Factors Distinguishing Skilled and Less Skilled Deaf Readers: Evidence From Four Orthographies

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This study aims to enhance understanding of the factors underlying variance in the reading comprehension skills of prelingually deaf individuals. Participants were 213 sixth through tenth graders with prelingual deafness recruited from four orthographic backgrounds (Hebrew, Arabic, English, and German) and allocated to three distinct reading profiles (levels). A sentence comprehension test manipulating the semantic plausibility of sentences and a word processing experiment requiring rapid determination of the semantic relationship between two real words or between a real word and a pseudohomophonic letter string were used to determine the factors distinguishing skilled from less skilled deaf readers. Findings point to deficits in structural (syntactic) knowledge and deficient knowledge structures, rather than differences in phonological processing skills, as making that distinction. Moreover, the acquisition of such knowledge seems to be modified by particularities of the read orthography.

Nearly half a century ago, Furth (1966) reported that deaf children aged 11–16 manifest reading comprehension skills comparable to hearing students in grade levels 2.7–3.5. Research conducted since this seminal report indicates that prelingually deaf individuals, as a group, continue to read at alarmingly poor levels in comparison to typically developing hearing counterparts (Allen, 1986; Gallaudet Research Institute, 2005; Holt, 1993; Miller, 2000, 2005a, 2010a; Traxler, 2000; Wolk & Allen, 1984; see also Monreal & Hernandez, 2005; Wauters, Van Bon, & Telling, 2006). Although the comprehension deficits of the prelingually deaf are well documented, the nature of the factors underlying them are still strongly disputed (e.g., Allen et al., 2009; Paul, Wang, Trezek, & Luckner, 2009). The aim of this study was to provide a better understanding of the primary cause(s) underlying this persistent reading failure.

Three principal—but not necessarily mutually exclusive—explanations have been proposed in the literature, each stressing weakness in a particular domain as the central cause of poor comprehension among prelingually deaf readers. The first of these explanations assumes phonology to play a central role in the reading process not only of the hearing, but also of the deaf (e.g., Bergeron, Lederberg, Easterbrooks, Miller, & Connor, 2009; Nielsen & Luetke-Stahlman, 2002; Paul et al., 2009; Perfetti & Sandak, 2000). Paul et al. (2009) argue that "Phonology cannot simply be abandoned even for children with limited or no access to it" (p. 348). In other words, to become skilled readers, prelingually deaf individuals have to develop

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sufficient phonemic awareness that sustains the efficient recognition of written words—an assumption in keeping with widely held explanations of reading failure among the hearing with specific reading disorders (e.g., Hulme, Snowling, Caravolas, & Carroll, 2005; Report of the National Reading Panel, 2000; Shaywitz & Shaywitz, 2005.

It makes sense to draw a causal link between the phonological word processing skills of prelingually deaf individuals and their poor reading comprehension (e.g., Kelly & Barac-Cikoja, 2007), as there is abundant evidence that such readers manifest phonological skills (e.g., phonemic awareness, phonological decoding) considerably below those of their hearing counterparts (e.g., Charlier & Leybaert, 2000; Dyer, MacSweeney, Szczerbinski, & Campbell, 2003; Hanson & Fowler, 1987; Hanson & McGarr, 1989; Miller, 1997, 2006a, 2006b, 2007; Miller et al., 2012; Sutcliffe, Dowker, & Campbell, 1999; Transler, Leybaert, & Gombert, 1999). This assumption is also supported by evidence suggesting that better deaf readers rely on a phonological memory code strategy for the temporary retention of written stimuli such as letters and words (e.g., Conrad, 1979; Hanson, 1982; Hanson, Liberman, & Shankweiler, 1984; Hanson & Lichtenstein, 1990; Harris & Moreno, 2004; Krakow & Hanson, 1985).

Interestingly, an increasing body of evidence seems to challenge the adequacy of a phonological word processing deficit hypothesis in explaining prelingually deaf readers' failure to comprehend written text. Studies have failed to corroborate the existence of a significant positive relationship between phonemic awareness, phonological word decoding skills, and reading comprehension among prelingually deaf readers (Hanson & Fowler, 1987; Hanson & McGarr, 1989; Izzo, 2002; Kyle & Harris, 2006; Leybaert & Alegria, 1993; McQuarrie & Parrila, 2009; Miller, 1997, 2007, 2010a, 2010b). Moreover, there is evidence that deaf readers with rather drastically impoverished phonological processing skills process written words with hearing-comparable efficiency (Kargin et al., 2012; Koo, Crain, LaSasso, & Eden, 2008; Miller, 2001, 2002, 2004a, 2004b, 2005a, 2005b, 2006a, 2006b, 2010b; Miller & Clark, 2011; see also Wauters et al., 2006). If the ability to process words phonologically indeed determines the efficiency of their processing, deaf readers should have underperformed hearing controls.

Of particular interest is a study in which prelingually deaf native signers and regular hearing readers were asked to categorize Hebrew real words and pseudohomophones of these real words (Miller, 2006a). For the hearing participants evidence pointed to a weak, yet statistically significant decrease in the ability to process the pseudohomophones in comparison to real words, with accuracy scores for the former dropping by three points. Interestingly, deaf participants performed at a hearing-comparable level when asked to categorize real words; however, they manifested a 20-point drop in doing the same with pseudohomophones. Miller concluded that—their poor phonological processing skills notwithstanding—prelingually deaf readers can develop orthographic representations that sustain the efficient processing of written words.

The counterevidence challenging phonology's determining role in the reading process of prelingually deaf readers warrants reconsideration of the relationship between phonological word processing skills and reading comprehension, a central target of the present study. The need for such reconsideration is also suggested by a meta-analysis of research designed to examine the development of phonemic awareness in individuals with profound early hearing losses (Mayberry, del Giudice, & Lieberman, 2011). Results from this endeavor suggest that the role of phonology in the reading of the prelingually deaf may have been overstated (see also Miller, 2010a, 2010b; Miller & Clark, 2011).

A second proffered explanation for the impoverished comprehension skills of prelingually deaf readers assumes that they often lack adequate structural (syntactic) knowledge to sustain the integration of correctly recognized written words into broader ideas at the supra-lexical (sentence) level (Miller, 2000). This hypothesis is supported by evidence implying that the structural knowledge of prelingually deaf individuals remains remarkably incomplete even after years of exhaustive schooling and training (Quigley, Power, & Steinkamp, 1977; Webster, 1986). Moreover, some findings suggest that, due to underdeveloped structural knowledge, such individuals tend to process written text without attending to particularities in its syntactic

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structure (Gormley & Franzen, 1978; Yurkowski & Ewoldt, 1986). Instead, they seem to recreate text meaning in a top-down manner by mapping the sentences' content words against their prior knowledge and life experience.

The hypothesis that prelingually deaf readers fail to process sentences syntactically is supported by studies that examined their understanding of semantically plausible (SP), semantically neutral, and semantically implausible (SI) sentences (Miller, 2000, 2005a, 2006b, 2010a, 2010b). Findings indicated clearly that the majority of such readers manifest remarkably good, often hearing-comparable understanding of sentences that convey a SP message (e.g., "The woman who watched the baby was reading."). In contrast, their comprehension drops to chance level or even below when the message of the sentence is semantically neutral (e.g., "The woman who watched the girl was smiling.") or SI (e.g., "The woman who watched the baby was crying."). This is because a sole top-down processing of content words in such sentences often leads to their misinterpretation, given that the conveyed message is not backed up by or even contradicts the reader's world knowledge and real-life experience. With SP sentences, in contrast, it is much less crucial to process their syntactic structure, as their meaning can be deduced by mapping their content words against one's prior knowledge (Miller, 2000, 2005a, 2006b, 2010a, 2010b). A central aim of the present study was to corroborate the generalizability of a structural knowledge deficit hypothesis in explaining comprehension variance among prelingually deaf readers.

Finally, it is well known that comprehension is significantly determined by the reader's prior knowledge (Allington & Cunningham, 2007; Anderson & Pearson, 1984; Pressley et al., 1992; Spires & Donley, 1998). Thus, even proficient readers struggle to comprehend what they read if they lack sufficient background knowledge regarding the topic of a text. In line with this insight, a third explanation of deaf readers' poor comprehension skills argues that, due to permanent lack of auditory stimulation and in the absence of an effective communication mode with their surroundings, the majority of this population is doomed to approach reading with underdeveloped, often unstructured world and domain-specific knowledge (Ceci, 1996), as well as marked deficits in their ability to apply metacognitive structures to text (Marschark & Wauters, 2008).

Regrettably, the prior knowledge of prelingually deaf readers, and their ability to use such knowledge strategically for proper understanding of what they read, has not received sufficient scholarly attention. The relevance of this issue is obvious, however, from some groundbreaking studies of content schemata that suggest general world knowledge, possessing information about a topic and personal experiences all markedly enhance comprehension among such readers (e.g., Jackson, Paul, & Smith, 1997). It is also indirectly supported by evidence that deaf children whose parents are deaf and who use sign language as their primary communication mode are proportionally overrepresented among skilled deaf readers (e.g., Conrad, 1979; Miller, 2010a, 2010b). Given that such readers are likely to grow up with a full-fledged language available—a language that facilitates the acquisition of world and domain-specific knowledge from their parents and other significant agents and sustains its integration into well-structured mental schemes they can apply at need to interpret a text—their preponderance among the more proficient deaf readers should not come as a surprise. The present study attempts to provide a better understanding of the role that prior knowledge plays for the prelingually deaf reader.

In sum, three basic hypotheses regarding the poor reading skills of prelingually deaf individuals have been proposed: (1) A phonological decoding deficit hypothesis, which attributes their comprehension failure to a phonological processing deficit that interferes with the efficient recognition of written words; (2) a structural knowledge deficit hypothesis, which associates this failure with insufficiently developed syntactic knowledge and, consequently, a tendency to ignore structural information (particularly word order) as a vital source for elaborating the final meaning of a sentence; and (3) a prior knowledge deficit hypothesis, which ascribes their reading failure to a dearth of well-structured general and domain-specific knowledge, critically inhibiting their comprehension in general, and their reading comprehension in particular. These hypotheses are not necessarily mutually exclusive; the alarmingly poor reading levels of the majority of prelingually deaf

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Table 1 Demographic characteristics of the participants

	Parental hearing status			
Orthography	Hearing	Deaf	All	Portion within whole sample
Hebrew	35	26	61	28.6%
Arabic	54	6	60	28.2%
English	10	20	30	14.1%
German	36	26	62	29.1%
All	135	78	213	100.0%

Note: The low incidence of deaf children with deaf parents in the Arab sample is paralleled by low prevalence in the Arab sector in general.

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individuals may well reflect the combined contribution of shortages in more than one of these areas.

Interestingly, with few exceptions (e.g., Miller, 2010b), researchers have addressed the performance of the prelingually deaf in these areas separately; with the vast majority of studies focusing on the role of phonology (see Mayberry et al., 2011). Moreover, such endeavors have primarily compared prelingually deaf readers with hearing controls, rather than comparing skilled and unskilled deaf readers in the area(s) of interest. In addition, conclusions about how the performance of deaf readers in a particular area contributes to their understanding of written text have often been derived from the interpretation of correlations as reflecting a directional causal relationship between the measured variables (e.g., enhanced phonemic awareness leads to enhanced comprehension, and not the opposite), although correlations by definition are neither causal nor directional in nature.

Finally, orthographies can be allocated along a shallow–deep dimension that reflects the consistency with which the phonological form of spoken words can be derived based on grapheme-to-phoneme conversion processes applied to a particular orthography (Frost, 2006, 2009). In orthographies that are considered shallow (e.g., German), this consistency is high given that letter graphemes predominately are associated with one and the same sound (phoneme), and vice versa (Seymour et al., 2003). In contrast, in orthographies that are considered deep this consistency is low for one of two reasons: (1) The grapheme-to-phoneme correspondence in such orthographies is irregular (e.g., English) with individual graphemes representing a number of different phonemes in different words or (2) word phonology is only incompletely depicted at the grapheme level (e.g., unpointed Hebrew, unpointed Arabic).

Based on an orthographic depth hypothesis (Lukatela, Carello, Shankweiler, & Liberman, 1995), shallow orthography is expected to facilitate the processing written words because it uses simpler grapheme-to-phoneme conversion rules (e.g., Spencer & Hanley, 2003, 2004). In particular, for readers with underdeveloped phonological skills such as the prelingually deaf (e.g., Mayberry et al., 2011; Miller, 2006a, 2010a, 2010b; for a review see Miller & Clark, 2011) such enhanced simplicity in grapheme-to-phoneme correspondence may create more favorable conditions. Regrettably, attempts to reveal the roots of prelingually deaf individuals' reading failure have been restricted almost exclusively to the study of individuals reading in the same language. It therefore remains unclear whether orthographic particularities of the read language—such as variation in grapheme-to-phoneme transparency—modify the problems that prelingually deaf individuals face as they read for meaning.

In view of the limitations outlaid above, the fact that there seems to be no notable progress in reaching a consensus about the factors underlying reading failure among prelingually deaf individuals is not surprising. The present study is part of an international effort to move the field a significant step forward toward the development of a reading theory for the prelingually deaf. It reports findings obtained from the analysis of data collected within a large-scale international reading study conducted in four countries (Israel, Turkey, Germany, and the United States). The overall goal of this project is to bring about a better understanding of the factors underlying reading failure in deaf as well as hearing readers from different orthographic backgrounds.

Research Questions

To shed light on the factors underlying reading failure among prelingually deaf readers, we formulated several research questions—one for each of the above-mentioned hypotheses and one with respect to the particularities of the investigated orthographies. First, we considered whether variance in the phonological word processing skills of prelingually deaf readers explains variance in their reading comprehension skills (phonological decoding deficit hypothesis). We expected all participants to process the semantic relationship between two words faster and more accurately when both were real words than when one was a real word and the other a pseudohomophone. Following the phonological decoding deficit hypothesis, the efficient identification of pseudohomophones will be easier for skilled deaf readers, as their phonological processing skills are assumed to be less impaired than those of less skilled readers. Thus, we expected skilled deaf readers to process both types of word pairs faster and more accurately than their less skilled counterparts, and we expected performance differences between them to be larger when processing pseudohomophones.

Second, to test the structural knowledge deficit hypothesis, we asked: Does variance in the ability of prelingually deaf readers to apply structural knowledge to text explain the variance in their reading comprehension skills? We examined this question by manipulating sentence comprehension along a dimension of semantic plausibility. Research findings (Miller, 2000, 2005a, 2006b, 2010a, 2010b) suggest that readers can derive proper sentence meaning by top-down processing of content words in SP sentences with reference to their prior knowledge, while SI sentences mediate information that contradicts normal real-life experiences, such that top-down processing must be supplemented by the processing of their syntactic structure for adequate comprehension. Consequently, if the structural knowledge deficit hypothesis is true, the impact of structural knowledge will be stronger for SI sentences than SP ones.

Third, we examined whether variance in reading comprehension skills is explained by variance in the ability of prelingually deaf readers to apply prior knowledge to the processing of written words (prior knowledge deficit hypothesis). Judging whether two things are semantically related requires the possession and efficient retrieval of well-structured prior knowledge. The retrieval and application of such knowledge is also a fundamental component of the processing of sentence meaning. Given these hypotheses to be true, we expected skilled deaf readers to determine the semantic relation between two words more accurately (fewer errors) than less skilled readers. Moreover, as determination of the quality of a semantic relation between two words requires the application of prior knowledge regardless of their presentation mode, we expected qualitative performance differences (error rates) between skilled and less skilled deaf readers to be similar under real word and pseudohomophone conditions.

Finally, we looked at the orthographic background of participants, in order to determine whether peculiarities of the read orthography, such as orthographic depth, impact the performance of prelingually deaf readers in the above areas and the way in which these areas contribute to their reading comprehension. As stated earlier, Orthographic Depth Hypothesis postulates that in shallow orthography—due to reduced complexity in grapheme-to-phoneme correspondence—the processing of written words is phonologically less demanding. We therefore expected deaf participants who read in a shallow orthography (German) to be more prevalent among the skilled readers than participants reading in a deep orthography (Hebrew, Arabic, and English).

Methods

Participants

Participants were 255 deaf sixth to tenth graders recruited from classes for the deaf. They were sampled from four orthographic backgrounds in three countries: Hebrew and Arabic in Israel, English in the United States, and German in Germany. In order to reduce variance originating from general motor slowness and/or attention deficits, we excluded 42 individuals from the original sample who were found to perform two standard deviations or more from their grade level mean on two baseline measures—one assessing their fine-motor speed and another assessing their ability to maintain attention. The remaining 213 individuals provided the final sample analyzed in this study. Participant distribution by orthographic background appears in Table 1.

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All participants were prelingually deaf, with their hearing impairment diagnosed prior to age two. Their hearing losses measured at the frequencies of 0.5, 1.0, and 2.0 kHz were 85 dBHL or higher in the better ear according to ANSI (American National Standards Institute, 1989). Their vision was either intact or corrected-to-normal and, according to their teachers, their intelligence was in the range considered normal. None was diagnosed as having specific learning disabilities. All reported sign language as their preferred mode of communication. The majority had hearing parents; about one-third had parents who were deaf (see Table 1). Only students who volunteered were tested after permission was obtained from relevant authorities. All were rewarded with a small gift for their willingness to participate.

All participants were enrolled in classes where teachers used some form of signing as a means of instruction. For all but the students with an Arabic background, the language they read was also their first spoken language. The Arab participants were raised in a diglossic context in which the first spoken language was Israeli Arabic, a spoken dialect that differs substantially from the formal Modern Standard Arabic they learn to read and write in school.

Instruments

A word-processing experiment and a sentence comprehension test (SCT) were used in order to explore the validity of different hypotheses regarding the origins of prelingually deaf readers' reading failure. The word-processing experiment served as a validation of the phonological decoding processing deficit hypothesis as well as for the substantiation of predictions made by the prior knowledge deficit hypothesis. The SCT served as a close examination of the structural knowledge deficit hypothesis. In addition, it was used in order to further corroborate deficits in the participants' ability to use their prior knowledge for the elaboration of sentence meaning.

Word-Processing Experiment

We used a computerized word-processing experiment to glean participants' phonological word processing and semantic word-processing skills. The experimental paradigm required participants to determine as fast as possible whether two words simultaneously presented on a computer display were semantically related and to indicate their decision by pressing a "YES" or "NO" key. The paradigm comprised two distinct experimental conditions: a real word condition and a pseudohomophone condition (see Appendix A). The basic assumption behind this experimental design was that significant differences between the semantic processing of pseudohomophones in comparison to real words in favor of the latter will be indicative of the participants' phonological processing skills. This is because for the processing of the semantic relationship in the pseudohomophone condition, the phonological decoding of the pseudohomophone letter string is a prerequisite. Moreover, the finding of marked differences between participants' semantic decision accuracy—in both the real word and the pseudohomophone conditions—was assumed to reflect variance in their ability to apply prior knowledge to the task.

Preparation of stimulus materials was based upon the same criteria in all tested languages. For the real word condition, we first identified a large set of high frequency nouns in each language that contained at least one phoneme which, at the orthographic level, could be represented by more than one grapheme (e.g., the phoneme "u" that in English can be written as "too," "true," "two"). The vast majority of these nouns were either mono or bisyllabic, although a few were comprised of three syllables. In a second step, we paired half of these nouns with another high frequency word that was clearly related semantically, creating a pool of semantically related word pairs (e.g., "lock, key"). We then paired the remaining nouns with words that were as semantically unrelated to them as possible (e.g., "comb, city"). In a third step, we excluded pairs built of words that were phonologically, orthographically, or visually similar to each other. Finally, we asked three experts—two primary school teachers of the deaf and a speech/language therapist of the deaf—to indicate word pairs that contained words they thought may not be familiar to deaf third to fourth graders, i.e., students that were at least two grade levels below those of the participants analyzed in this study. Only word pairs rated by all three experts as being in the realm of deaf third to fourth graders were used for experimentation.

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In order to create the experimental stimulus pair set, we selected, from among the semantically related word pairs, 10 pairs comprised of a word with one interchangeable grapheme and another 10 pairs with a word with two interchangeable graphemes, for a total of 20 semantically related real word pairs. We then used the same selection principle to create the 20 nonidentical real word pairs used for stimulation. The 40 stimulus pairs—half semantically related and the remainder semantically unrelated—were supplemented by 10 additional word pairs to be used for task explanation and practice.

To prepare the 40 stimulus pairs of the pseudohomophone condition, we used the same word pairs created for the real word condition, turning one word in each pair into a pseudohomophone by replacing one or two of its legitimate graphemes with a homophonic yet invalid grapheme (e.g., "lock, key" became "lock, kee" and "comb, city" became "comb, sity"). Accordingly, we also prepared 10 additional stimulus pairs for task explanation and practice.

Sentence Comprehension Test

We administered an SCT to assess participants' reliance on structural knowledge as well as prior knowledge for reading comprehension. The test comprised 16 active sentences built from very basic vocabulary that was ascertained to be familiar to participants. All were syntactically complex sentences, with half (8) including one subordinate and the remainder (8) two subordinates. Using a forward-and-backward translation procedure, identical versions of the test were prepared in all four languages (Hebrew, Arabic, English, and German). Half of the sentences conveyed a SP message (e.g., "The car that hit the train was totally destroyed."), while the remainder conveyed a SI message (e.g., "The truck driver who hit the man was badly hurt."). Appendix B presents additional test sentences. Each of the SI sentences paralleled a SP sentence by having exactly the same syntactic structure and a vocabulary of comparable difficulty, so as to control for the potential contribution of these factors to comprehension variance. The number of words comprising the two sentences was closely matched.

The semantic plausibility status of each sentence (SP or SI content) was determined by six independent judges (university students). For this purpose, pairs of test sentences were shown to each judge separately, one pair at the time. One sentence in each pair was assumed to depict a SP scenario whereas the other syntactically paralleling sentence was assumed to convey a SI scenario. Three of the six judges were instructed to indicate which of the two sentences in a pair describes a scenario that is compatible with how things normally happen in real life. The other three judges were instructed to indicate which of the two sentences in a pair describes a scenario that is not compatible with how things normally happen in real life. Test sentences were used for experimentation only when their semantic plausibility status was confirmed in both ways.

As mentioned earlier, the basic assumption underlying the design of the SCT was that for a proper understanding of SI sentences their semantic top-down processing is insufficient, though it may generate proper understanding of SP sentences given the reader is in possession of adequate prior knowledge. In other words, mere semantic top-down processing generates sentence meaning according to the readers' prior knowledge only; a meaning that—for SI sentences—is incompatible with the one produced by their syntactic bottom-up processing. Therefore, poor comprehension of syntactically implausible sentences, in contrast to proper understanding of SP sentences, is assumed to be indicative of failure to properly process sentences' syntactic structure.

Comprehension of each sentence was tested by a short question, with two or three multiple choice answers. Questions referenced either the subject or the object of the main or the subordinate sentences. An additional set of four sentences was used for task explanation and practice. The 16 test sentences were mixed and presented randomly. Performance time was measured but not limited. Chance level performance was 42%. Test reliability (Cronbach's α) was 0.72.

Procedure

All participants were tested individually by a trained research assistant in a quiet room. The same test protocol was used in all countries. All instructions were communicated in sign language, supplemented when necessary by a physical demonstration of the task requirements. The SCT was always administered first, followed by the word-processing experiment.

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Sentence Comprehension Test

Sentences used for task explanation and warm-up appeared separately on the first page of the test. The experimenter informed participants that the aim of the experiment was to learn how students read. Participants were then asked to read the first practice sentence and the following question carefully and instructed to indicate their answer by circling one of the choices. If participants did not understand the instructions, the experimenter provided the first answer and then told participants to try to solve the other three practice sentences. Participants were told they could ask for help if they encountered an unfamiliar word. They were also informed that they would not be graded and that their performance would be kept confidential. Only after the experimenter was confident that participants understood the test requirements did he or she tell them to solve the actual test sentences, reminding them once again to read both sentences and questions thoroughly before choosing an answer.

Word-Processing Experiment

Stimulus presentation and reaction time measurements were handled by DMDX software developed by Forster and Forster (2003). This technology measures response latencies with an exactitude of milliseconds and records them together with response accuracy for subsequent analysis.

Each participant was tested individually. Participants were told that the goal of this experiment is to see how fast they can tell if two words are related or not and provided some examples of related word pairs (e.g., *light* and *switch*) and unrelated word pairs (e.g., *rain* and *book*). The stimulus word pairs in the real word and pseudohomophone conditions were presented in two separate blocks, with the real word condition always administered first. The word pairs appeared in the center of a laptop display placed at a comfortable distance in front of the participant.

While testing the real word condition, the experimenter instructed participants to put their index fingers on the two Shift keys, one marked "YES" and the other "NO," initiated the display of the first practice word pair and said: "Here are two words. Please press the YES key if they are related and the NO key if they are not." Following the task explanation, participants were given eight practice trials in succession as a warm-up. During task explanation and practice, the experimenter corrected the participants if they provided a wrong response and explained them why their response is not correct. None of the participants exhibited difficulties in understanding task requirements.

The experimenter continued with the experimental section only after being confident that the participant in question understood the task requirements properly, based on observed performance in the practice session. Before initiating the stimulus display, the experimenter informed the student that he or she would now be tested and that response time would be measured, so it was very important to work as quickly as possible. The participant was urged not to stop in case of error, but to continue without hesitation. All 40 stimulus pairs of the RW condition were displayed in succession, with a filler mask (####) of 550 ms inserted between indication of the response and presentation of the next stimulus pair. When no response was given within 3,500 ms, presentation of the stimulus pair was aborted and marked by DMASTR software as invalid; after a masked interval of 550 ms, the next item was presented. The display of ***** indicated the end of an experimental block.

The pseudohomophone condition was tested immediately after the real word condition. Except for explanations regarding the nature of the stimulus pairs, the administration procedure was the same. With regard to pseudohomophone stimulus pairs, the experimenter displayed the first practice sample and informed the participant that—like before—he or she had to decide whether the two words were related. However, this time only one of the words was a legitimate written word, while the other was a letter string that was not a real word, but sounded like one when read aloud. The participant was then asked to try to determine the relationship of the words in the first two practice pairs, with the experimenter providing feedback. Once confident that the participant understood the task, the experimenter instructed him or her to continue with the remaining eight practice pairs.

The experimental part of the pseudohomophone condition was administered only after performance on the practice items demonstrated participant understanding of task requirements. As in the real word condition, prior to the initiation of the experiment, the

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experimenter reminded the participant to work as fast as possible and not to stop in case of error.

Results

Data were analyzed in four main steps. First, we assigned participants to three distinct reader profiles based on their comprehension of SP and SI sentences. Second, we compared sentence comprehension between profiles, overall and for SP and SI sentences separately, by read orthography. Third, we examined the distribution of participants into the three profiles by orthographic background and parental hearing status. Finally, we compared the phonological and semantic word processing skills of the reader profiles and correlated them with their comprehension of SP and SI sentences.

Creation of Distinct Reading Levels

To create reader profiles with markedly distinct comprehension levels, we performed a *K-means* cluster analysis, with participants' comprehension scores on SP and SI sentences serving as the clustering criterion. Analysis yielded three reader profile clusters, reaching maximum distance between cluster centers after six iterations.

Participants assigned to the first cluster manifested high and comparable comprehension scores for both SP, $M = 6.92$ (1.09), and SI sentences, $M = 6.47$ (1.08); maximum score = 8.00. As SI sentences are assumed to require the application of syntactic knowledge for proper understanding, we labeled participants assigned to this cluster "syntactic readers." Participants assigned to the second reader profile cluster had relatively high comprehension scores for SP sentences, $M = 5.94$ (0.98), but poor scores for SI sentences, $M = 2.43$ (1.13). As the understanding of SP sentences is assumed to be possible by the semantic top-down processing of content words, we labeled participants assigned to this cluster "semantic readers." Finally, participants in the third cluster demonstrated strikingly weak comprehension scores for both SP and SI sentences, $M = 2.92$ (0.91), 2.63 (1.14), respectively. Because participants from this cluster seemed to use neither a syntactic nor a semantic knowledge effectively for making sense of what they read, we labeled them "unspecified readers." Table 2 presents mean comprehension scores by reader profile and orthographic background.

Detailed Analysis of the Reading Comprehension of Each Profile

To clarify whether overall differences between the three profiles existed with respect to specific sentence categories, we ran two post hoc one-way ANOVAs, examining comprehension of SP and SI sentences separately. The reader profile main effect was highly significant for both sentence categories, $F(2,210) = 302.45$, $p < .001$; $F(2,210) = 242.05$, $p < .001$, $\eta^2 = .65$, respectively. Tukey's honestly significant difference (HSD) post hoc analysis (Tukey HSD was used for the post hoc examination of all between-subject main effects reported in this paper. Significance level in all post hoc analyses was set to $p < .05$) contrasting the profiles in terms of their understanding of SP and SI sentences, pointed to marked differences regarding the comprehension of SP sentences (all $p < .001$). Interestingly, both semantic and unspecified readers significantly underscored syntactic readers on SI sentences, but, there was no statistical evidence that semantic readers understood such sentences better than unspecified readers.

The orthographic background main effect yielded by ANOVA was statistically significant, $F(3,201) = 6.84$, $p < .001$, $\eta^2 = .09$, suggesting that participants from the four orthographies differed markedly in their ability to comprehend the test sentences. Tukey HSD post hoc analysis indicated that Hebrew participants were, overall, notably better readers than participants reading Arabic, English, or German. Moreover, English readers had significantly better understanding than Arab readers. Participants who read German or Arabic were statistically indistinguishable. Of note, ANOVA revealed a significant interaction between reader profile and orthographic background main effects, $F(6,201) = 4.36$, $p = .001$, $\eta^2 = .11$, suggesting that variance in comprehension related to the read orthography was not the same for the three reader profiles, a finding we shall return to later.

The semantic plausibility effect (semantically plausibility effect = scores for SP − scores for SI sentences) yielded by ANOVA was highly significant, $F(1,201) = 131.48$, $p < .001$, $\eta^2 = .40$, implying that,

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Table 2 Mean sentence comprehension scores of deaf readers with syntactic, semantic, or unspecified reader profiles (standard deviations in parentheses)

	Sentence type			
Reader profile	Semantically plausible[a]	Semantically implausible[a]	All sentences[b]	Semantic plausibility effect[c]
Hebrew readers				
Syntactic readers	7.26 (0.86)	6.74 (0.98)	14.00 (1.33)	0.52 (0.94)
Semantic readers	6.27 (1.02)	2.60 (1.07)	8.87 (1.33)	3.67 (1.60)
Unspecified readers	3.25 (0.96)	2.63 (1.14)	6.00 (2.16)	0.50 (0.58)
All	6.51 (1.36)	4.44 (2.31)	10.95 (3.19)	2.07 (2.04)
Arabic readers				
Syntactic readers	5.17 (0.98)	5.50 (0.55)	10.67 (0.82)	0.33 (1.37)
Semantic readers	6.00 (1.07)	2.33 (1.11)	8.33 (1.35)	3.67 (1.72)
Unspecified readers	2.85 (0.93)	2.82 (1.02)	5.67 (1.38)	0.03 (1.40)
All	3.87 (1.71)	2.97 (1.33)	6.83 (2.16)	0.90 (2.17)
English readers				
Syntactic readers	7.56 (0.73)	6.89 (1.17)	14.44 (1.51)	0.67 (1.23)
Semantic readers	5.75 (1.06)	2.83 (0.84)	8.58 (1.62)	2.92 (1.00)
Unspecified readers	2.56 (1.13)	2.56 (0.88)	5.11 (1.54)	0.00 (1.32)
All	5.33 (2.22)	3.97 (2.16)	9.30 (4.62)	1.37 (1.73)
German readers				
Syntactic readers	6.44 (0.73)	5.89 (1.05)	12.33 (1.23)	0.56 (1.33)
Semantic readers	5.67 (0.80)	2.13 (1.25)	7.80 (1.69)	3.53 (1.25)
Unspecified readers	2.92 (0.91)	2.30 (1.36)	5.43 (1.27)	0.83 (1.80)
All	4.84 (1.55)	2.74 (1.81)	7.58 (2.69)	0.29 (1.51)
All participants				
Syntactic readers	6.92 (1.09)	6.47 (1.08)	13.39 (1.55)	0.45 (1.12)
Semantic readers	5.94 (0.98)	2.43 (1.13)	8.37 (1.87)	3.52 (1.44)
Unspecified readers	2.92 (0.91)	2.63 (1.14)	5.55 (1.40)	0.29 (1.51)
All	5.11 (1.93)	3.46 (2.03)	8.58 (3.37)	1.65 (2.09)

[a]Maximum = 8.
[b]Maximum = 16.
[c]Semantic plausibility effect = semantically plausible − semantically implausible sentence scores.

overall, participants understood SP sentences better than SI sentences (see Table 2). A statistically marked interaction between the main effects semantic plausibility and reader profile, $F(2,201) = 90.06$, $p < .001$, $\eta^2 = .48$, indicated, however, that the size of the semantic plausibility effect varied notably between reader profiles. Semantic plausibility was not found to interact with orthographic background, $F(3,201) = 1.23$, $p > .05$, nor was the triple interaction semantic plausibility × orthographic background × reader profile significant, $F(6,201) = 0.88$, $p > .05$. We therefore ignored orthographic background as a between-subject factor in post hoc analyses conducted to clarify the final significance of the semantic plausibility effect and the way it interacted with the reader profile.

We conducted two lines of post hoc analyses to obtain a deeper understanding of how semantic plausibility contributed to reading comprehension for each reader profile. In the first of these analyses, we compared the size of the semantical plausibility effect for the three profiles by one-way ANOVA and then contrasted profiles using Tukey HSD. Findings revealed a marked semantic plausibility main effect, $F(1,210) = 92.06$, $p < .001$, $\eta^2 = .48$, with Tukey HSD indicating that semantic readers exhibited markedly larger semantic plausibility effects than both syntactic and unspecified readers (all $p < .001$). Of note, syntactic and unspecified readers were not found to be statistically distinguishable in this regard.

In a second analysis, we ran a series of paired (one-tailed) *t*-tests, comparing comprehension of SP and SI sentences for each reader profile directly. All three profiles exhibited significantly better understanding of SP sentences, although this advantage was found to be truly prominent only for semantic readers $t(86) = 22.82$, $p < .001$; while it was moderate for

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Table 3 Distribution of participants into reader profiles (%) by orthographic background and parental hearing status

	Orthography				
Reader profile	Hebrew	Arabic	German	English	Overall
All participants					
Syntactic readers	44.3%	10.0%	14.5%	30.0%	23.9%
Semantic readers	49.2%	25.0%	48.4%	40.0%	40.8%
Unspecified readers	6.5%	65.0%	37.1%	30.0%	35.3%
Participants with hearing parents					
Syntactic readers	37.1%	9.3%	13.9%	20.0%	18.5%
Semantic readers	54.1%	24.1%	44.4%	20.0%	37.0%
Unspecified readers	8.6%	66.6%	41.7%	60.0%	44.5%
Participants with deaf parents					
Syntactic readers	53.8%	16.7%	15.4%	35.0%	33.3%
Semantic readers	42.4%	33.3%	53.8%	50.0%	47.4%
Unspecified readers	3.8%	50.0%	30.8%	15.0%	19.3%

semantic and unspecified readers, $t(50) = 2.88$, $p < .01$; $t(74) = 1.68$, $p < .05$, respectively.

Next, we ran Pearson's product-moment correlations to determine the relationship between the comprehension of SP and SI sentences. Analysis revealed a statistically marked positive correlation between comprehension of the two sentence categories for syntactic readers, $r = .47$, $p < .001$, $n = 51$, but no relation for semantic or unspecified readers.

Finally, we correlated participants' level of education (grade) and their reading comprehension—overall and for SP and SI sentences separately. None of these analyses yielded evidence that participants' level of education was indicative of their comprehension skills.

Distribution Into Reader Profiles by Read Orthography and Parental Hearing Status

Earlier, we presented simple main effects and interactions between these effects as a means of highlighting how participants' orthographic background modified their comprehension skills. To complete the picture, we added parental hearing status to the equation—a potential explanatory variable we thought may prove helpful in discerning the factors determining reading skills among the prelingually deaf—and ran crosstab analysis (Table 3) to reveal the distribution of participants into the three profiles with reference to their read orthography and their parents' hearing status.

The crosstab analysis discloses a wealth of noteworthy data, several aspects of which we would like to highlight. First, about 75% of the prelingually deaf readers in our study fell in the categories of semantic and unspecified readers. Thus, the vast majority seem to use reading comprehension strategies that are inadequate for the proper understanding of written text, even though they have been enrolled in formal education for at least 6 years. Second, the chance of being among the poorest deaf readers (unspecified readers) is, overall, more than twice as high as for participants with hearing parents; for readers of some of the orthographies, the situation is even more discouraging. Prelingually deaf readers of Hebrew seem to be rather outstanding, with almost half of them (44%) manifesting a syntactic reader profile and less than 10% being among the unspecified readers. Their enhanced comprehension skills are even more marked among those with deaf parents. German readers—although somewhat better than readers from an Arabic background—were found to be markedly underrepresented (14.5%) in the syntactic reader profile representative of skilled readers, in comparison to Hebrew (44%) and English readers (30%). Finally, students reading in Arabic seem to be particularly at risk of becoming unspecified readers (see Table 3).

Participants' Phonological and Semantic Word Processing Skills

We conducted two lines of analysis to obtain a profound understanding of the semantic word processing skills of each reader profile and the way these are biased by orthographic background and phonological

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Table 4 Average error rates for real word and pseudohomophone conditions by reader profile and orthographic background (standard deviations in parentheses)

	Stimulus type		
Reader profile	Real word[a]	Pseudohomophone[a]	Phonological processing effect
Hebrew readers			
Syntactic readers	2.81 (2.56)	4.63 (5.24)	1.82 (3.83)
Semantic readers	4.90 (3.60)	8.20 (5.51)	3.30 (5.10)
Unspecified readers	9.50 (7.14)	13.75 (4.03)	4.25 (5.32)
All	4.28 (3.83)	6.98 (5.80)	2.70 (4.59)
Arabic readers			
Syntactic readers	12.67 (4.46)	15.67 (7.53)	3.00 (3.90)
Semantic readers	9.87 (6.72)	12.33 (4.56)	2.47 (4.74)
Unspecified readers	13.54 (5.65)	17.10 (5.25)	3.56 (5.19)
All	12.53 (5.95)	15.77 (5.63)	3.23 (4.92)
English readers			
Syntactic readers	3.00 (2.96)	6.11 (3.86)	3.11 (2.32)
Semantic readers	4.08 (2.11)	6.67 (4.70)	2.58 (3.70)
Unspecified readers	6.33 (4.50)	10.56 (5.59)	4.22 (4.35)
All	4.43 (3.39)	7.67 (4.99)	3.23 (3.52)
German readers			
Syntactic readers	3.33 (3.50)	7.11 (4.62)	3.78 (3.07)
Semantic readers	5.67 (3.48)	10.43 (5.04)	4.77 (2.90)
Unspecified readers	6.87 (3.53)	12.57 (5.62)	5.70 (4.50)
All	5.77 (3.63)	10.74 (5.03)	4.97 (3.60)
All participants			
Syntactic readers	4.10 (4.33)	6.63 (6.15)	2.53 (3.49)
Semantic readers	5.91 (4.47)	9.47 (5.04)	3.56 (4.23)
Unspecified readers	10.41 (5.96)	14.75 (5.85)	4.33 (4.89)
All	7.06 (5.72)	10.65 (6.45)	3.59 (4.35)

[a]Maximum = 40; chance level performance = 20 errors.

processing skills: One that examined processing accuracy and another that considered speed of processing.

Processing Accuracy

In order to understand how participants' reader profiles, orthographic background, and phonological processing skills biased accuracy of their semantic word-processing skills, we conducted ANOVA computing reader profile (syntactic, semantic, and unspecified) and orthographic background (Hebrew, Arabic, English, and German) as two between-subject factors and phonological processing (real words vs. pseudohomophones) as a within-subject factor. Average error rates for real words and pseudohomophones, with reference to reader profiles and read orthography, are presented in Table 4.

The main effect of reader profile was statistically marked, $F(2,201) = 12.06$, $p < .001$, $\eta^2 = .11$, pointing to notable variance in the number of errors made by participants from all three profiles. Tukey HSD post hoc statistics used to clarify the final significance of the reader profile main effect showed that, overall, the number of semantic processing errors made by syntactic readers was markedly smaller than that of semantic and unspecified readers, while semantic readers were significantly more accurate than unspecified readers (see Table 4).

The main effect of orthographic background was also statistically marked, $F(3,201) = 21.30$, $p < .001$, $\eta^2 = .24$, suggesting that the error rates produced by participants from different orthographic backgrounds were not uniform. The absence of a significant interaction between the main effects of reader profile and orthographic background, $F(6,201) = 1.62$, $p > .05$, $\eta^2 = .05$, further implied that orthography-related variance was uniform over the three reader profiles (see Table 4). Tukey HSD for clarification of the final significance of the orthographic background main effect disclosed that, overall, participants reading in Arabic

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Table 5 Mean reaction times (in milliseconds) for real word and pseudohomophone conditions by reader profile and orthographic background (standard deviations in parentheses)

	Stimulus type		
Reader profile	Real word	Pseudohomophone	Phonological processing effect
Hebrew readers			
Syntactic readers	862 (170)	914 (280)	52 (336)
Semantic readers	797 (190)	857 (308)	60 (296)
Unspecified readers	785 (404)	696 (401)	−88 (507)
All	824 (198)	872 (302)	47 (324)
Arabic readers			
Syntactic readers	570 (251)	540 (212)	−29 (238)
Semantic readers	704 (233)	618 (312)	−86 (302)
Unspecified readers	644 (230)	500 (303)	−144 (277)
All	652 (232)	533 (298)	−118 (278)
English readers			
Syntactic readers	749 (126)	694 (237)	−55 (197)
Semantic readers	728 (125)	653 (131)	−75 (156)
Unspecified readers	776 (216)	623 (140)	−153 (204)
All	749 (153)	656 (168)	−93 (182)
German readers			
Syntactic readers	757 (170)	694 (401)	−63 (221)
Semantic readers	659 (130)	607 (191)	−52 (176)
Unspecified readers	660 (109)	544 (195)	−115 (160)
All	674 (132)	597 (195)	−77 (177)
All participants			
Syntactic readers	790 (194)	792 (281)	3 (286)
Semantic readers	723 (179)	701 (275)	−22 (348)
Unspecified readers	672 (211)	539 (265)	−133 (250)
All	721 (199)	666 (290)	−55 (263)

made significantly more semantic processing errors than participants from any other orthographic background (all $p < .001$). Deaf German readers made more errors than deaf Hebrew readers, but were statistically indistinguishable from deaf English readers. Finally, no difference was found in the error rates of deaf English and Hebrew readers.

The phonological processing effect (pseudohomophone score – real word score) yielded by ANOVA was statistically highly significant, $F(1,201) = 90.57$, $p < .001$, $\eta^2 = .31$, implying that, overall, participants made notably fewer errors when processing the semantic relationship between two real words than when processing the same relationship between a real word and a pseudohomophone, which required reliance on a phonological decoding strategy (see Table 4). The phonological processing effect was not found to significantly interact with reader profile, $F(2,201) = 1.29$, $p > .05$, $\eta^2 = .01$, or orthographic background, $F(3,201) = 1.48$, $p > .05$, $\eta^2 = .02$. Moreover, the triple interaction, phonological processing × reader profile × orthographic background, was close to zero, $F(6,201) = 0.22$, $p > .05$, $\eta^2 < .01$. These results indicate that the size of the phonological processing effect was not significantly biased by reader profile or orthographic background.

Processing Speed

For a deeper understanding of how reader profiles, orthographic background, and phonological word decoding skills biased the speed with which participants processed the semantic relationship between two real words versus a real word and a pseudohomophone, we conducted ANOVA computing reader profile (syntactic, semantic, and unspecified) and orthographic background (Hebrew, Arabic, English, and German) as two between-subject factors and phonological processing (real words vs. pseudohomophones) as a within-subject factor. Only response latencies of correct responses were analyzed. Mean reaction times with

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reference to reader profile and read orthography are presented in Table 5.

The main effect of reader profile failed to reach statistical significance, $F(2,201) = 1.44$, $p > .05$, $\eta^2 = .01$, suggesting that, overall, participants from the three profiles processed the semantic relationship in stimulus pairs with comparable speed. Of note, however, more fine-tuned post hoc analyses conducted with Tukey HSD indicated that unspecified readers were significantly faster in making a semantic decision than syntactic and semantic readers ($p \leq .001$), while semantic readers were significantly faster than syntactic readers ($p < .05$) (see Table 5).

The main effect of orthographic background was statistically marked, $F(3,201) = 8.23$, $p > .001$, $\eta^2 = .11$, suggesting that speed of processing varied according to the read orthography. Tukey HSD to further clarify the significance of this main effect indicated that, overall, Hebrew readers judged stimulus pairs notably slower than participants from all other examined orthographies (all $p < .01$). Arabic readers, in contrast, manifested overall markedly shorter reaction times than English readers ($p < .05$). The response latencies of German readers were not found to be different than those of English and Arabic readers.

The phonological processing main effect was statistically marked, $F(1,201) = 7.82$, $p < .01$, $\eta^2 = .04$, suggesting the existence of notable speed-of-processing differences between real word and pseudohomophone conditions (see Table 5). The phonological processing effect did not interact with reader profile or with orthographic background, nor was there a significant triple interaction between the three main effects, suggesting that speed-of-processing differences between real word and pseudohomophone conditions tended to be uniform across participants.

To further clarify the significance of the phonological processing main effect, we conducted two series of post hoc analyses by paired (one-tailed) *t*-tests—one comparing the three reader profiles in terms of speed of processing under real word and pseudohomophone conditions directly, and another comparing speed of processing under these conditions in relation to the read orthography. The first of these analyses showed that syntactic and semantic readers needed about the same time to determine the semantic relationship under both conditions, $t(50) = 0.09$, $p > .05$; $t(86) = -0.84$, $p > .05$, respectively, while unspecified readers processed the semantic relationship markedly faster under the pseudohomophone condition than under the real word condition, $t(74) = -4.64$, $p < .001$. The second analysis revealed that, while Hebrew readers had comparable reaction times for real word and pseudohomophone conditions, readers of Arabic, English, and German determined semantic relatedness under the pseudohomophone condition significantly faster, $t(59) = -5.29$, $p < .01$; $t(29) = -2.89$, $p > .01$; $t(61) = -3.44$, $p = .001$, respectively.

Relation Between Sentence Comprehension and Semantic Word Processing

Finally, we examined the relation between performance on the SCT (overall and for SI and SP sentences) and the semantic processing (speed and accuracy) of real words and pseudohomophones, for each reader profile. To do so, we conducted a series of Pearson's product-moment correlations. Findings from this line of analyses are presented in Table 6.

We further correlated the phonological processing main effect (response errors in the real word condition–response errors in the pseudohomophone condition) with overall sentence comprehension scores, and more specifically with the scores of SP and SI sentences. For syntactic readers, a weak but statistically significant negative correlation was revealed with regard to their overall sentence comprehension scores, $r = -.25$, $p < .05$, $n = 51$. However, there was no significant evidence for the existence of a similar correlation in analyses that focused on either SP or SI sentences. For neither of the two other reader profiles was the phonological processing main effect significantly correlated with sentence comprehension.

Discussion

The general aim of the present study was to offer a better understanding of the factors underlying the poor reading skills of the majority of the prelingually deaf and to clarify whether these factors are modified by peculiarities of the read orthography. We approached this task by comparing the performance of skilled and less skilled prelingually deaf readers on an SCT and a semantic word-processing task. We expected these

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Table 6 Correlations between sentence comprehension and semantic processing of real words and pseudohomophones by reader profile

	Error rate		Processing speed	
Sentence type	Real words	Pseudohomophones	Real words	Pseudohomophones
Syntactic readers (n = 51)				
Semantically plausible	−.29*	−.32*	.29*	.33**
Semantically implausible	−.54**	−.51**	ns	.24*
All sentences	−.48**	−.48**	.28*	.33**
Semantic readers (n = 87)				
Semantically plausible	−.39**	−.37**	.18*	.25*
Semantically implausible	ns	ns	ns	ns
All sentences	−.24**	−.26**	ns	ns
Unspecified readers (n = 75)				
Semantically plausible	ns	ns	ns	−.30**
Semantically implausible	.25*	ns	ns	ns
All sentences	ns	ns	ns	−.20*

*$p < .05$; ** $p < .01$.

two measures to externalize areas of weakness and strength that would allow us to determine the relative validity of three central hypotheses proposed in the literature to explain the poor reading skills manifested by prelingually deaf individuals: the phonological decoding deficit hypothesis; the structural knowledge deficit hypothesis; and the prior knowledge deficit hypothesis.

Phonological Decoding Deficit Hypothesis

Phonology is hypothesized to play a central role in the reading process of the hearing and the deaf alike (e.g., Bergeron et al., 2009; Nielsen & Luetke-Stahlman, 2002; Paul et al., 2009; Perfetti & Sandak, 2000). According to this approach, the poor reading skills of the prelingually deaf originate from a phonological word coding deficit that hampers the efficient recognition of written words, a dearth that is carried over to higher order processes and, finally, leads to reading comprehension failure.

To test the validity of this hypothesis, we first examined whether participants would process the semantic relationship between two real words faster and more accurately than between a real word and a pseudohomophone, which would suggest a phonological deficit. Indeed, participants from all three reader profiles categorized word dyads under the real word condition significantly more accurately than under the pseudohomophone condition. Given that they processed exactly the same words in both conditions, it can be concluded that participants failed to identify some of the pseudohomophones which they were able to recognize correctly when presented as real words (see also Miller, 2006a; Miller & Abu Achmed, 2010). In other words, their phonemic awareness failed to sustain recognition of words based on their phonological form, generated via the grapheme-to-phoneme conversion of an invalid letter string, a finding that highlights their phonological deficits. Of note, with the exception of better (syntactic and semantic) readers among the Hebrew participants, all tended to process the semantic relationship between words under the pseudohomophone condition faster than under the real word condition, a finding we will return to later.

We next assessed whether the more skilled deaf readers (syntactic readers) processed the semantic relationship under real word and pseudohomophone conditions more accurately and faster than the less skilled readers (semantic and unspecified readers). Consideration of the qualitative semantic word processing skills of each reader profile in isolation (Table 4) ostensibly corroborates a phonological decoding deficit hypothesis, as error rates increased with descending reading proficiency (unspecified > semantic > syntactic readers). However, examination of performance from a more quantitative perspective (the processing speed of each profile) suggests that some caution is warranted, since, contrary to expectations, speed of processing decreased as semantic processing accuracy increased (syntactic > semantic > unspecified

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readers). This negative tradeoff between speed and accuracy may imply that the advantage of better readers was somehow related to the decision-making process, rather than to recognition of the two words in a stimulus pair per se. In other words, it is possible that the better readers allocated more time to think about the semantic relationship between the two words than the less skilled readers and, consequently, made more accurate decisions.

Finally, we examined whether performance differences between skilled and less skilled deaf readers were smaller under the real word condition than the pseudohomophone condition. We looked for an interaction between the reader profile and the size of the phonological processing effect (real word—pseudohomophones), as less skilled deaf readers would be expected (according to the phonological decoding deficit hypothesis) to have weaker phonological processing skills than their skilled counterparts, a weakness that should be a disadvantage to them particularly when making semantic decisions with respect to pseudohomophones, where proper phonological decoding of the letter string is a prerequisite for success. Comparison of performance under real word and pseudohomophone conditions between the three reader profiles failed to corroborate this theory. Specifically, the qualitative (error rate) and quantitative (reaction time) phonological processing effects exhibited by the three profiles were not found to be different. This implies that the most skilled readers among the tested participants, the syntactic readers, were not markedly better phonological processors than the weakest among them, the unspecified readers (see also Miller, 2010b). Otherwise, the performance discrepancy between real word and pseudohomophone conditions would have been significantly smaller for the former. Moreover, for all three profiles, standard deviations related to the phonological processing effect were impressively high (see Tables 4 and 5), pointing to a rather remarkable intragroup difference in phonological processing skills. Finally, analyses failed to corroborate the existence of a significant negative association between the size of the phonological processing effect and the three reader profiles' comprehension of SP and SI sentences. The lack of such an association necessarily supports a conclusion that phonology may not occupy a central role in the reading of prelingually deaf readers.

Together, our findings suggest that contrary to the widely held position (e.g., Bergeron et al., 2009; Nielsen & Luetke-Stahlman, 2002; Paul et al., 2009; Perfetti & Sandak, 2000), variance in prelingually deaf readers' reading comprehension skills may not be directly causally related to their phonological processing skills. This conclusion supports research challenging the validity of a strong phonological coding deficit hypothesis in explaining reading failure in the prelingually deaf, due to a failure to find significant positive correlations between phonemic awareness, phonological word decoding skills, and reading comprehension (Hanson & Fowler, 1987; Hanson & McGarr, 1989; Izzo, 2002; Kyle & Harris, 2006; Leybaert & Alegria, 1993; McQuarrie & Parrila, 2009; Miller, 1997, 2007, 2010a, 2010b). Moreover, these findings from the current study supplement research showing that, despite markedly poor phonological processing skills, deaf readers process written words with hearing-comparable efficiency (Kargin et al., 2012; Koo et al., 2008; Miller, 2001, 2002, 2004a, 2004b, 2005a, 2005b, 2006a, 2006b, 2010b; Wauters et al., 2006).

The convergent evidence presented above does not necessarily mean that, unlike hearing readers, prelingually deaf readers cannot use phonology as a gateway to word meaning (e.g., Conrad, 1979; Hanson, 1982; Hanson et al., 1984; Hanson & Lichtenstein, 1990; Harris & Moreno, 2004; Krakow & Hanson, 1985). However, what it tells us is that the importance of phonology in the reading process of the prelingually deaf reader—and maybe also in that of the hearing reader (see Swanson, Trainin, Necoechea, & Hammill, 2003)—should be reconsidered (Miller & Clark, 2011).

Our interpretation of findings revealed as a result of these word processing experiments was based on the assumption that participants—as instructed by the experimenter—determined word relatedness by referring to word meaning. The two words in a word pair, however, eventually also exhibited some other common properties such as their lengths, overlapping orthographic peculiarities, word familiarity, etc. This raises the possibility that nonsemantic between-word commonalities and not the detection of a semantic

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relationship may have served participants for determining word relatedness, a possibility one may have to keep in mind in reading the above interpretation.

Although the use of nonsemantic word processing strategies cannot be definitely ruled out, the likelihood that such strategies were indeed involved seems to be rather low. First, as stated in the Procedure, prior to experimentation the experimenter exemplified the nature of the target relationship and verified its application by the participants during practice. It seems reasonable to assume that participants relied on one and the same strategy also under experimental conditions. Second, in the real word condition the error rates—although higher for unspecified readers—were relatively low and far below chance level for all three reader profiles. This suggests reliance on a consistent criterion for determining word relatedness. As can be seen in Appendix A, except for the semantic relatedness criterion, there seems to be no other criterion according to which half of the word pairs are related and the remainder not. In the absence of such balance, error rates logically should have been found to be markedly higher when using a nonsemantic strategy. Finally, the semantic relationship between the two words in a pair reflected basic human experience of primarily concrete nature and was presented by means of words familiar to the participants. The relatively small error rates indicate that the participants indeed relied on this experience in their judgment of the relatedness of the words comprising the stimulus pairs.

Structural Knowledge Deficit Hypothesis

As mentioned earlier, a proffered explanation for the impoverished reading comprehension skills of prelingually deaf readers assumes that they often lack adequate structural (syntactic) knowledge to sustain the integration of correctly recognized written words into broader ideas at the supra-lexical (sentence) level (Miller, 2000). It is noteworthy in this regard that in the present study, semantic processing accuracy under both real word and pseudohomophone conditions was correlated with the comprehension of both SP and SI sentences for syntactic readers, was correlated with SP but not SI sentences for semantic readers, and was indicative for neither of them for unspecified readers (Table 6). Given that the three profiles reflect readers that differed in their ability to use structural knowledge to elaborate sentence meaning, the divergent correlation pattern indeed points to deficits in structural knowledge as a potential explanation for variance in reading skills among prelingually deaf individuals.

To validate the tenability of the structural knowledge deficit hypothesis, we examined whether differences between skilled and less skilled deaf readers were more prominent regarding the comprehension of SI sentences than of SP ones, as proper understanding of the former requires structural processing (Miller, 2000). Our findings indeed show that the comprehension gap between syntactic and semantic readers was about three times larger for SI sentences in comparison to SP ones. Moreover, whereas comprehension scores of semantic readers were well above chance level with respect to SP sentences, they dropped markedly below chance level for SI sentences. This not only highlights the failure of semantic readers to generate sentence meaning via the application of proper structural knowledge, but may indicate—as suggested by some researchers (see Gormley & Franzen, 1978; Yurkowski & Ewoldt, 1986)—that they did not process the syntactic structure of the sentence in the first place, merely assimilating content words into their prior knowledge and experience in order to understand what they read. However, some caution is warranted in taking this interpretation too far given that semantic readers did not wrongly answer all SI sentences (2.43 [standard deviation 1.13] correct answers out of 8). This raises the possibility that—rather than skipping syntactic processing entirely—they may have relied on a limited set of simplistic syntactic rules (e.g., choosing the noun nearest the verb as the verb's subject) that failed to produce proper sentence comprehension most of the time (e.g., Quigley, Power, & Steinkamp, 1977).

As can be seen from Table 3, with the exception of those reading Arabic (the majority of whom were unspecified readers), semantic top-down processing of sentences was indeed the predominant reading strategy used by participants. This supports similar findings regarding prelingually deaf Hebrew readers at different levels of education (Miller, 2000, 2005a, 2006b).

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Interestingly, a more recent study (Miller, 2010b) also conducted with hearing reader suggests that the semantic reader profile reveal in the present study may not be unique to prelingually deaf readers. In fact, the Miller study convincingly shows that a substantial portion of hearing primary school students manifested a semantic reader profile, while all hearing readers at more advanced levels of schooling manifested a syntactic reader profile. This suggests that reliance on a semantic top-down processing strategy in reading may represent a transitional stage on the way to proficient reading.

Syntactic and unspecified readers both showed somewhat better understanding of SP sentences than SI sentences, a finding that implies some reliance on prior knowledge to make sense of the sentences. For syntactic readers, such top-down processing seems to have been backed up by a properly working syntax-based bottom-up processing strategy that corrected deviant sentence meaning generated by the mere top-down processing of content words. For unspecified readers, however, neither top-down nor bottom-up processes seemed to operate satisfactorily. This is obvious from their strikingly poor comprehension of both SP and SI sentences. It is, of course, tempting to interpret such generally poor performance as evidence for their reliance on a nonstrategic approach to reading, that is, they guessed the correct answer rather than elaborating it based on the information provided by the sentence. Interestingly, however, their marked below chance level performance, together with some evidence of reliance on a top-down processing strategy, indicate that this was not the case. Rather, it seems that—as suggested with respect to semantic readers—they approached reading with insufficient and/or simplistic structural knowledge (see also Quigley et al., 1977; Webster, 1986). However, unlike that of semantic readers, the poor performance participants with an unspecified reader profile on SP sentences seem to hint at a more general dearth, rooted in an apparent weakness to strategically apply prior knowledge and experience to what they read.

Prior Knowledge Deficit Hypothesis

To examine whether variance in prelingually deaf readers' ability to apply prior knowledge to the processing of written words explains variance in their reading comprehension skills (prior knowledge deficit hypothesis), we compared skilled and less skilled readers in terms of their accuracy in determining the semantic relationship between two items, expecting qualitative performance differences (error rates) between them to be similar under real word and pseudohomophone conditions. We indeed found skilled readers to make fewer errors (highly significant reader profile effect), with similar performance differences for the two conditions (no significant interaction between reader profile and phonological processing effect). These findings imply that poor reading skills in prelingually deaf readers may be causally linked to a more general weakness in their metacognitive structure and the way it interrelates and retains their prior knowledge and experience (see Ceci, 1996; Marschark & Wauters, 2008).

The present findings fail to disclose, in a straightforward manner, the direction of the relationship between participants' performance on the comprehension test and their ability to determine the semantic relatedness of two words. However, if one assumes language to facilitate the acquisition of knowledge, on the one hand, and to sustain its integration into well-organized metacognitive structures, on the other hand, the finding that variance in reading comprehension was paralleled by variance in the participants' semantic processing skills makes sense. In other words, better readers have better language skills that enhance the acquisition of knowledge, as well as its integration into well-organized metacognitive structures in permanent memory. This conclusion is supported by the finding that participants with deaf parents were overrepresented among the more skilled readers. It is also in line with the finding that Arab readers, who grew up in a diglossic context that limits their linguistic development, were predominately found among the poorest readers and manifested outstandingly high error rates in determining the semantic relationship between words.

Undoubtedly, both choosing answers on the comprehension test and determining the semantic relationship between two words involved the retrieval and application of prior knowledge. It is therefore of interest to take a closer look at qualitative correlations between the two tasks. As can be seen from Table 6,

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only for syntactic readers was within-group variance mutually reflected in the performance of the two tasks. For semantic readers, this was only true for SP sentences; for unspecified readers, it was not true in either of these categories. This suggests that, for semantic and unspecified readers, the contribution of semantic processing to comprehension scores was overshadowed, at least partly, by a reading/language-specific dearth, such as their apparently deficient structural knowledge.

Orthographic Background

A final question of this study referred to the impact of orthographic background on the reading skills of the prelingually deaf. Research comparing deaf individuals who read in different orthographies is strikingly lacking. As a consequence, conclusions from this study are necessarily of a general nature, but may nevertheless provide a starting point upon which future research in this area can be oriented. With this in mind, we examined results in terms of orthographic depth in an attempt to shed light on some rather prominent variance in the reading skills of deaf individuals from different orthographies (see Table 3). Specifically, we expected participants from countries with a shallow orthography (German) to be more prevalent among skilled deaf readers than participants from countries with deep orthographies (Hebrew, Arabic, and English).

Evidence based on exact translations for all four orthographies of the same test sentences failed to support this theory, however. German readers, despite their reading in shallow orthography, were notably underrepresented in the syntactic reader profile representative of skilled readers, in comparison to Hebrew and English readers who read in deep orthographies (see Table 6). These findings suggest that even if orthographic depth determines the acquisition of reading and the processing of written text to some degree, its effect on the reading comprehension of prelingually deaf readers is overshadowed by factors that are much more influential than gains originating from variance in the transparency of the grapheme-to-sound relationship across orthographies.

Having found quality of syntactic abilities to distinguish between skilled and less skilled deaf readers, it is, of course, tempting to assign differences in comprehension across the tested orthographies to variance in the syntactic processibility of the language. However, there are at least two findings that refute this assumption. First, Hebrew readers manifested enhanced comprehension not only of SI sentences, but also of SP ones, the comprehension of which was assumed to be less contingent on syntactic processing. Second, they also proved to be more effective in determining the semantic relationship between two words, a task that did not require syntactic processing. This suggests that variance in the reading skills of participants from different orthographic backgrounds may reflect differences of a more profound nature intrinsic to peculiarities of the read orthography and the way reading is acquired.

For example, Arab readers in Israel, unlike the other participants, are faced with a diglossic context in which the spoken dialect at home differs notably in vocabulary, structure, and phonology from Modern Standard Arabic (MSA), a literary language they learn to read at school. Research indeed has shown that acquiring mastery in MSA—essentially a second language for Arab readers—is a major challenge even for normally developing hearing readers (e.g., Ibrahim & Aharon-Peretz, 2005). This is because their ability to recruit their spoken language knowledge for the processing of written text is seriously restricted as a result of its linguistic distance from MSA. Up to school entry at age six, prelingually deaf Arab children are almost exclusively exposed to the spoken dialect, with no access to MSA in its spoken form on TV and radio, typical of their hearing counterparts. Moreover, they are likely to enter formal schooling with only rudimentary and often distorted knowledge of the code spoken in their surroundings. Taking these constraints into consideration, along with many others, their remarkably poor reading skills, reflected in performance on the comprehension test and their distribution among the reader profiles, can hardly be a surprise.

While linguistic distance between the spoken and the read language is likely to contribute to variance in the comprehension skills of deaf readers from different orthographic backgrounds, this does not explain the relatively poor comprehension of participants reading German. Clearly, additional orthographic factors have to be considered for a more holistic understanding of

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the barriers that prevent far too many deaf individuals from becoming fully literate. A thorough discussion of such factors, which is regrettably beyond the scope of this paper, requires analysis of our data in relation to more specific background variables, such as parental hearing status (Table 3), method of instruction, and home communication. It also requires consideration of a more basic level of text processing than that examined here (see Miller et al., 2012).

Practical Implications

In sum, the study findings suggest that poor comprehension skills of prelingually deaf readers are primarily related to variance in their ability to apply structural knowledge as they read for meaning. Comprehension failure in this population appears to arise from reliance on a reading strategy that skips the processing of sentence structure as a vital source of information, as well as reliance on insufficiently developed and/or deviant structural knowledge for the processing of text meaning. Although this reading strategy seems to sustain comprehension when the conveyed message refers to events reflected in the reader's prior knowledge and experience, it fails to turn reading into a tool for learning. The finding that, despite at least 6 years of formal schooling, about 75% of the tested participants (semantic and unspecified readers) manifested the above-mentioned deficits is alarming, particularly in view of evidence that fails to link variance in participants' reading comprehension with their grade level.

The prevalence of semantic and unspecified readers among deaf students was found to be remarkably high for all orthographies. Nonetheless, marked variance in their prevalence across the orthographies indicates that factors inherent to their orthographic background essentially determine the development of proper structural knowledge that sustains the adequate comprehension of written text. Regrettably, findings from the present study fail to disclose the exact nature of these factors, although linguistic distance between the spoken and the read language seems to be one potential candidate. More specific analyses currently being conducted on the data, together with findings from data collected with additional paradigms developed within the international reading project of which this study is a part (e.g., Kargin et al., 2012), are likely to provide further insight into the peculiarities in a particular orthography that determine reading proficiency among prelingually deaf individuals.

Notably, structural processing/knowledge deficits typical of the majority of the prelingual deaf students tested were paralleled by a difficulty to determine the semantic relatedness between two items. In other words, poor reading skills among deaf readers may be causally linked to a more general weakness in their metacognitive structure and the way it interrelates and retains their prior knowledge and experience. Our findings thus suggest that the impact of limited control of the spoken code may not be restricted to the domain of reading, but may also hamper the acquisition of knowledge and its integration into a well-organized metacognitive structure that sustains the efficient processing of information. Based on the findings from this study and from evidence reviewed elsewhere (Mayberry et al., 2011), competence in a language—and not necessarily spoken language—seems to be a fundamental requirement in this regard. The current finding that participants with deaf parents were overrepresented among the most successful (syntactic) readers and, even more important, were markedly underrepresented among the poorest readers directly supports this conclusion.

Nearly a century of research demonstrates that, on average, prelingually deaf readers graduate from high school with reading skills comparable to hearing third and fourth graders. Evidence from the present study suggests some conclusions with practical implications that may provide a starting point for changing this situation. First and foremost, it shows unequivocally that deafness per se does not create a condition that prevents individuals from becoming skilled readers. Second, it corroborates that the reading skills of prelingually deaf individuals develop independently of their phonological processing skills, suggesting that substantial efforts in the development of phonemic awareness may not be a conditio sine qua non strategy for enhancing their comprehension skills. Interestingly, some recent evidence obtained from a meta-analysis of research on the reading skills of hearing individuals indeed implies that the role of phonology in reading may have been overstated (Swanson et al., 2003). Third, evidence is straightforward and clear: *Full access*

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to language—including Sign Language—facilitates the acquisition of structural and semantic knowledge essential for the adequate processing of written language and, consequently, reduces risk of failure when prelingually deaf individuals are asked to read for meaning. This challenge seems to be magnified as such individuals grow up without possession of a full-fledged language that sustains and mediates the acquisition of such knowledge.

Given the nature of our findings and in line with evidence reviewed elsewhere (see Miller & Clark, 2011), it is clear that this situation is unlikely to change for the majority of prelingually deaf individuals unless they are provided with experience that includes the following: (1) Access to a language they can acquire easily and in accordance with their cognitive and emotional needs from intact role models in their surrounding; (2) the promotion of awareness of sentence word order as an important source of information in the processing/comprehension of written/spoken language; (3) instruction that systematically and explicitly traces modification in sentence meaning back to specific modification in syntactic structure; (4) opportunities to apply and generalize newly acquired rule-based knowledge through repeated practice within reader-relevant reading materials; (5) the provision of consistent feedback on accurate use of rules; and (6) encouragement of the development and use of prior knowledge in the form of elaborated knowledge domains and structures to allow deaf students to infer meaning from written texts by mapping words to prior metacognitive structures.

For the majority of prelingually deaf individuals, reasonable access to the sociocultural reality that surrounds them may not be possible except through reading. Therefore, curriculum that implements the principles outlined above not only increases the chance of enhancing their average reading comprehension, but is also likely to lead to a mutually more satisfactory integration of such individuals within the dominant hearing society.

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Appendix A

Real word and pseudohomophone stimulus pairs

Real word/real word				Real word/pseudohomophones			
Related		Unrelated		Related		Unrelated	
lock	key	bug	once	lock	kee	bug	wunce
popcorn	movie	comb	city	popcorn	moovee	comb	sity
pudding	dessert	sad	bone	pudding	dezirt	sad	boan
tree	green	orange	mitten	tree	grean	orange	mitin
video	camera	melon	pencil	video	kamera	melon	pensill
water	cup	cow	hope	water	kup	cow	hoap
cotton	candy	apple	glue	cotton	kandee	apple	glew
ski	snow	tent	pants	ski	snoh	tent	pance
birthday	balloon	thunder	parrot	birthday	ballune	thunder	parret
good	news	wind	cake	good	nuze	wind	kake
vegetable	potato	net	nose	vegetable	potaytoh	net	noze
ball	play	computer	crocodile	ball	pley	computer	crokodile
sand	box	water	office	sand	boks	water	awfice
boy	girl	hair	dream	boy	gurl	hair	dreem
sticky	honey	street	grape	sticky	huney	street	greype
toe	nail	winter	laundry	toe	nale	winter	lohndry
button	jacket	table	yellow	button	jackit	table	yelo
sky	blue	pink	cat	sky	bloo	pink	kat
happy	people	paper	actor	happy	peeple	paper	akter
track	train	truck	ear	track	treyn	truck	eer

For experimentation, the semantically related and the semantically unrelated word pairs were presented randomly mixed.

Appendix B

Examples of test sentences

Semantically plausible	Semantically implausible
One subordinate clause	
The teacher who caught Sara copying homework left the classroom.	The boy who saw the policeman stealing gum escaped through the window.
Who copied homework?	Who stole the gum?
Sara	the policeman
the teacher	the boy
The kindergarten teacher told the girl to climb the ladder in the playground.	The patient told the doctor to lie on the bed in the operating room.
Who was told to climb the ladder?	Who was told to lie on the bed?
the girl	the patient
the kindergarten teacher	the doctor
Two subordinate clauses	
The student who teased the teacher who was sitting in the park was punished by the principal.	The baby who was watching the babysitter playing in the crib got money from the mother.
Who was punished?	Who got money?
the principal	the babysitter
the student	the mother
the teacher	the baby
The woman who was walking down the street gave some chocolate to the girl who helped her grandmother.	The mother who returned home gave a drink of milk to the babysitter who was watching the baby.
Who got the chocolate?	Who got the milk?
the woman	the baby
the girl	the mother
the grandmother	the babysitter

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