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Research Article

Orthographic, Phonological, and Semantic Dynamics During Visual Word Recognition in Deaf Versus Hearing Adults

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Purpose: Studies on reading in individuals with severe-to-profound hearing loss (deaf) raise the possibility that, due to deficient phonological coding, deaf individuals may rely more on orthographic–semantic links than on orthographic–phonological links. However, the relative contribution of phonological and semantic information to visual word recognition in deaf individuals was not directly assessed in these studies. The aim of the present study, therefore, was to examine the interplay between orthographic, phonological, and semantic representations during visual word recognition, in deaf versus hearing adults.
Method: Deaf and hearing participants were asked to perform a visual lexical decision task in Hebrew. The critical stimuli consisted of three types of Hebrew words, which differ in terms of their relationship between orthography, phonology, and semantics: unambiguous words, homonyms, and homographs.
Results: In the hearing group, phonological effects were more pronounced than semantic effects: Homographs (multiple pronunciations) were recognized significantly slower than homonyms or unambiguous words (one pronunciation). However, there was no significant difference between homonyms (multiple meanings) and unambiguous words (one meaning). In contrast, in the deaf group, there was no significant difference among the three word types, indicating that visual word recognition, in these participants, is driven primarily by orthography.
Conclusion: While visual word recognition in hearing readers is accomplished mainly via orthographic–phonological connections, deaf readers rely mainly on orthographic–semantic connections.

Interactive "triangle" models of word recognition (e.g., Grainger & Ferrand, 1994, 1996; Seidenberg & McClelland, 1989) assume a reading mechanism in which orthographic, phonological, and semantic representations are fully interconnected (i.e., are bidirectionally connected to each other). With practice, these bidirectional mappings become automatic such that orthographic representations automatically activate their corresponding phonological and semantic representations, and these in turn influence the recognition process via feedback connections. Interactive models further assume that visual word recognition is influenced by the consistency of the mappings between orthographic, phonological, and semantic codes. Cross-code consistency is maximal when there is a one-to-one relation between different codes. Inconsistencies occur when a single orthographic representation is associated with multiple phonological or with multiple semantic representations, or vice versa. Thus, in a fully interconnected network, consistent symmetrical relations result in stable and fast activation, whereas inconsistent asymmetrical relations should slow down word recognition (Grainger & Zeigler, 2008; Peleg et al., 2010).

Consistent with this interactive assumption, studies in hearing adults have repeatedly shown that visual word recognition (an orthographic task) is influenced not only by orthographic information but also by phonological and semantic information (e.g., Pexman et al., 2001; Rodd et al., 2002). For example, Pexman et al. (2001) utilized a visual lexical decision task to investigate the role phonological codes play in visual word recognition. In this task, letter strings are presented, one at a time, and participants are asked to decide, as quickly and as accurately as possible, whether the presented letter string is a word or a nonword. Phonological effects were investigated by comparing homophones (words with high-frequency homophonic counterparts,

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e.g., *maid* – MADE) with nonhomophone control words (e.g., *mess*). In both cases, a "yes" response is required. However, if orthographic representations automatically activate their corresponding phonological representations and if these phonological activations influence visual word recognition, then homophones and nonhomophones should be processed differently. Consistent with this prediction, Pexman et al. (2001) observed a homophone interference effect. That is, it was more difficult for participants to recognize homophones than nonhomophones, probably due to the orthographic competition created by feedback activation from phonology.

Similarly, to investigate semantic effects in visual word recognition, Rodd et al. (2002) utilized the lexical decision task in the context of three types of words: homonyms (words associated with two or more unrelated meanings, e.g., *bat*), polysemous words (words associated with two or more related meanings, e.g., *chicken*), and unambiguous words (words associated with a single meaning, e.g., *guitar*). Again, in all cases, a "yes" response is required. However, if orthographic representations automatically activate their corresponding semantic representations and if these semantic activations influence visual word recognition, then words that differ in terms of their relationship between orthography and semantics should be processed differently. Indeed, consistent with this prediction, Rodd et al. reported shorter RTs for polysemous words than for unambiguous words, due to their rich semantic representations, and slightly longer RTs for homonyms than for unambiguous words, due to the competition between the different meanings. Taken together, such findings demonstrate that visual word recognition, in hearing readers, involves not only orthographic but also phonological and semantic processes.

As detailed below, studies on reading in individuals with severe-to-profound hearing loss (deaf) raise the possibility that reading processes in deaf readers may be qualitatively different from those in hearing readers. (Note that, in this article, we use the word "deaf" to refer to all people with severe-to-profound hearing loss, regardless of their preferred mode of communication.) In particular, it has been suggested that, due to deficient phonological coding, deaf individuals may rely more on orthographic–semantic links than on orthographic–phonological links (e.g., Bélanger et al., 2013; Emmorey et al., 2013; Ormel et al., 2010; Yan et al., 2015). However, the relative contribution of phonological and semantic information to visual word recognition in deaf individuals was not directly assessed in these studies. The aim of the present study, therefore, was to examine the interplay between orthographic, phonological, and semantic representations during visual word recognition, in deaf versus hearing adults.

Reading Abilities in Deaf Individuals

The majority of deaf children show difficulties learning to read whether they speak or sign (T. Allen, 1986; Chamberlain & Mayberry, 2008; Conrad, 1979; Geers, 2003; Mayberry, 2002; Miller, 2006; Musselman, 2000; Strong & Prinz, 1997; Wauters et al., 2006). About 60% of students leaving high school read at or below fourth grade (T. Allen, 1986; T. E. Allen, 1994). Only about 10% of deaf students read beyond eight-grade level (Traxler, 2000). Even among deaf high school students who use cochlear implant (CI) from early childhood, only 36% read at ninth-grade level or above, whereas 17% read below fourth-grade level (Geers & Hayes, 2011). Thus, although fluency in reading is essential for academic achievements, many deaf individuals lag behind their peers despite early intervention and technological advances that improve access to sound through hearing aids (HAs) and CIs (e.g., Harris et al., 2017; Mayberry et al., 2011; Pimperton et al., 2016).

Reading difficulties in deaf individuals are in many cases attributed to difficulties with phonological processing, including phonological awareness (i.e., the ability to attend to and make judgments about the general sound structure of language; see Schuele & Boudreau, 2008), and phonological working memory (e.g., Nielsen & Luetke-Stahlman, 2002; Ormel et al., 2010; Paul et al., 2009; Wang et al., 2008). It is assumed that deaf readers have difficulties in developing phonological representations of words through the auditory channel because of limited or partial access to sound. Hence, nonauditory channels including visual lip reading and articulatory speech production might be involved in phonological representations (e.g., Elliott et al., 2012). However, limited auditory information combined with nonauditory cues may be insufficient for developing fully specified phonological representations of words (Kelly & Barac-Cikoja, 2007). Thus, the process of conversion from print to phonology through reading might be compromised (e.g., Perfetti & Sandak, 2000).

Reduced phonological processing in deaf participants may include both phonological skills, such as phonological memory, awareness, and manipulation of sounds in words (Geers & Hayes, 2011), as well as automatic activation of phonology during the reading process (e.g., Ormel et al., 2010). Geers and Hayes (2011), for example, assessed the contribution of phonological skills to reading in deaf adolescents with CI. The phonological skills included manipulation of sounds in words, phonological memory, and phonological production. The results show that phonological measures played a major role in successful reading, explaining 38.3% of added variance in literacy level (reading and writing). Furthermore, the contribution of phonological processing skills was independent of the influence of performance intelligence. Other studies with prelingual deaf participants also show associations between phonological awareness and reading (Dyer et al., 2003; Hogan et al., 2005; Holmer et al., 2016; Luckner & Handley, 2008). Some studies suggest that deaf children can develop phonological skills, but these skills lag compared to hearing children (Hanson & Fowler, 1987; Nielsen & Luetke-Stahlman, 2002; Perfetti & Sandak, 2000; Spencer & Tomblin, 2009; Sterne & Goswami, 2000). It has also been argued that deaf persons use phonological skills in reading to the extent they gained proficiency in reading, speech intelligibility, and lip reading (Perfetti & Sandak, 2000).

Thus, according to these studies, access to phonology is directly correlated with reading success.

Other studies, however, suggest that phonological processing abilities (e.g., phonological awareness) are not necessary for reading acquisition in deaf participants. According to these studies, reading ability in deaf readers is associated with the development of orthographic knowledge, as well as with vocabulary and higher level syntactic and semantic knowledge, but not necessarily with phonological abilities (e.g., T. E. Allen et al., 2009; Chamberlain & Mayberry, 2000; Clark et al., 2011; Izzo, 2002; Koo et al., 2008; Kyle & Harris, 2006; Mayberry et al., 2011; Miller & Clark, 2011). Taken together, these studies suggest that deaf readers may rely more on orthographic and semantic information than phonological information during visual word recognition.

Visual Word Recognition in Deaf Individuals

Studies on visual word recognition in deaf individuals focused mainly on phonological effects. Empirical findings obtained in these studies, however, have not been monolithic. On the one hand, several studies have shown that phonological encoding (i.e., spelling to sound translation) is available to deaf readers (Gutierrez-Sigut et al., 2017; Hanson & Fowler, 1987; Transler & Reitsma, 2005). For example, in a seminal study, Hanson and Fowler (1987) utilized a lexical decision task, in which response times (RTs) to orthographically similar rhyming (e.g., WAVE – SAVE) and nonrhyming (e.g., HAVE – CAVE) word pairs were compared. Both deaf college participants (American Sign Language signers) and hearing college participants showed shorter RTs to rhyming (phonologically similar) pairs than to nonrhyming (phonologically dissimilar pairs), indicating that access to phonological information is possible despite prelingual and profound hearing loss.

Similarly, Transler and Reitsma (2005) utilized a lexical decision task, in which the critical stimuli were either pseudohomophones (nonwords that sound like real words, e.g., *brane* that sound like "brain") or orthographically matched pseudowords (nonwords that do not sound like real words). The participants were deaf children (Dutch Sign Language signers) and hearing children matched on written word recognition. Both hearing children and deaf children made significantly more mistakes on pseudohomophones than on control pseudowords. Another piece of evidence for automatic sublexical phonological recoding in deaf readers comes from a study conducted by Gutierrez-Sigut et al. (2017). In that study, deaf adults who used Spanish Sign Language and matched hearing controls were asked to perform a lexical decision task in conjunction with the masked priming paradigm. In both groups, target recognition was speeded by the prior brief presentation of a masked pseudohomophone prime (koral – CORAL) relative to an orthographic control (toral – CORAL). Taken together, such results indicate that phonological encoding is available to deaf readers from the early sublexical stages of visual word recognition.

On the other hand, other studies did not find evidence for phonological activation during visual word recognition in deaf participants (e.g., Beech & Harris, 1997; Cripps et al., 2005; Merrills et al., 1994; Waters & Doehring, 1990). For example, Beech and Harris (1997) investigated phonological effects in visual word recognition by comparing the recognition of two types of real words and two types of nonwords. The real words were either words with regular spelling–sound correspondences (e.g., this) or irregular words (e.g., knew). The nonwords consisted of pseudohomophones or nonpseudohomophones. Compared to reading-age-matched hearing controls, deaf children (whose preferred mode of communication was either by signing or exclusively oral) were not affected by these phonological manipulations, indicating that phonological encoding is not an automatic process in deaf children.

Similarly, Cripps et al. (2005) asked participants to perform a lexical decision task on targets preceded briefly by identical word primes (e.g., sample – SAMPLE), unrelated word primes (caught – SAMPLE), pseudohomophone nonword primes (bloo – BLUE), or unrelated nonword primes (caft – BLUE). The participants were English speakers (i.e., hearing) and American Sign Language signers (i.e., deaf). In both groups, target recognition was speeded by the prior brief presentation of a masked identical prime (sample – SAMPLE) in comparison to unrelated controls (caught – SAMPLE). However, only hearing participants showed a pseudohomophone facilitation effect, that is, faster responses in the pseudohomophone (bloo – BLUE) than in the nonpseudohomophones condition (caft – BLUE). On the basis of these results, the authors concluded that deaf signers do not have automatic access to the word's phonology. These results demonstrate that at least under certain conditions (e.g., when the language in question is less transparent), deaf readers do not rely on phonological information in the same way that hearing readers do.

While phonological processing differences in deaf and hearing readers are now well documented (e.g., Bélanger et al., 2013; Emmorey et al., 2013; Ormel et al., 2010), only a few studies focused on differences in the use of semantic information during visual word recognition (Yan et al., 2015). Interestingly, these studies suggest that the connections between orthography and semantics may be more robust (i.e., stronger) for deaf compared to hearing readers. In particular, Yan et al. (2015) manipulated different types of information available in the parafovea (i.e., before the word is fixated) during the reading of Chinese sentences and showed that Chinese deaf readers process parafoveal semantic information more efficiently than hearing readers. However, Yan et al. focused on sentences (rather than separate words), thereby emphasizing comprehension (rather than recognition) processes. The aim of the present study, therefore, was to further investigate the role of phonological and semantic factors in visual word recognition in deaf versus hearing individuals.

The Present Study

Studies on reading in deaf individuals raise the possibility that reading processes in deaf readers may be qualitatively different from those in hearing readers. In particular, these studies suggest that, due to deficient phonological coding, deaf readers (as opposed to hearing readers) may rely more on orthographic–semantic links than on orthographic–phonological links. However, the relative contribution of phonological and semantic information to visual word recognition in deaf readers was not directly assessed in these studies. The aim of the present study, therefore, was to examine the interplay between orthographic, phonological, and semantic representations during visual word recognition, in deaf versus hearing readers. Previous studies on visual word recognition in deaf individuals focused either on children (whose reading ability is still in the developmental stage) or on adults (both skilled and less-skilled readers). The current study focused on highly proficient deaf adult readers. Our goal was to investigate whether visual word recognition in highly skilled deaf and hearing readers is qualitatively different. Discovering these differences can provide insight not only on the mechanisms underlying skilled reading but also on reading education in the deaf population. Specifically, understanding how skilled reading is attained by deaf individuals can provide insight on how literacy skills in deaf learners can be developed and improved.

In particular, the present study focused on prelingually and profoundly deaf individuals who have achieved university-level reading skills and who use spoken language as their main mode of communication. (Note that, in Israel, deaf adults who use spoken language as their main communication mode are very common; see also Gold & Segal, 2017, 2020.) As mentioned above, several studies have suggested differences in the way deaf and hearing readers identify visual words (e.g., Bélanger et al., 2013; Emmorey et al., 2013; Yan et al., 2015). However, these studies typically focused on deaf readers who use sign language as their main mode of communication. A question arises whether similar differences can be found in the case of oral-deaf readers. On the one hand, this population might be expected to read more like hearing readers (e.g., Barca et al., 2013). On the other hand, several studies reported significant differences between these two groups (e.g., Beech & Harris, 1997; Campbell & Wright, 1988; Waters & Doehring, 1990). In particular, it has been suggested that, despite technological advances that improve access to sound through HAs and CIs, oral-deaf readers may still exhibit phonological deficiencies that may reduce their ability to automatically activate phonological representations during visual word recognition (e.g., Herman et al., 2019). Thus, the present study investigated whether oral-deaf readers use orthographic, phonological, and semantic information in the same way that hearing readers do.

To directly examine orthographic, phonological, and semantic dynamics during visual word recognition, deaf and hearing participants were asked to perform a lexical decision task in Hebrew (i.e., to decide whether a given letter string is a real word in Hebrew or not). The critical stimuli consisted of three types of Hebrew words that differ in terms of their relationship between orthography, phonology, and semantics: (a) unambiguous words, the orthographic representation is associated with one pronunciation and one meaning (e.g., כיסא /kise/ "chair"); (b) homonyms, the orthographic representation is associated with one pronunciation, but with multiple meanings (e.g., גיל /gil/ "age" or "happiness"); and (c) homographs, the orthographic representation is associated with multiple pronunciations, each associated with a different meaning (e.g., ספר /sefer/ "book" or /sapar/ "hairdresser"; for English examples, see Table 1). (Note that, in contrast to Indo-European languages, in Hebrew, most letters represent consonants, and vowels may be optionally added as diacritical points. Because the vowel marks are usually omitted, Hebrew readers often encounter not only homonyms, e.g., bank, but also homographs, e.g., tear.) If the recognition of a written word is influenced by its semantic and phonological features, as predicted by interactive "triangle" models, then these three types of words should be processed differently.

Specifically, phonological effects were investigated by comparing the processing of homonyms and homographs (e.g., Bitan et al., 2017; Peleg & Eviatar, 2009, 2012, 2017). Both word types have one orthographic representation associated with two different meanings. They are different, however, in terms of the relationship between orthography and phonology: In the case of homonyms (e.g., bank), the orthographic representation is associated with a single phonological code. In the case of homographs (e.g., tear), the orthographic representation is associated with two phonological codes (e.g., tear: /tɪər/ or /tɛər/). If visual word recognition relies on orthographic–phonological connections, then homographs should be more difficult to recognize, due to the competition between the different phonological alternatives.

Semantic effects were investigated by comparing the processing of homonyms and unambiguous words (e.g., Bitan et al., 2017; Rodd et al., 2002). Both word types have one orthographic representation associated with one phonological code. They are different, however, in terms of the relationship between orthography and semantics: In the case of unambiguous words, the orthographic representation is associated with one meaning. In the case of homonyms (e.g., bank), the orthographic representation is associated with two different meanings (e.g., the money

Table 1. Examples in English for each word type.

Word type	Orthography	Phonology	Semantics
Unambiguous *tent*	tent	tent	tent
Homonyms *bank*	bank	/bæŋk/	money river
Homographs *tear*	tear	/tɪr/ /ter/	eye hole

vs. the river meaning of bank). If visual word recognition relies on orthographic–semantic connections, then homonyms should be more difficult to recognize, due to the competition between the different semantic alternatives.

In particular, we speculated that while the connections between orthography and phonology may be more robust for hearing compared to deaf participants (e.g., Bélanger et al., 2013), the connections between orthography and semantics may be more robust for deaf readers compared to hearing readers as they rely on this channel more frequently (Yan et al., 2015). That is, we expected phonological effects (i.e., slower RTs for homographs than for homonyms) to be more pronounced in hearing than in deaf participants and semantic effects (i.e., slower RTs for homonyms than for unambiguous words) to be more pronounced in deaf than in hearing participants.

Method

Participants

A total of 40 native Hebrew speakers participated in the study. Twenty participants (six men, 14 women) with prelingual severe-to-profound hearing loss (mean unaided pure-tone average [PTA] in the better ear was 93.33 dB HL, $SD = 17.14$) composed the deaf group, and 20 hearing participants (six men, 14 women) composed the control group. All participants (hearing and deaf) were undergraduate or graduate students at Tel-Aviv University or at other institutes for higher education in Israel.

All the deaf participants were habilitated aurally and used spoken language for everyday communication. They all had hearing parents. They studied in regular schools with students who can hear and received the same literacy instruction as their normal-hearing classmates. In addition, they received individual treatment from a speech and language pathologist once a week during elementary school and junior high school for improving speech and language skills. The mean (M) age of the deaf participants was 27.4 years ($SD = 2.9$). They were all diagnosed at birth or during the first months of life (mean age of diagnosis of hearing loss [in months] was 4.11, $SD = 4.48$). Six deaf participants used HAs in both ears, three participants used one HA and no additional device in the other ear, four participants used CIs in both ears, five participants used one CI and no additional device in the other ear, and two participants used CI in one ear and HA in the other ear. Mean aided PTA in the better ear = 19 dB HL, $SD = 2.47$. All deaf participants had verbal IQ scores within the normal range (range: 98–117, $M = 107.8$, $SD = 5.4$) as tested by the verbal section of the Hebrew adaptation of the Wechsler Adult Intelligence Scale–Third Edition (WAIS-III; Wechsler, 1997). (None of these background variables [verbal IQ, PTA in the left and right ear, and age of diagnosis] correlated with performance on the lexical decision task (all p values > .10) and thus will not be discussed any further.) The hearing participants were matched to the deaf participants with regard to age ($M = 26.3$, $SD = 3.5$; $t = -0.29$, $p = .78$; Cohen's $d = .0$), gender (six men, 14 women), and level of education (all undergraduate and graduate university students).

Stimuli

The experimental materials consisted of three types of Hebrew words (all nouns): 25 homographs (e.g., tear - /tɪər/ /tɛər/), 25 homonyms (e.g., bank), and 25 unambiguous words ($N = 75$). Stimuli were selected following a battery of pretests: First, to ensure that the three word types are balanced in terms of subjective frequency, 90 participants were presented with the words and were asked to rate their frequency on a 10-point scale, ranging from 0 (*never encountered*) to 9 (*highly frequent*). The average rates on the frequency scale did not vary across conditions: homographs: 7.33, homonyms: 7.54, and unambiguous: 7.55, all p's > .39.

In addition, two pretests were performed in order to ensure that the two types of ambiguous words (i.e., homonyms and homographs) were balanced in terms of polarity (i.e., the distance in salience between the two meanings of the ambiguous word). In the first pretest, 20 participants were presented with the ambiguous words and their paraphrased meanings and were instructed to indicate the frequency of each one of the meanings of a given ambiguous word on a 1–10 scale. The average score of each meaning across judges multiplied by 10 served as the salience score for that meaning in Pretest 1. In Pretest 2, 20 different participants were presented with the ambiguous word and were instructed to write down their first association of that word. On the next screen, the different meanings of the ambiguous word were presented and participants had to ascribe their association to the most appropriate meaning. The percentage of participants that selected each meaning served as the salience score for that meaning in Pretest 2. A combined salience score was computed for each meaning as the average score from Pretests 1 and 2. The difference between the salience scores of the two selected meanings served as the polarity index, which was balanced across the two conditions: homographs: 30.53, homonyms: 29.56, $p > .87$. Furthermore, in order to ensure that the deaf participants were familiar with both meanings of each homonym/homograph, a posttest was conducted in which the same group of deaf participants were presented with the ambiguous words and their paraphrased meanings and were instructed to indicate their degree of familiarity with each one of the meanings of a given homonym/homograph on a scale from 1 (*not at all familiar*) to 5 (*extremely familiar*). The results of the posttest revealed that all the participants were familiar with both meanings of the ambiguous words (all ratings ≥ 3).

The three types of words were also balanced in terms of length (number of letters) and objective frequency. The means for number of letters—homographs: 3.28, homonyms: 3.40, and unambiguous: 3.40—did not differ (all $ps > .45$). Objective frequency was determined by using the word-frequency database for printed Hebrew (Frost & Plaut, 2005). The means were 49.12, 49.36, and 48.16 for homographs, homonyms, and unambiguous words, respectively, and did not differ (all $ps > .94$).

Finally, given that the 75 experimental words always required a "yes" response, 75 pronounceable nonwords were added as fillers. Words and nonwords were matched in terms of length (number of letters)–words: 3.36, nonwords: 3.37, $p > .89$.

Procedure

Participants were tested individually in a sound-attenuated room, seated approximately 60 cm from the screen. Participants were asked to make a lexical decision (i.e., to decide whether each letter string is a real word in Hebrew or not) by pressing a "Yes" or a "No" key. The correct response for all experimental stimuli was "Yes," and for the additional fillers "No." After participants read and understood the instructions, a practice session consisting of 10-letter strings, half requiring a "Yes" response and half requiring a "No" response, was conducted, during which a visual feedback for correct and incorrect responses was provided. The same list of 150 letter strings (75 word and 75 nonwords), divided into six blocks, was presented randomly to each participant. At the start of each trial, participants were presented with a central fixation marker for 500 ms. The offset of the marker was followed by a centrally presented letter string, which remained on the screen until participants responded or until 2,000 ms. If a letter string expired without a response, a tone signified the move to the next trial. Tonal feedback was provided for incorrect decisions. RTs were measured from the onset of letter-string presentation, and accuracy in each trial was recorded. All the participants signed an informed consent form before the research session. The procedure was approved by the ethical committee of Tel-Aviv University, Israel.

Results

Two participants (one deaf and one hearing participant) whose RTs were particularly slow (RTs > 2.5 *SD*s from the sample average) were removed such that overall results are based on 38 participants: 19 deaf and 19 hearing participants. (The two groups were still matched in terms of age, sex, and level of education.) A two-way mixed analysis of variance was conducted for both accuracy data and correct RT data, with participant group (deaf vs. hearing) as a between-participants factor, and word type (homographs, homonyms, or unambiguous words) as a within-participants factor. Mean RTs and accuracy rates for the two participant groups in the different word conditions are provided in Table 2.

RT data: A normality test (Kolmogorov–Smirnov) confirmed normal distribution of RTs in both groups ($p > .05$). The RT analysis showed a main effect of word type, $F(2, 72) = 6.94$, $p = .004$, $\eta^2 = .16$, but no main effect for participant group, $F(1, 36) = 2.01$, $p = .165$, $\eta^2 = .053$. Importantly, as shown in Figure 1, the hypothesized two-way interaction between participant group and word type was significant, $F(2, 72) = 3.46$, $p = .048$, $\eta^2 = .09$. Further pairwise comparisons with Bonferroni correction (adjusted standard 0.05/6 = .008) showed that, in the group of hearing participants, RTs for homographs were longer compared to homonyms ($p = .008$, Cohen's $d = 0.47$) and unambiguous words ($p = .0005$, Cohen's $d = 0.78$), but there was no significant difference between homonyms and unambiguous words ($p = .02$). In contrast, in the group of deaf participants, there was no significant difference between homographs and homonyms ($p = .016$). However, a statistically marginal difference was found between homonyms and unambiguous words ($p = .01$, Cohen's $d = 0.48$).

Accuracy data: Average accuracy in the lexical decision task across all conditions and both participant groups was 98%. There was no main effect for participant group, $F(2, 72) = 0.000$, $p = 1.00$, $\eta^2 = .00$, or word type, $F(2, 72) = 0.027$, $p = .76$, $\eta^2 = .08$, and no interaction between the two factors, $F(2, 72) = 0.027$, $p = .76$, $\eta^2 = .08$.

Table 2. Mean correct response times (RTs), in milliseconds, and percentages of accuracy as a function of participant group (hearing vs. deaf) and word type (homographs, homonyms, or unambiguous words). Standard deviations are presented in parentheses.

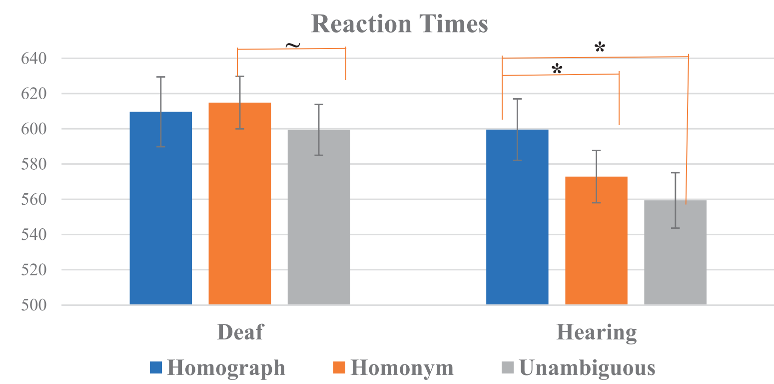
Participant group	Word type	Mean RT	Accuracy
Hearing	Homographs	600 (86)	98 (3)
	Homonyms	573 (65)	99 (2)
	Unambiguous words	559 (63)	99 (3)
Deaf	Homographs	610 (76)	98 (3)
	Homonyms	615 (65)	98 (3)
	Unambiguous words	599 (69)	99 (3)

Discussion

The aim of the present study was to investigate the interplay between orthographic, phonological, and semantic representations in deaf versus hearing readers. In particular, we speculated that while the connections between orthography and phonology may be more robust for hearing compared to deaf participants, the connections between orthography and semantics may be more robust for deaf compared to hearing readers.

To investigate these assumptions, deaf and hearing participants were asked to perform a visual lexical decision task in Hebrew. The critical stimuli consisted of three types of Hebrew words, which differ in terms of their relationship between orthography, phonology, and semantics: (a) unambiguous words (e.g., כיסא /kise/ "chair"), (b) homonyms (e.g., גיל /gil/ "age" or "happiness"), and (c) homographs (e.g., ספר /sefer /"book" or /sapar/ "hairdresser"). The three types of words were balanced in terms of polarity, frequency, and length. Thus, differences in their recognition process can be attributed to their phonological and/or semantic status. Specifically, semantic effects were investigated by comparing the processing of homonyms (multiple meanings) and unambiguous words (one meaning); phonological effects were investigated by comparing the processing of homographs (multiple pronunciations) and homonyms (one pronunciation).

Figure 1. Response times on correct responses as a function of participant group (hearing vs. deaf) and word type (homographs, homonyms, or unambiguous words). *Significant, $p \leq .05$; ~marginally significant, $p = .06$.



The results of the study indicate a qualitative difference between hearing and deaf participants, as phonological effects were found only in the case of hearing participants. Moreover, in the hearing group, phonological effects were more pronounced than semantic effects: Homographs (multiple pronunciations) were recognized significantly slower than homonyms or unambiguous words (one pronunciation). However, there was no significant difference between homonyms (multiple meanings) and unambiguous words (one meaning). In contrast, in the deaf group, there was no significant difference among the three word types, indicating that visual word recognition, in these participants, is driven primarily by orthography. In what follows, we discuss these findings in more detail.

Phonological Effects

Consistent with previous studies (e.g., Bitan et al., 2017; Peleg & Eviatar, 2009, 2012, 2017; Pexman et al., 2001), we show that phonological activations during visual word recognition are automatic in hearing readers. That is, hearing participants recognized homonyms (one pronunciation) faster than homographs (multiple pronunciation), even though making a word/no-word judgment does not require the activation of phonological representations. In particular, these results replicate and extend a previous fMRI study in Hebrew (Bitan et al., 2017) that showed that the presentation of ambiguous words without any context resulted in greater activation for homographs than for homonyms in left IFG (inferior frontal gyrus) pars opercularis, known to be associated with phonological decoding of written words (e.g., Bitan et al., 2005). Taken together, the findings with hearing participants are consistent with the idea that the recognition of a familiar letter string is modulated by the way its orthographic representation is mapped onto its phonological representation (e.g., Frost, 1998; Grainger & Ferrand, 1994, 1996; Seidenberg & McClelland, 1989).

In contrast, deaf participants did not spontaneously activate phonological codes during visual word recognition. That is, they did not distinguish between homonyms and homographs. These findings are consistent with previous studies that reported reduced access to phonology in deaf participants (e.g., Beech & Harris, 1997; Cripps et al., 2005). However, while these studies focused mainly on deaf participants who used sign language, the present study focused on deaf participants who received auditory habilitation early in life and used oral–aural communication as their main communication mode. Thus, the present findings add to our knowledge of visual word recognition in oral deaf readers by showing that, despite of the use of spoken language as their main communication mode in everyday situations and in academic life that may facilitate phonological representation of words and despite their academic achievements that require good reading and writing skills, the deaf participants of the present study did not show evidence for activation of phonological representations during visual word recognition.

Our findings, however, are inconsistent with several studies suggesting that phonological encoding is available to deaf readers (e.g., Gutierrez-Sigut et al., 2017; Transler & Reitsma, 2005). A possible explanation for these inconsistent findings may be related to the specific language and/or to the type of stimuli used in these studies. First, it is possible that phonological effects are more pronounced in languages with a more transparent orthographic system (i.e., an orthographic system with highly regular grapheme–phoneme correspondences). In Spanish, for example, a given letter of the alphabet is almost always pronounced the same way irrespective of the word it appears. Hebrew, on the other hand, is considered an extremely opaque orthography in which spelling to sound correspondences can be very ambiguous. Given that the current study was conducted in Hebrew, a question that remains open is whether the lack of phonological effects found in this study reflects a unique property of Hebrew or can be generalized to different languages and writing systems. In addition, phonological effects may be more pronounced when nonwords are used because the only way to read these nonwords is via phonological encoding. Specifically, while the abovementioned studies used nonwords (pseudohomophones vs. pseudowords) as their critical stimuli, the present study focused on familiar, meaningful words (homographs vs. homonyms). Under these conditions, we show that orthographic–phonological connections are more robust for hearing compared to deaf participants.

Semantic Effects

While the two groups differed significantly in their ability to use phonological codes during visual word recognition, there were only insignificant differences between the two groups in their ability to access semantic information. Specifically, in both groups, the difference between homonyms and unambiguous words did not reach statistical significance.

The fact that semantic effects were not observed in the case of hearing participants may be related to the type of stimuli used in the present study: homonyms versus unambiguous words. Previous lexical decision studies that focused on semantic processing during visual word recognition (e.g., Rodd et al., 2002) reported larger ambiguity effects (differences between ambiguous and unambiguous words) in the case of polysemous words (words with multiple related meanings) than in the case of homonyms (words with multiple unrelated meanings). Thus, it is possible that larger semantic effects can be obtained with other stimuli (e.g., polysemous vs. unambiguous words). Nevertheless, while the strength of the semantic effect may depend on the particular stimulus list, the general principle identified in the current study, namely, that in hearing participants orthographic–phonological connections are stronger than orthographic–semantic connections, is consistent with previous studies (e.g., Pattamadilok et al., 2017).

Our results also indicate that, in terms of orthographic–semantic connections, there is no significant difference between hearing and deaf participants: In both groups, the semantic manipulation did not produce significant effects. Nevertheless, the nearly medium effect size in the case of deaf participants raises the possibility that the study may have been underpowered to detect differences with small effect sizes, such as group differences in semantic effects. Thus, further studies with larger sample size are needed in order to investigate the possibility that semantic effects in visual word recognition may be stronger in deaf participants than in hearing participants. This suggestion is consistent with Yan et al.'s study who showed that Chinese signing deaf readers process parafoveal semantic information more efficiently than hearing readers. Clearly, more research is needed in order to evaluate if the semantic advantage reported by Yan et al. can also be found in tasks that emphasize recognition rather than comprehension processes (i.e., a visual lexical decision task rather than reading sentences for comprehension) and in deaf readers who use spoken language as their main mode of communication.

Limitations, Implications, and Conclusions

The results of the study indicate a qualitative difference between hearing and deaf participants, as phonological effects were found only in the case of hearing participants. Thus, consistent with interactive triangle models (e.g., Grainger & Ferrand, 1994, 1996; Seidenberg & McClelland, 1989), we show that visual word recognition may be influenced by both orthographic and phonological sources of information. Importantly, however, while visual word recognition in hearing readers is accomplished mainly via orthographic–phonological connections, deaf readers rely mainly on orthographic–semantic connections (i.e., the data imply that they do not spontaneously activate phonological representations during visual word recognition).

One limitation of the current study is the fact that, besides matching for age, gender, and level of education, only one criterion was used to ensure that the two groups had similar language abilities (the deaf participants all had verbal IQ scores within the normal range). Although the results of the present study suggest that the two groups did not differ in terms of their word-level abilities (the focus of our study), future studies should include more measures of cognitive and language abilities. Another limitation is the relatively small sample size in each group. Although our sample size is similar to those of previous studies (e.g., Bélanger et al., 2013), it is possible that we were underpowered to detect differences with small effect sizes, such as group differences in semantic effects. Thus, further studies with larger sample size are needed to evaluate the impact of feedback semantics in visual word recognition in deaf versus hearing readers. Finally, because this study focused solely on oral–deaf readers, it should also be replicated with signing deaf participants to determine whether the mode of communication influences the ability to activate phonological and/or semantic representations during visual word recognition.

Nevertheless, the finding that even skilled oral-deaf readers recognize words orthographically (rather than phonologically) further stresses the notion that reading processes in deaf readers may be qualitatively different from those in hearing readers. In particular, our findings are consistent with eye-movement findings, showing that deaf readers may rely more on orthographic–semantic links than on orthographic–phonological links (e.g., Bélanger et al., 2013; Yan et al., 2015). In terms of practical implications, these findings suggest that interventions aimed at developing orthographic (and morphographic) knowledge may support reading acquisition in deaf children (Gaustad, 2000; Miller, 2018).

To summarize, the present study presents preliminary evidence that orthographic, phonological, and semantic dynamics may be different in deaf and hearing readers. In particular, we show that hearing loss may modulate visual word recognition processes such that skilled hearing readers access words phonologically (i.e., rely mainly on orthographic–phonological connections), whereas skilled deaf readers access words visually (i.e., rely mainly on orthographic–semantic connections). Given that several studies have recently suggested hemispheric differences in the functional connectivity between orthographic, phonological, and semantic codes (e.g., Peleg & Eviatar, 2012, 2017), the next challenge is to investigate whether visual word recognition in deaf readers involves a different pattern of hemispheric performance.

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