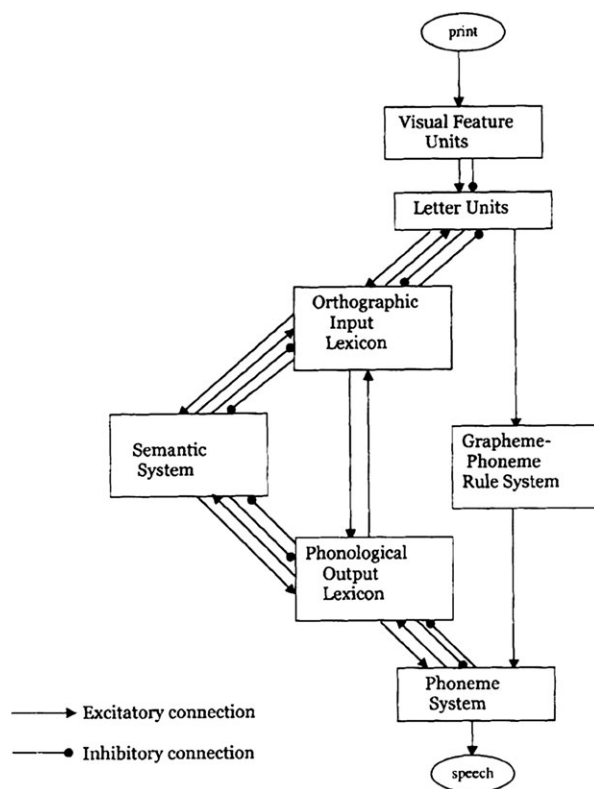


Figure 1 The dual-route cascaded model of visual word recognition and reading aloud, reprinted with permission from Coltheart et al. (2001).

only the lexical and sublexical routes are implemented in the computational model. The lexical route (also called the direct route) consists of an orthographic input lexicon and a phonological output lexicon. The orthographic lexicon contains 7,981 units corresponding to all monosyllabic words of up to eight letters in the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993). The phonological lexicon contains 7,131 units. The reason that there are more entries is the orthographic lexicon than the phonological lexicon is because of homophony. That is MEAT and MEET are separate entries in the orthographic lexicon but only one entry /mi:t/ in the phonological lexicon. A letter in the letter unit layer will activate all lexical entries that share that letter in that position and inhibit all those that do not. For example, (m) in first position will activate MEAT and MOON but inhibit SOON. Once all the letters have fed their activation downward, one entry in each lexicon will have received more activation than all the others. Activation from the lexicons will activate single phonemes in the phoneme system. The phoneme system contains 43 units corresponding to 43 English phonemes plus a blank unit. The blank unit is required to indicate the end of a letter or phoneme string. In this layer, a phoneme string is assembled which is available for output as speech. The phoneme system will also simultaneously be receiving activation from the indirect route (also called the sublexical route). This route consists of a layer that uses rules to convert graphemes into phonemes. For example (t) will be converted into /t/, (gh) occurring at the end of a word will be converted into /f/. In summary, the visual input MEAT will be converted to a string of letter units which activate or inhibit a number of entries in the orthographic and phonological lexicons which activate phonemes in the phoneme system. It will also activate a rule system that assigns a grapheme to a phoneme through prespecified rules. At the end, the string of phonemes /mi:t/ in the phoneme system receives the most amount of activation from both routes and can be used by the system to respond to any of the three following tasks: lexical decision, reading aloud, and perceptual identification. The DRC model has also been implemented in German (Ziegler, Perry, & Coltheart, 2000).

Table 3 Example of how stimuli were created and their visemic representation

	Base word from which the nonword stimuli were generated	Pseudo-homovisemic nonword	Spelling control nonword	Word
	REICH	RAICH	REUCH	AFFE
Visemic notation	[-AI-]	[-AI-]	[-OI-]	[AF-]
English gloss	Empire			Ape

Note. The base words used to generate the nonwords were themselves not used as stimuli.

Note that the layers in this model interact with each other bidirectionally, except for the two first layers that only feed information forward. Interaction between layers and within a layer can be both excitatory and inhibitory, with the exception of the connections between the orthographic lexicon and the phonological lexicon, which are only excitatory. This means that the indirect and direct routes can activate or inhibit each other. Additionally, the lexicons are frequency sensitive: activation for high-frequency words rises faster than for low-frequency words.

In Figure 2 below, we present our proposal for a DRC model of how deaf individuals read, closely following the structure of the original DRC model. We specified 11 sublexical units for German reading based on mouthings, called visemes. The role of these visemes in reading for deaf individuals is hypothesized to be identical to that of phonemes for the hearing. That is, whereas in the DRC model there exist 43 units for each phoneme plus a blank unit in the phoneme system, the DRC model of reading by deaf individuals would contain 11 units for each viseme in the viseme system plus a blank unit. In other words, we propose that the architecture used by deaf and hearing individuals for reading is fundamentally the same. We hypothesize that the differences between these populations lie not in the architecture of the cognitive system but in the amount and type of units in the grapheme–phoneme rule system, the phonological output lexicon, and the phoneme system. Note, however, that at this point in time, our model has not been implemented computationally so it remains a verbal model. (See Jacobs & Grainger [1994, p. 1,312] for a discussion regarding verbal and algorithmic models.)

As an illustration of how the DRC model of reading by deaf adults would work, let us take the printed German input “Mann” (“man” in English) as an example: The visual features of the word will activate

letter detectors in the letter layer that share the input features and inhibit those that do not. The letter units, in turn, will activate words in the orthographic lexicon that have the input letters in their specific positions and inhibit those that do not. The orthographic word form “Mann” will then activate its corresponding viseme form, [PAT]. [PAT] activates individual visemes in the viseme system, which feeds back into the visemic lexicon. Note that—according to our analysis—[PAT] is homovisemic (analogous to homophonous) for eight entries in the CELEX database, for example, the words “Matt” (English: Matt) and “Bann” (English: a Spell). So, for deaf people, eight different entries in the orthographic lexicon could activate the same visemic lexical entry. At the same time, the grapheme–viseme conversion (GVC)

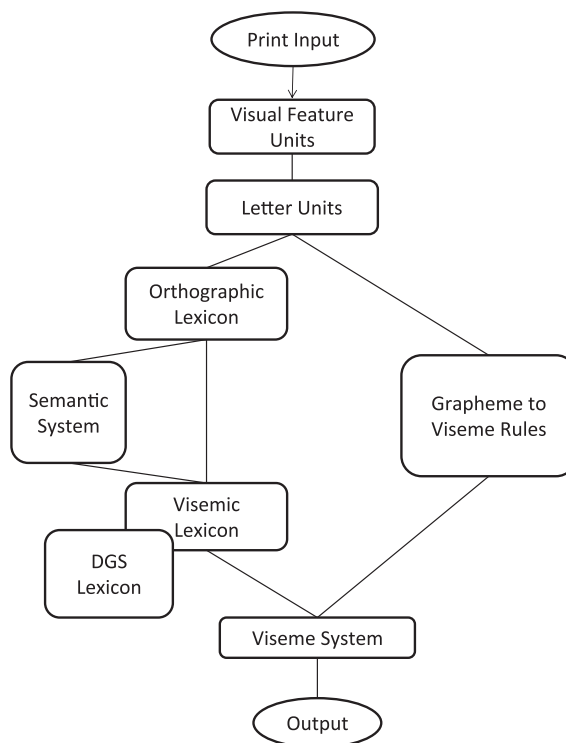


Figure 2 A dual route cascaded model of reading by deaf adults.

route will also be active. Using a set of rules, the GVC route will convert graphemes into a string of visemes. “M” will be converted to [P], “a” into [A], and “nn” into [T]. These viseme codes will activate individual visemes in the visemic system, through which the GVC route can also activate the visemic lexicon. Note that in Coltheart et al. (2001), the authors emphasize that both routes of the model are always active and not completely independent, for they receive input from the same layer, and feed output to a common layer which in turn feeds back to the visemic (or for hearing people the phonological) lexicon. They thus state that “horse race” metaphors to describe the two routes of the model are inaccurate and also not supported by empirical findings.

The DRC model proposed by Coltheart et al. (2001), which we adopt for deaf readers, does not include a level to account for bilingual readers. However, there is evidence that L1 and L2 lexicons are both activated during reading tasks in either one of a bilingual’s languages (Dijkstra, Hilberink-Schulpen, & Van Heuven, 2010; van Heuven & Dijkstra, 2010; van Heuven, Dijkstra, & Grainger, 1998). This also seems to be the case for Sign Languages (Morford et al., 2011). We therefore include in our model the DGS lexicon as a separate lexicon that overlaps with the German Visemic lexicon. Activation from the DGS lexicon could feed into the system following the same general principles of modeling mentioned above, namely through cascaded activation and inhibitory and excitatory connections within the layer and between layers. However, our model remains a verbal model as yet. We have not implemented it computationally and therefore do not yet know if such a structure would simulate reading by deaf individuals.

The question of whether deaf people access sublexical structure while reading can be better tested once the sublexical units involved and their role in the reading process are actually specified. Earlier studies that report behavioral responses of deaf readers, suggesting that they are using a dual-route system, have not offered a possible description of the sublexical units involved. Although, as mentioned above, it has been suggested that deaf individuals can derive sublexical units from speechreading, to the best of our knowledge, no study has made an explicit inventory of the hypothetically involved

units. However, the DRC model of reading by deaf adults sketched above and the included German viseme set is only a first step toward a fully specified model of single-word reading by deaf individuals. We address the need for further development in the discussion section below.

We emphasize that we propose that the cognitive architecture used for reading by hearing and deaf individuals, as well as various subgroups among the deaf population, is fundamentally the same. The DRC model could account for reading by various subgroups of the deaf population in the following manner:

Individuals with a greater amount of aided or unaided residual hearing might have access to more phonological contrasts than those relying on visual input only. For such a reader, it may be that they have access to say 20 or more sublexical units derived from audio-visual input, as opposed to 11 sublexical units that can be derived from visual input alone (visemes). The closer an individual’s hearing is to normal levels, the closer their reading should approximate normal reading levels all else being equal.

More experience with a language that is fully accessible to them (i.e., a Sign Language) from an early age could result in a child coming to school with a larger semantic system and a large Sign Language lexicon that may facilitate the acquisition of a large orthographic lexicon, perhaps via the process proposed in Hermans et al. (2008a).

Deaf individuals raised in a predominantly oral environment may have stronger visemic representations and perhaps display a stronger pseudo-homoviseme effect. In addition, they would not have a Sign Language lexicon that would interact with their reading.

Methods

In order to test whether deaf individuals access sublexical information while reading, as hypothesized in the GVC route of our DRC model of reading by deaf adults, we investigated the pseudo-homoviseme effect using an LDT. The LDT is a well-established paradigm in psychology and psycholinguistics (first used in the early 1970s by Meyer and Schvaneveldt [1971]) in which a participant is presented with a letter string that is either a word (BRAIN) or a nonword (BLANE). The participant is asked to indicate whether the letter string

is a word or not usually by button press. For hearing readers, the following effects are well attested and also simulated by the DRC model (Coltheart et al., 2001, p. 228): high-frequency words are accepted faster than low-frequency words; words are accepted faster than nonwords are rejected; low-frequency words with dense neighborhoods are accepted faster than low-frequency words from sparse neighborhoods; and pseudo-homophonic nonwords (e.g., BRANE) take longer to reject than matched nonword spelling controls (e.g., BLANE). We hypothesize that if visemes are activated during single-word reading for deaf individuals, pseudo-homovisemes will take significantly longer to reject than their matched spelling controls.

Participants

Twenty-three right-handed deaf adults (eight male, mean age 34 years) participated in this study. All participants reported a severe-to-profound hearing loss (70 dB or above) from birth. None of them had cochlear implants. All reported normal or corrected to normal vision. Two participants were excluded from the analysis, one for misunderstanding the instructions and one for having average response latencies longer than 1,000 ms across all trials. Trials with response times below 200 and above 2,000 ms were excluded from analyses.

Average age of first exposure to German Sign Language (DGS) was 7.4 years of age, and 4 participants were native signers (born to at least one signing parent), 10 were early DGS acquirers (between 1 and 5 years), and the remaining 7 were late acquirers (5 years and above, maximum age 23).

All subjects were primarily educated in German with Lautsprachbegleitende Gebärden (manually coded German). Eleven also received education in DGS at university level or at special vocational courses.

Table 4 gives the amount of time participants spend reading per month.

Stimuli

The stimuli were adapted from a well-controlled set used with hearing participants (Braun et al., 2009). Our set consists of 280 items. Half of the items are words and half are nonwords. Half of the words are of high frequency and the other half of low frequency.

The nonwords were constructed from high (more than 20 occurrences per million) and low (less than 20 occurrences per million)-frequency base words in which one letter was altered, while keeping word likeness high. A base word such as “REICH” (“empire”), for example, was altered to the pseudo-homophonic version of “RAICH” and also to an orthographic control of—“REUCH.” The nonwords were all three to five letters (one to two syllables) in length. Examples of the stimuli are presented in Table 3 above.

We converted all the original stimuli from the experiment of Braun et al. (2009) into visemic transcription. Some of the spelling controls from the Braun study visemically are words even though phonologically they are not. For example: the control word “Bid” transcribed according to our viseme set is /PI:T/. /PI:T/ is the visemic realization of the word “mies” (“appalling”), so we rejected the pair “Bat” and “Bid” as stimuli for deaf readers, as it may activate the lexical entry for “mies” and create a confounding effect. The control nonword for the pseudo-homoviseme “RAICH,” which is “REUCH” [-OI-], is not homovisemic for any other entry in the CELEX database (Baayen et al., 1995), so we accepted this pair as suitable stimuli.

Procedure

Participants were asked to fill in a background questionnaire. The questionnaire included a section on their hearing level, on their exposure to different languages during education, the amount of time they spend reading, and age of DGS acquisition. They were then given a 20-item spelling test, in which they were shown a DGS sign from a video, and asked to write the corresponding German word. Afterward, they were given the Salzburger Reading Fluency test (Hutzler & Wimmer, in preparation). This test consists of making a true or false

Table 4 Reported time spent reading per month

Time spent reading per month	Number of participants		
	Books	Newspapers	Internet
Above 10 hr	8	8	13
5–10 hr	4	0	3
1–5 hr	3	8	5
Less than 1 hr	5	4	2
0 hr	2	3	0

Note. Data on book reading was missing for one participant.

semantic judgment on sentences. There are 77 items on this test and participants are given 3 min to judge as many sentences as they can. Participants are given one point for each correct judgment. This score is then assigned a normed reading quotient value.

Lastly, participants were seated in front of a computer and given instructions both in DGS and in written German to indicate with a button press whether a stimulus was a word or not as fast and correct as possible. They used their left and right index fingers. A break appeared half way through the experiment. They were given 10 practice trials to familiarize them with the task. The experimental trials were presented in pseudo-randomized order for each participant. Each trial began with a fixation mark in the center of the screen, which was replaced by the stimulus that stayed on the screen until button press. The stimuli were presented in white on a black screen in upper case letters Times New Roman 20 pt font. The experiment, including the questionnaire and administration of the tests lasted about 1 hr.

Results

The average error rate on the spelling test was 1.6 out of 20.

The average reading quotient for the participants was 78, based on norms for the hearing. Normal hearing reading levels lie between 85 and 115, 9 of the participants were within this range. The highest score was 113.

There was also a correlation between reading quotient and average reaction time ($r = -.77$). Participants with faster mean reaction times showed higher reading quotient values.

Table 5 below shows the reaction time means and error rates for pseudo-homovisemes derived from low- and high-frequency base words, spelling controls derived from low- and high-frequency base words, and for low- and high-frequency words. On average, pseudo-homovisemes were responded to slowest, followed by spelling controls followed by low-frequency words and finally high-frequency words.

A 2×3 (word frequency: high vs. low by word type: pseudo-homoviseme, spelling control, and word) repeated-measures ANOVA showed a significant main effect of word frequency, $F(1, 20) = 8.098$, $p = .01$, a significant main effect of word type $F(1, 40) = 26.029$,

$p < .01$, and a significant interaction between word frequency and word type $F(1, 40) = 24.656$, $p < .01$. The Effect of Word frequency is caused by the Word stimuli. High-frequency words were responded to faster than low-frequency words. Both pseudo-homovisemes and spelling controls showed the reverse pattern; items derived from high-frequency base words were responded to slower than low-frequency ones (see Table 5). This difference was not significant as revealed by a 2×2 (base word frequency: high vs. low by word type: pseudo-homoviseme vs. spelling control) repeated-measures ANOVA $F(1, 20) = 1.423$, $p = .247$.

The effect of word type derives mainly from faster reaction to word stimuli, but the test of within-subject contrasts showed that the crucial comparison of pseudo-homovisemes to spelling controls was significant $F(1, 20) = 9.928$, $p = .005$.

In summary, we found: a significant frequency effect—deaf participants responded faster to high-frequency words than low-frequency words; a significant lexicality effect—deaf participants responded faster to words than they did to nonwords and a pseudo-homoviseme effect—deaf participants responded faster to the spelling control nonwords (e.g., REUCH) than they did to pseudo-homovisemic nonwords (e.g., RAICH).

When examining individual reaction times, all participants showed a frequency effect, four, however, did not show a lexicality effect, and six did not show a pseudo-homoviseme effect. This suggests that there are individual differences in reading strategies. However, our sample size was too small for subgroup analyses.

Discussion

Unlike many previous studies on phonological recoding in deaf readers, we did not directly attempt to measure the phonological awareness of deaf readers. Rather, we

Table 5 Reaction time means (ms) and error rates (%) for pseudo-homovisemes, spelling controls, and words

	RTs (ms)		SDs		Error rates (%)	
	Low	High	Low	High	Low	High
Pseudo-homovisemes	726.77	733.07	74.74	102.04	4.91	4.59
Spelling controls	704.83	717.97	77.31	90.14	2.46	3.95
Words	690.59	624.25	72.32	62.79	21.48	5.31

were interested in whether sublexical information is automatically accessed during visual word recognition, even when the experimental task does not in principle require the activation of sublexical codes. We found a significant effect of pseudo-homovisemy and interpret this finding within the DRC framework as the result of a mismatch between information from the indirect GVC route and the direct route (cf. Briesemeister et al., 2009; Ziegler et al., 2001). On encountering a pseudo-homoviseme, no entry in the orthographic lexicon reaches a sufficient level of activation that would lead to a timed-out “no” response. However, activation from the GVC route that feeds into the visemic system and from there feeds into the visemic lexicon activates an entry. The greater activation caused by pseudo-homovisemes compared to their spelling controls would prompt the system to extend its time-out criterion resulting in longer response latencies to pseudo-homophones than spelling controls. However, this account fails to explain base-word frequency effects, so Ziegler et al. (2001) proposes the involvement of a spelling verification mechanism. High-frequency words and more dominant spellings can be verified faster, which would match the empirical findings for hearing readers so far. Note that, even though we assume that the LDT involves access to whole word representations and a response based on the orthographic form of the stimulus (as opposed to a phonological decision task such as used in Steneken et al. [2005]), sublexical information is automatically invoked during this process and probably affects response latency and accuracy.

We found no base-word frequency effect for the pseudo-homovisemes among the deaf participants as has sometimes been found in hearing readers (e.g., Ziegler et al., 2001). The extremely high error rate for deaf participants on accepting low-frequency words might offer a clue to an explanation. As shown in Table 5, participants had an error rate of 21.48% for low-frequency words. It is not implausible to assume that they have smaller German mental lexicons than the hearing. If so, it is possible that some of the low-frequency pseudo-homoviseme base-words have no entries in their lexicons at all and therefore are treated as regular nonwords, diminishing the pseudo-homoviseme effect for the low base-word frequency stimuli.

In this study, we only gathered evidence for the sublexical route and thus only give an account of how and why PCA and speechreading could contribute to reading skill. Skilled speech readers may have strong visemic representations that can be mapped onto graphemes when learning to read, which could lead to the establishment of a well-functioning GVC route in the mature reader. However, it is important to note that the DRC model of reading by deaf adults proposes that semantic, orthographic, lexical, and sublexical information are also activated and interact with each other in a specific way when reading.

The role of the GVC route in reading by deaf adults is complicated by the fact that although on average we obtained a pseudo-homovisemy effect in our LDT, an inspection of individual effects showed that six participants did not display an effect. Although our sample was too small to carry out statistical as well as correlation analyses, a visual inspection of the data showed that among the six participants who did not show an effect were both participants with high and low reading quotients. This suggests that not all deaf people phonologically recode while reading and that whether they do or not does not correlate with reading skill. This does not, however, necessarily mean that the DRC model’s architecture is not applicable to all deaf readers. It would be possible to account for different strategies by different subgroups through altering parameter settings in the model rather than proposing different architectures (see Coltheart et al., 2001, p. 209) regarding strategies and architectures) as we stated in the DRC model section above.

The finding that some participants did not show a pseudo-homovisemy effect is in line with the results of the meta-analysis by Mayberry et al. (2011) on PCA effects. Future studies comparing deaf readers who do and do not show effects of PCA and whether the difference can indeed be shown to stem from the use of different strategies for word recognition will be necessary for development of models of reading by deaf individuals.

As we stated above, we only gathered data relevant to the contribution of sublexical codes to reading skill among deaf individuals. However, below we also address how the DRC model of reading by deaf adults could account for the other skills shown to correlate

with reading skill in the literature. Regarding the effect of Sign Language proficiency (Chamberlain & Mayberry, 2008), we speculate that exposure to Sign Language from early on in life could facilitate the building up of a large Sign lexicon and semantic system, which perhaps through a system like the one proposed in Hermans et al. (2008a) elaborated above, would in turn facilitate the acquisition of a large orthographic lexicon in the language that deaf individuals would be learning to read. We would account for the effect of vocabulary size (Kyle & Harris, 2010, 2011) in the same manner; for the DRC model specifies the involvement of lexicons (orthographic and phonological) as well as grapheme–phoneme rules in reading. Furthermore, even though a semantic system is not yet implemented in the model computationally, this unit too plays a part in the online reading process.

In summary, we propose a model that should be general enough to capture reading by all deaf individuals in principle. In fact, we propose that it is general enough to account for reading by both deaf and hearing individuals. As Coltheart et al. (2001, p. 246) describe, the architecture of the DRC model is a proposal of what a mature well-functioning reading system looks like. Mature meaning that the DRC model does not reflect the learning process of how such a system is arrived at but states what the end product of the learning process is. However, the model can explain developmental dyslexias as a difficulty in acquiring any one component of the model. In a similar manner, we propose that reading deficits of different types of deaf individuals can also be explained through a difficulty in acquiring any one component of the model. Whether this is the case in fact, rather than just possible in principle, will only be established through continued empirical research.

We also would like to address the predictions we make for outcomes for reading by deaf individuals in different orthographies; we expect the relationship between visemes and different orthographies to be almost equivalent to the relationship of phonemes to different orthographies. By almost equivalent, we mean that for any language, the visemes will always map many to one to the phonemes, so deaf people of any country will always have access to fewer contrasts of a hearing person's language and perceive the lexicon

of that language as more homophonous (homovisemic) compared to the hearing. Crucially, however, the relationship between a viseme and a grapheme is the same as the relationship between a phoneme and a grapheme, even though there will always be less visemes than phonemes. Therefore, the same problems that arise when accounting for the effects of phonology in nonalphabetic orthographies for hearing readers would hold for deaf readers. The work by Perfetti, Liu, and Tan (2005) on East Asian orthographies illustrate the point. Their findings were that in nonalphabetic scripts, hearing readers do show effects suggesting phonological mediation. It is our prediction that deaf readers of such orthographies would show the same phonological/viseme effects as the hearing readers based on deaf person's access to visemes. For Chinese deaf readers, it may be that they have visemic–syllabic representations that serve the function of the acoustic–syllabic representations the hearing Chinese activate when reading Chinese characters. From this, it would follow that future studies on how deaf individuals read, regardless of language and orthography, should always start with a specification of the viseme set available to the deaf readers. This is similar to the view of Perfetti et al. (2005, p. 54) on the role of phonology in different writing systems: "The difference between writing systems thus becomes not whether there are connections to phonology but rather what the relevant units are."

Perfetti et al. (2005) put forth a general theory for word reading across orthographies called the Lexical Constituency Model which states that word identities are comprised of linked semantic, orthographic, and phonological constituents. We are in general agreement with the idea that word identification always involves these three types of information, and the DRC models of English (Coltheart et al., 2001) and German (Ziegler et al., 2000) and of reading by deaf adults reflect this.

In terms of the "qualitative similarity hypothesis" (Paul & Lee, 2010), the proposed DRC model of reading by deaf adults assumes that deaf individuals use the same reading architecture as the hearing, the differences being (a) the sublexical units in the GVC route are visemes, not phonemes and (b) most deaf readers are bilingual in Spoken and Signed languages, so they have access to a bilingual lexicon that also affects reading.

Regarding point (a), this study is the first, to our knowledge, to specify possible sublexical units of deaf readers and to test their psychological validity in an LDT using a standard RT paradigm of the word recognition literature for hearing persons. The obtained pseudo-homoviseme effect suggests that sublexical units, in the form of visemes, could indeed be automatically accessed by some deaf individuals during reading. However, further work on identifying the exact units and assessing individual differences among deaf readers in their use needs to be carried out. For example, we defined the viseme set based on visual features, not on tactile ones. It is plausible that deaf individuals have more visemic distinctions than presented in this inventory if tactile features are taken into consideration.

Results from recent studies (Hermans, Knoors, Ormel, & Verhoeven, 2008b; Morford et al., 2011) support point (b). Namely, there is evidence that both orthographic and Sign Language lexicons of deaf readers are activated during reading. The visemic lexicon proposed here would be a case of sublexical form that overlaps between the two lexicons for German/DGS bilinguals. As mentioned above, DGS makes robust use of German derived mouthings, so some DGS signs and German words overlap in form, that is, they share common mouth shapes. That is, just as German and English have a subset of shared phonemes, we propose that mouthings constitute the subset of shared sublexical units between German and DGS.

In summary, our working model of single-word reading by deaf adults attempts to describe the relationship between the various factors thought to contribute to reading skill among deaf individuals including orthographic knowledge, sublexical and lexical representations of spoken languages, and a Sign Language lexicon as a DRC system. We have found some evidence supporting the existence of the GVC route among deaf individuals. All the components of the model, including the viseme set, require further elaboration and empirical testing.

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Conflicts of Interest

No conflicts of interest were reported.

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