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Phonology and orthography in deaf readers: Evidence from a lateralized ambiguity resolution paradigm

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ABSTRACT

This study explored differences between the two hemispheres in processing written words among deaf readers. The main hypothesis was that impoverished phonological abilities of deaf readers may lead to atypical patterns of hemispheric involvement. To test this, deaf participants completed a metalinguistic awareness test to evaluate their orthographic and phonological awareness. Additionally, they were asked to read biased or neutral target sentences ending with an ambiguous homograph, with each sentence followed by the request to make a rapid lexical decision on a target word presented either to the left (LH) or right hemisphere (RH). Targets were either related to the more frequent, dominant, meaning of the homograph, to the less frequent, subordinate, meaning of the homograph or were not related at all. An Inverse Efficiency Score based on both response latency and accuracy was calculated and revealed that deaf readers' RH perform better than their LH. In contrast to hearing readers who in previous studies manifested left hemisphere dominance when completed the same research design. The apparent divergence of deaf readers' hemisphere lateralization from that of hearing counterparts seems to validate previous findings suggesting greater reliance on RH involvement among deaf individuals during visual word recognition.

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KEYWORDS Deafness; reading; laterality; ambiguity resolution; visual field

Introduction

Visual word recognition is influenced not only by the visual form of the word -its orthography, but also by pronunciation—its phonology (e.g., Ferrand & Grainger, 1992, 1993). Most models of reading posit that phonological processing is primary, mandatory (e.g., Goswami & Bryant, 1990), and occurs

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automatically (Frost, 1998) during reading. Differences in the involvement of the two cerebral hemispheres in the processing of phonological and orthographic information have been reported by many researchers (e.g., Peleg & Eviatar, 2008, 2009, 2012; Neville et al., 1998; Marsolek, Kosslyn, & Squire, 1992; Marsolek, Schacter, & Nicholas, 1996). Evidence from "split-brain" patients suggest that both hemispheres can process written words, but do so differently, and while automatic phonological processing may occur in the LH (Left Hemisphere), this may not be case for the RH (Right Hemisphere) (e.g., Zaidel, 1985; Zaidel & Peters, 1981).

Peleg and Eviatar (2008, 2009; Peleg, Markus, & Eviatar, 2012) proposed a model that explores the different relations between phonology, orthography and semantics during word processing in the two cerebral hemispheres. The *split reading model* (SRM) (illustrated in Figure 1) assumes that phonological, orthographic, and semantic representations are fully interconnected in the left hemisphere, while in the right hemisphere there are no direct connections between phonological and orthographic representations. Rather, the connection between the two is mediated by semantics. According to the SRM, this difference alone can lead to visual word recognition in the LH being usually faster and more accurate than in the RH, because it can use both visual and phonological cues to guide lexical access (Peleg et al., 2012).

The present study seeks to test the SRM on readers with prelingual deafness (hearing loss diagnosed before the age of two). As a group, such readers tend to show marked deficiencies in their phonological processing abilities (e.g., Charlier & Leybaert, 2000; Colin, Magnan, Ecalle, & Leybaert, 2007).

In order to test the SRM, Peleg & Eviatar (2008) examined patterns of lexical ambiguity resolution of homographs in written Hebrew, using lexical priming in a Divided Visual Field (DVF) paradigm. They took advantage of the Hebrew writing system, an abjad system in which letters mainly represent consonants, with vowels being predominantly indicated by diacritics (pointing). This results in the existence of both a shallow version orthography, in which phonology is explicitly represented by the diacritics, and a deep version of the orthography in which vowel information is mostly omitted, as words'

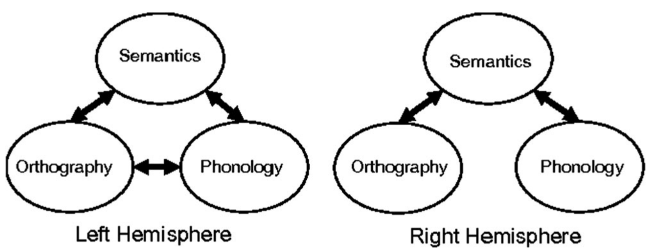

Figure 1. The split reading model (Peleg & Eviatar, 2012).

consonantal letter string is sufficient for their reliable and efficient recognition. Children are firstly taught to read in the shallow, vowelled version, and the diacritics are gradually deleted beginning in 3rd grade. However, vowel diacritics are sometimes used to disambiguate the meaning of homographic consonant strings (e.g., Katz & Frost, 1992).

Most Hebrew written materials do not include diacritics, resulting in two types of common homographs: homophonic homographs and heterophonic homographs. A homophonic homograph is a written word with a unique pronunciation (phonology) associated with multiple meanings (e.g., *bank*). In contrast, a heterophonic homograph is a written word with multiple pronunciations (phonologies), with each of them associated with a different meaning (e.g., *tear*). Thus, both types of homographs have one orthographic representation that is associated with several meanings; the difference is in the relations between phonology and orthography. For homophonic homographs, a single phonological representation is associated with two meanings, whereas for heterophonic homographs, the single orthographic representation is associated with two different phonological representations. The latter are rare in alphabetic writing systems such as English, but very common in an abjad system, such as unpointed Hebrew.

In their experiments, Peleg and Eviatar asked hearing participants to read sentences presented on a computer display that ended with either a homophonic or heterophonic homograph, and then to perform a lexical decision on a target that appeared in their left visual field (LVF) or in the right visual field (RVF). They manipulated the timing at which the target appeared after the homograph, the sentential context in which the homograph appeared, and the relatedness of the target word to the homograph (related to the more frequent dominant meaning, to the less frequent, subordinate meaning or not related at all). The results from these experiments revealed different patterns of priming between homophonic homographs and heterophonic homographs in the RVF (LH), but not in the LVF (RH) (see summary in Peleg & Eviatar, 2012). Hemispheric involvement during ambiguity resolution is influenced by the phonological status of the homograph, and by the contextual bias of the sentence (whether it biases the interpretation of the homograph to one or the other meaning). Although both hemispheres showed sensitivity to sentential context and meaning frequency, only the LH was sensitive to the phonological status of the homograph, responding differentially to homophonic and heterophonic homographs. These results converge with other findings suggesting that the RH does not directly translate orthography into phonology (e.g., Zaidel & Peters, 1981; Smolka & Eviatar, 2006). They interpreted these findings as supporting the SRM model shown in Figure 1.

Reading in deaf individuals

Difficulties in achieving reading proficiency are assumed to be associated with deficient phonological processing skills (e.g., Perfetti & Sandak, 2000). For example, dyslexic readers have been found to exhibit poor phonological skills, and especially, reduced awareness of the phonological components of words (Report of the National Reading Panel, 2000; Stanovich, 2000; Troia, 2004; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Similarly to dyslexic readers, prelingually deaf readers show a decreased ability to achieve proper reading proficiency. Numerous studies reveal a sad reality—the vast majority of prelingual deaf readers achieve the reading level of a hearing 4th grader by the time they graduate from high school (Conrad, 1979; Gallaudet, 2005; Holt, 1993; Miller, 2010; Musselman, 2000; Pintner & Patterson, 1916; Traxler, 2000; Treiman & Hirsh-Pasek, 1983; Wauters, Van Bon, & Telling, 2006; Wolk & Allen, 1984). Hall (2017) claims that there is a long-lasting belief that learning sign language, a language that is more natural for deaf individuals, interferes with the acquisition of spoken language knowledge. This assumption leads many educators of the deaf to advocate an oral-only approach in teaching their students, this despite lack of empirical evidence that unambiguously proves the effectiveness of this approach (Humphries et al., 2016). Moreover, according to Perfetti and Sandak (2000) it may well be that for deaf readers, reading is built upon linguistic processes that rely on sign language knowledge. Strong and Prinz (1997) found in a longitude study that highly skilled signers had better English literacy skills then non proficient signers.

Like dyslexic readers, readers with prelingual deafness, tend to have poor phonological processing abilities reflected in significantly reduced phonemic awareness (Charlier & Leybaert, 2000 Colin et al., 2007; Dyer, MacSweeney, Szczerbinski, & Campbell, 2003; Hanson & Fowler, 1987; Hanson & McGarr, 1989; McQuarrie & Parrila, 2008; Miller, 1997, 2006, 2007, 2010; Miller & Abu Achmed, 2010; Sutcliffe, Dowker, & Campbell, 1999; Transler, Leybaert, & Gombert, 1999). Scarborough and Brady (2002) define phonological awareness as the conscious ability to attend to, think about, and manipulate the phonological building blocks of spoken language, its phonemes, and the ability to manipulate the internal sound structure of words. If phonology is so important in achieving reading proficiency, then how can a child with prelingual deafness, who never heard spoken language, learn to read?

The *dual route model of reading* (Jackson & Coltheart, 2001), posits that written word recognition proceeds along two possible routes, the indirect (non-lexical) route and/or the direct (lexical) route. Letter strings processed along the indirect route will activate phonological recoding that is mediated by the orthography of the word and activates a phonological representation (Frost, 1998; Van Orden & Kloos, 2005), which arouses the meaning of the written word. Here phonological access is prelexical. Words processed via the direct route activate orthographic representations that trigger meaning directly without any phonological mediation, such that phonological access, in this case, is assumed to be post-lexical. Thus, the indirect route allows the reading of nonwords and unknown words, whereas the direct route can only be used to recognize words that are already in the reader's lexicon. According to such dual route models, access to the meaning of a written word can be achieved via either route. Alternatively, some scholars (e.g., Frost, 1998; Paul, Wang, Trezek, & Luckner, 2009; Wang, Trezek, Luckner, & Paul, 2008) claim that there is only one route from orthography to meaning, namely the indirect route that extracts meaning from written words based on their phonological decoding. According to this view, the development of reading skills in the deaf and in the hearing is qualitatively similar, and the main difference is that the development in deaf readers is quantitatively delayed (Paul et al., 2009; Paul & Lee, 2010; Wang et al., 2008). Paul and colleagues assume that (a) phonological knowledge is obligatory to reading comprehension; and that (b) deaf readers can gain some level of phonological skills, and thus can to some point develop phonological awareness that can lead to segmentation of words into their smaller phonological components.

The *Qualitative Similarity Hypothesis* QSH (e.g., Paul, 2012; Paul & Lee, 2010; Paul, Wang, & Williams, 2013) suggests that both hearing and deaf children go through the same developmental stages while learning to read, thus making them qualitatively similar, although some deaf children may be quantitatively delayed in comparison to hearing children. In other words, the generally poor reading skills of deaf individuals reflect delayed development of phonological skills. Recently, Gurierrez-Sigut, Vergara-Martínez, and Perea (2017) an automatic phonological coding activation for congenitally deaf readers, similar as in hearing readers. However, they concluded as for sub-lexical use of phonological coding may be a main contributor to reading ability among hearing readers, it may not be the case for deaf readers. Several research findings suggest that QSH may not be appropriate for explaining why deaf individuals often fail to comprehend what they read (Miller & Clark, 2011). First, a meta-analysis conducted by Mayberry, del Giudice, and Lieberman (2010) on studies that assessed deaf readers' phonological abilities and their reading skills, revealed only a weak correlation between the two domains. McQuarrie and Parrila (2014) claim that profoundly deaf bilinguals may be using phonological abilities derived from sign language during literacy development, and posit a dual language interaction between signed and written language similar to the mechanism in second language hearing learners. According to their view, the reason for phonological deficiencies among deaf individuals is their impaired auditory perception. The changed sensory information input may change the nature of the phonological information deaf individuals develop. McQuarrie and Parrila (2008, 2014) suggest that deaf individuals may use different representational structure of words that derive from different sources of lexical information. They claim for a "qualitative different reading processes for bilingual deaf readers—one that centred on the relationships among signed language phonology, lexical restructuring and written language literacy acquisition" (McQuarrie & Parrila, 2014, p. 381). Morover, Mehravari, Emmorey, Pratt, Klarman, and Ostehout (2017) found that proficient hearing and deaf readers, process written words differently and rely on different types of linguistic information. Their findings suggest that while their most proficient hearing readers respond to both grammatical and semantic cues, proficient deaf readers respond to semantic clues.

Convergent data has also been presented by Miller (2006), who demonstrated that despite having strikingly poor phonological processing skills, some deaf readers were comparable to typical readers in categorizing written real words. In addition, Miller (2010) showed that despite deficient phonological skills, there are some very skilled deaf readers. He suggested that instead of relying on phonological processes for the recognition of written words, skilled deaf readers mediate their semantics based on well-internalized orthographic representations.

Miller (2010, p. 555) defined orthographic awareness as "the ability to consciously attend to, think about, and manipulate orthographic aspects of written language, especially the internal orthographic/graphemic structure of written words, in the absence of the physical stimulus based upon detailed, permanently internalized mental representation" Based upon his and others findings, Miller (2018) hypothesized that fostering orthographic knowledge in deaf readers might in fact be sufficient to sustain skilled reading. Provided this assumption is correct and hemispheric division of labour during reading indeed occurs along phonology- LH/orthography-RH axis, one would expect deaf readers' enhanced orthographic sensitivity, in conjunction with their poor phonological processing skills, to manifest in a norm-divergent pattern of relative hemispheric involvement. The present study examined this possibility via the comparison of the hemispheric patterns of performance revealed among deaf readers in the process of phonological and semantic written word ambiguity. Farinña, Dunñabeitia, and Carreiras (2017) used a shallow orthography language (Spanish) in skilled deaf readers and found that they did not rely on phonology as a mediator, and still showed the ability to use orthogaraphy as hearing readers. They concluded that, at least for shallow orthography languages, phonological coding is not a prerequisite in order to access lexical meaning from text.

Hemispheric asymmetry in deaf readers

The results from studies that compared patterns of hemispheric asymmetry in processing orthography and phonology between deaf and hearing readers are sparse and inconclusive. Phippard (1977) reported a LVF/RH superiority for the identification of letters in deaf individuals educated according to the oral only approach. In contrast, both hearing and deaf individuals who were signers showed an opposite RVF/LH superiority. Of note however, other studies using English words failed to reveal differences in lateralization between participants with prelingual deafness and hearing participants (e.g., Manning, Goble, Markman, & LaBerche, 1977; Poizner, Battison, & Lane, 1979). Sanders, Wright, and Ellis (1989) asked deaf and hearing participants to perform a lateralized semantic categorization task for words, pictures and signs. They found that hearing participants showed a RVF/LH advantage for words, while the deaf participants showed the opposite LVF/RH advantage. Interestingly, hearing participants' responses to targets in the RVF/LH were significantly faster than that of the deaf participants, but comparable in the LVF/RH. In another experiment, Sanders et al. (1989) found pseudohomophone effects for hearing but not for deaf participants.

Neville et al. (1998) examined the brain mechanisms that are involved in linguistic processing using fMRI technology, with focus on the differences between signed and spoken language processing among deaf and hearing readers. For this purpose, they tested individuals from three groups: hearing English monolinguals, deaf signers who learned to read English in school, and hearing bilinguals, children of deaf parents who were both native signers and native speakers. All participants read English sentences and participants who signed also saw sentences in American Sign Language (ASL). Expectedly, while reading sentences, hearing English monolinguals exhibited activation in classical language specific areas in the LH. Hearing bilinguals showed classical language specific activation in the LH while reading English, and classical LH and additional RH activation when processing ASL sentences. The same classical LH activation with additional right hemisphere activation was observed when deaf signers were asked to process ASL sentences. Of note however, when these deaf participants read English sentences, they did not show activations in the classical LH language regions, but instead revealed robust RH activation. Neville and her colleagues suggested that this may be because the native language of the deaf signers (ASL) is visual, and therefore relies more on RH mechanisms than on LH mechanisms. Morford, Wilkinson, Villwock, Piñar, and Kroll (2011) suggested that when signing deaf individuals read English, the English words are automatically translated into their sign equivalents, which could result in a right hemisphere rather than a left hemisphere specialization for reading in deaf individuals. Such atypical hemispheric activation suggests that deaf individuals may rely on non-phonological knowledge during the processing of written materials. It may be possible to generalize this hypothesis to their greater reliance on orthographic knowledge, based on the findings of Marsolek and colleagues (Marsolek et al., 1992; Marsolek et al., 1996) who showed that the RH is more sensitive to the visual form of written words and is more influenced by orthographic factors than the LH.

The present study

To clarify whether permanent profound hearing loss from early childhood modifies the nature of the strategy used for the processing of written text, we asked deaf participants to read sentences presented on a computer display, with the last word being either a homophonic or heterophonic homograph, and to subsequently perform a lexical decision on a target word presented to their LVF or to their RVF (see Peleg & Eviatar, 2012 for a review of the paradigm). In addition, all deaf participants performed a test that assessed their phonological and orthographic awareness (Miller, 1997, 2010). Two research hypotheses were tested. Recall that the Split Reading Model suggests that the RH accesses phonology only after semantic access, whereas the LH accesses phonology directly from the orthography. Therefore, we hypothesized that the impoverished phonological abilities of deaf readers will result in a different pattern from hearing readers in the RVF/LH, but not in the LVF/RH conditions. In addition, given that in hearing individuals the LH responds differentially to heterophonic and homophonic homophones, while the RH does not, we asked whether this pattern would also be found in deaf readers. Moreover, if, as suggested by Miller (2010), deaf readers, due to their impoverished phonological processing skills, tend to process written text based on orthographic rather than on phonological knowledge, then their performance on the lexical decision task is expected to be strongly correlated with their scores on a test of orthographic awareness, but not with their scores on a test of phonological awareness.

Method

Participants

Twenty-three deaf adults, 15 women and 8 men (mean age 31.5, age range 18–57) participated in the study. All participants were prelingually deaf (hearing loss diagnosed before the age of two), and they all manifested an unaided hearing loss of at least 85 dB or higher in the better ear (profound deafness) (American National Standards Institution, 1989). All were right-handed with normal or corrected-to-normal vision and were not diagnosed as having specific learning disabilities or suffering from emotional disorders.

Table 1. Deaf participants knowledge in Israeli Sign Language (self-report).

Israeli Sign Language mastery		
Mother tongue	Good knowledge	Partial knowledge
13	9	1

All participants had finished at least 12 years of schooling and successfully passed the Israeli high school matriculation examination (Te'udat Bagrut). For all of them, Hebrew was the first spoken and read language. Table 1 shows the participants' subjective, self-estimated level of mastery in Israeli Sign Language, mother tongue being the highest level of mastery and reflects that the person prefers to use that language, and poor knowledge being the lowest mastery level with which a person feels partially comfortable to use that language. 14 of our participants had a deaf relative (parent/ sibling/ uncle)

Stimuli and design

Metalinguistic Awareness test. The metalinguistic test (Miller, 1997; 2010) consists of 24 stimulus sets, each set composed of four drawings of familiar items. The task of the participants was to point to the two drawings, from among the four, whose names have the same initial or final phonemes (12 per condition). In half of the sets (phonological condition) making the correct decision required phonemic awareness (e.g., the drawing series: **C**AR, LAMP, APPLE, **K**EY) whereas in the other half (orthographic condition) recruiting orthographic awareness was sufficient for success (e.g., the drawing series: **D**OG, KNIFE, **D**ISK, FORK). More specifically, in the phonological condition the targeted phoneme (/k/ in the example) is represented at the orthographic level by two different, yet homophonic letters. In contrast, in the orthographic condition, the target phonemes of the drawings are represented at the orthographic level by the same letter. (for illustration in Hebrew see Figure 2). The basic assumption of the test is that poor performance in the phonological condition, yet good performance in the orthographic condition is indicative of reliance on orthographic rather than phonological awareness for task performance (Miller, 1997). Test Reliability (Cronbach's alpha) for the deaf participants in this test is 0.83.

Lexical decision task. The stimulus materials used in the lexical decision task were the same as those used by Peleg and Eviatar (2008, 2009) and Peleg et al. (2012). The task was simple and included a lexical decision for highly frequent Hebrew words. A set of pretests was conducted among non-participants judges in order to test the subjective frequency of the words (for a complete review see Peleg & Eviatar, 2008, 2009). These consisted of 56 homophonic and 56 heterophonic homographs, each occurring at the end of a sentence, were used as the priming stimuli for the target items presented

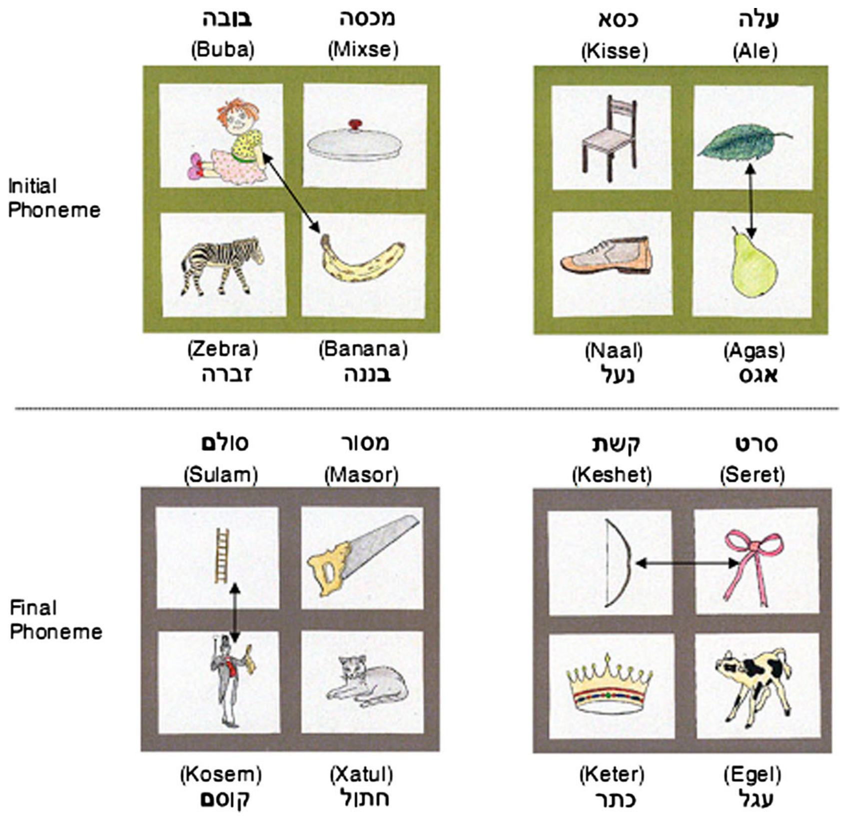

Figure 2. Illustration of the stimuli presented in the metalinguistic test—The left column emphasizes the orthographic condition where the initial/final phoneme is identical in both orthographic and phonological levels. The right column emphasizes the phonological condition where the initial/final phoneme is identical only on the phonological level.

in the lexical decision task. The sentences and primes were shown in the centre of the screen, and the target words were shown in one of the peripheral visual fields (see below for details). For each homograph two possible target words were selected: one related to its more frequent, dominant meaning and the other to its less frequent, subordinate meaning. In addition, each homograph was also presented with two unrelated target words. Each homograph was presented at the end of two different sentences. In one of these sentences the content was neutral with regard to the homograph meanings (e.g., the man went to the bank) whereas in the other it was biased in a way that favoured the retrieval of the subordinate meaning of the homograph (e.g., the fisherman went to the bank.). Each target word appeared twice, once after the homograph, and once after a control sentence in which the last word was unambiguous and not related to the target. This allowed us to compute the degree of priming for each target word from the homograph vs. from an unrelated word. See Table 2 for examples translated from Hebrew. In addition, 224 filler sentences were used in which the last word was not a homograph, and the targets appearing in the peripheral visual fields were nonwords. Thus, each participant performed 448 trials. Of these, half required the response "word" and half required the response "nonword". The responses to nonwords were not analysed. Of the 224 experimental trials, 56 ended with a homophonic homograph (e.g., *bank*) and 56 ended with a heterophonic homograph (e.g., *tear*). The remaining 112 trials used the same target word after an unrelated prime. The target after the unrelated prime always appeared in the same visual field as after the related prime. This allowed us to compute priming (the difference between responses to related vs. to unrelated prime—target pairs) within each visual field. For each type of homograph, 28 of the sentences biased the meaning of the homograph towards the less frequent meaning of the homograph (e.g., river bank), and 28 were unbiased. Of these, 14 appeared in the RVF and 14 appeared in the LVF.

Apparatus

Stimulus presentation and response accuracy in lexical decision task were controlled and recorded by means of a portable computer. Stimuli were presented as white letters on a gray coloured screen. An adjustable chin-rest setting kept participants at fixed viewing distance of 57 cm from the computer screen.

Procedure

Participants were tested individually. Instruction and explanations were given in Israeli Sign Language (ISL) by an ISL interpreter. The deaf participants always completed the metalinguistic task before the lexical decision task. Each task included practice trials.

Table 2. Translated examples of stimuli presented in the lexical decision task.

Homograph type	Sentence context	Homograph	Pronunciation	Target words
Homophonic homograph	Unbiased: They looked at the …	חוזה Contract/Seer	/XOZE/	Dominant-document
	Subordinate: The children of Israel listened to the …			Subordinate-prophet
Heteropohnic homograph	Unbiased: The young man looked for the …	Book/ Hairdresser	/SEFER/ /SAPAR/	Dominant-reading
	Subordinate: The bride made an appointment with the …	ספר		Subordinate-hair

Assessment of meta-linguistic awareness (phonological and orthographic). Participants were told that they will see a series of four drawings. On 12 out of the 24 trials, they were to point to two drawings of objects that begin with the same sound. Of these, six required phonological awareness and 6 required orthographic awareness. On the remaining 12 drawings they were to point to the objects whose name ends with the same sound, again, with 12 requiring phonological and 12 requiring orthographic awareness. Participants were tested only after correctly identifying all the objects, and when their performance in the practice trials reflected proper understanding of the task requirements.

After the participant confirmed his/her readiness, the experimenter showed the first of the four-drawing stimulus series on the table in front of the participant, until the participant pointed to a second drawing of his/her choice. For each series, response accuracy was recorded for further analysis.

The six stimulus sets of the orthographic condition, testing awareness to the initial phoneme, were always presented first, immediately followed by the six series of the phonological condition. Awareness of the final phoneme position was immediately assessed after completing awareness to the initial phoneme. The maximum score for the whole test is 24, a point per series, 12 points for each condition (phonological, orthographic).

Assessment of hemispheric specialization (lexical decision task). The experimenter informed the participants in the explanation and practice block that they would see a series of sentences presented in the centre of the computer display, the last word of the sentence (the homograph or unambiguous control word) always appeared alone in the centre of the screen. After the last word disappears, a letter sequence will appear, either to the left or to the right of the fixation point. The task is to decide if this sequence represents a real word in Hebrew or not, as fast and as accurately as they can, by pressing either the "YES" or the "NO" buttons on the input box. The experimenter then asked the participant to put their chin on the chin-rest setting, instructing them to constantly focus at the centre of the screen.

Each test sentence was presented in the centre of the computer display for 3000 ms, with its final word missing. The sentence then disappeared and the final word—a homograph in experimental trials and an unambiguous word in filler trials—was then presented centrally for 230 ms. After an ISI of 500 ms, the target letter sequence was presented for 180 ms either in the LVF or the RVF (total SOA of 730 ms). The letter closest to the centre was always offset 2 degrees of visual angle from fixation. Reaction time and decision accuracy were automatically recorded for further analysis.

Results

Phonemic and orthographic awareness

The overall average meta-linguistic awareness score was 17.42 (SD = 4.02) out of 24 (72.58% correct), with the phonological awareness score being 7.16 (SD = 2.89) out of 12 (59.33% correct) and orthographic awareness score 10.26 out of 12 (SD = 2.02) (86.5% correct). A significant type of metalinguistic awareness effect was found, (t (22) = 6.23, $p < .001$), indicating, as expected, that deaf participants had significantly better orthographic than phonological awareness.

Lateralized lexical decision task

There was a significant positive correlation between response time and errors, such that slower participants made more errors ($r(21) = .50$, $p = .016$). Therefore, to reduce the number of analyses, performance on the Lateralized Lexical Decision Task was treated as an Inverse Efficient Score (IES) that combines speed of processing and processing accuracy (IES = mean RT/proportion correct) as a single score (Rach, Diederich, & Colonius, 2011; Townsend & Ashby, 1978, 1983). Table 3(a,b) shows the speed of processing means and processing accuracy for each condition in each sentential context, together with the IES scores. Recall that IES are response times normalized by accuracy, such that lower values indicate more efficient processing.

The scores of 23 participants were analysed using a within-subject ANOVA with Context (neutral vs. subordinate), VF (LVF vs. RVF), Phonology (homophones vs. heterophones) and Frequency (whether the target was related to the more frequent meaning (Dom), or related to the less frequent meaning (Sub), or was unrelated (U)). The analysis revealed a significant interaction between VF and Frequency, $F(2,44) = 4.34$, $p = .019$, $\eta_p^2 = 0.164$; a trend towards an interaction between Context and Frequency, $F(2,44)2.55$, $p = .089$, $\eta_p^2 = 0.103$, a main effect of VF, $F(1,22) = 20.33$, $p = 0002$, $\eta_p^2 = 0.48$; and a main effect of frequency, $F(2,44) = 4.73$, $p = .0138$, $\eta_p^2 = 0.176$. It is notable that there is no main effect or interaction that includes the phonology of the ambiguous words. The cell means from the 2 context conditions in each visual field, for each frequency are shown in Figure 3.

It can be seen that overall, the deaf participants reveal a performance advantage of the LVF/RH (1096 ms in the LVF vs. 1546 ms in the RVF) that is reflected in the significant VF main effect as reported above. It can also be seen that the unrelated words resulted in the highest IES scores, indicating lower efficiency, especially in the RVF. Given that our primary interest in this study were effects arising from context and phonology in relation to the two visual fields, we reanalysed the data without the unrelated words. This analysis revealed a strengthened interaction between Context and Frequency, *F*

Table 3. (a) Mean speed of processing (RT) and processing accuracy (%Err) for each experimental condition in neutral sentential context. (b) Mean speed of processing (RT), processing accuracy (%Err), and Inverse efficient scores (IES) for each experimental condition in subordinate sentential context.

		Homophones		Heterophones	
		LH/RVF	RH/LVF	LH/RVF	RH/LVF
Dominant	RT (SD)	855.17 (328.43)	715.65 (283.46)	758.96 (200.13)	704.26 (253.52)
	%Err (SD)	16.36 (22.007)	9.17 (10.73)	14.04 (13.81)	7.79 (13.18)
	IES (SD)	1311.18 (823.16)	863.58 (335.74)	1029.88 (372,84)	914.11 (593.55)
Subordinate	RT (SD)	869.41 (403.08)	753.57 (316.64)	764.57 (215.75)	764.43 (375.49)
	%Err (SD)	27.02 (20.33)	15.8 (20.62)	26.08 (24.05)	16.82 (16.8)
	IES (SD)	1421.81 (724.54)	1368.43 (2152.03)	1517.27 (1284.88)	1091.44 (547.41)
Unrelated	RT (SD)	767.15 (220.01)	699.37 (248.47)	878.22 (233.01)	735.96 (256.84)
	%Err (SD)	28.34 (24.68)	17.27 (18.94)	29.3 (24.26)	19.6 (1.36)
	IES (SD)	1524.06 (915.93)	1053.87 (556,97)	1728.26 (1173.35)	1217.89 (1071.12)
		Homophones		Heterphones	
		LH/RVF	RH/LVF	LH/RVF	RH/LVF
Dominant	RT (SD)	809.85 (270.69)	774.09 (228.98)	792.67 (345.20)	683.5 (220.32)
	%Err (SD)	25.80 (16.87)	15.78 (20.67)	23.6 (24.98)	10.81 (17.34)
	IES (SD)	1322.26 (567.31)	1131.97 (657.003)	1455.86 (1133.45)	959.82 (546.60)
Subordinate	RT (SD)	774.30 (225.04)	669.04 (183.97)	737.83 (231.99)	718.20 (211.64)
	%Err (SD)	24.11 (21.43)	12.26 (14.17)	22.64 (20.86)	18.96 (16.89)
	IES (SD)	1303.34 (774.39)	891.001 (347.42)	1232.96 (700.60)	1085,75 (566.32)
Unrelated	RT (SD)	864.41 (330.93)	713.33 (215.73)	976.13 (520. 33)	711.20 (216.24)
	%Err (SD)	25.79 (26.62)	19.80 (24.97)	33.91 (24.73)	15.4 (21.69)
	IES (SD)	1961.27 (2898.46)	1265.88 (1004.55)	2746.85 (4473.80)	1304.07 (1843.76)

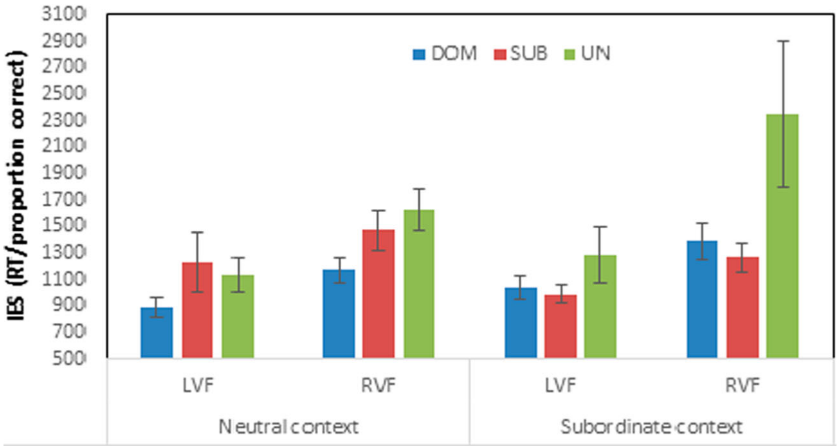

Figure 3. Performance efficiency scores in both visual fields in different sentential context (Neutral; subordinate). [To view this figure in color, please see the online version of this journal.]

(1,22) = 4.08, $p = .0557$, $\eta_p{}^2 = 0.156$; the main effect of VF $F(1,22) = 21.83$, $p < .0001$, $\eta_p{}^2 = 0.48$, (LVF = 1038 ms, RVF = 1324) was unchanged; and erased the main effect of Frequency ($p > .25$). The interaction between Context and Frequency is shown in Figure 4.

Although the simple main effect of Context did not reach significance for responses to words related to either the dominant or the subordinate meaning of the homograph, the interaction between Context and Frequency suggests that our participants were sensitive to the sentential context. It can

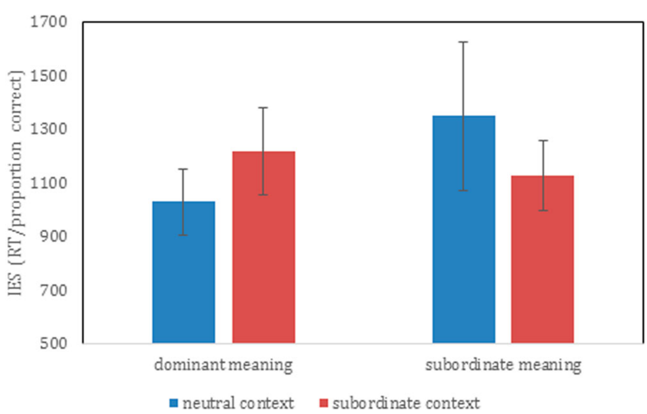

Figure 4. Interaction between sentential context and frequency of the meaning of the target word (related to the dominant, more frequent, or subordinate, less frequent, meaning of the homographic prime). [To view this figure in color, please see the online version of this journal.]

be seen that for targets related to the dominant, more frequent meaning of the homograph, responses were more efficient in the neutral context than in the context biasing towards the subordinate meaning ($F(1,22) = 7.69$, $p = .0111$, $\eta_p^2 = 0.258$). Words related to the (appropriate) subordinate meaning of the homographs, were responded to more efficiently in the context biasing towards the subordinate meaning of the homograph (1128 ms) than words related to the dominant (inappropriate) meaning of the homograph (1350 ms), although not significantly so ($p = .2$). The hypothesis that the deaf participants were sensitive to sentential context is also supported by the long and inefficient responses to unrelated words, especially in the RVF (see Figure 3), where the sentential context may have aroused expectations that were not fulfilled.

Correlations between metalinguistic awareness and lexical decision efficiency

We computed separate Pearson correlation analyses to unveil potential relationships between the deaf participants' metalinguistic awareness and their efficiency of lexical decisions in the different word processing conditions. None of these analyses indicated that performance efficiency in the lexical decision task was significantly associated with the measures of participants' metalinguistic awareness.

Discussion

The goal of this study was to examine the manner in which the cerebral hemispheres of deaf readers process written words. Specifically, we asked whether the phonological status of homographs would affect lateralized performance in deaf readers as it has been found to do in hearing readers. Our design enabled us to examine the use of context by our participants, by pairing neutral and biased sentences with targets related to the different meanings of the homographs.

In comparison to patterns of performance previously found for hearing participants (Peleg et al., 2012; Peleg & Eviatar, 2008, 2009), the present results reveal both similarities and differences among deaf who participated in our task. Recall that Peleg & Eviatar (2012) reported that the phonological status of the homograph affected responses to stimuli presented in the RVF (directly to the left hemisphere), but not in the LVF (directly to the right hemisphere). Overall, Peleg and Eviatar found that the meanings of the homophonic homographs (one orthography, one phonology, multiple meanings) are activated and decayed faster in the LH then in the RH. The opposite was true for heterophonic homographs (one orthography, two phonologies, multiple meanings), where meaning was activated and decayed faster in the RH then in the LH. They interpreted this pattern as indicating direct activation of phonology from orthography in the LH, but not in the RH, where orthography first activates semantics, which in turn activates phonology. In addition, the manipulation of context revealed that the more frequent, dominant meanings of homographs are activated with neutral context, while context biased towards the subordinate, less frequent meaning, results in higher activations for the subordinate meaning, but that the dominant meaning are also activated, inappropriately.

The patterns evinced by our deaf participants were similar to those shown by hearing participants in some aspects and differed in others. As expected, deaf participants did not show effects rooted in the phonological status of the homographic primes. However, like the hearing participants tested by Peleg and Eviatar, they reveal sensitivity to the sentential context in which the homograph appeared, and revealed the same pattern: without biasing context, the more frequent meaning of the homograph was activated exclusively, while bias towards the subordinate meaning activated that meaning, but also activated the dominant meaning as well.

Most interestingly the pattern shown by the deaf participants in both visual fields is similar to that shown by hearing participants in the LVF\RH, but different from the pattern shown by hearing participants in the RVF \LH. These findings support the assumptions of the Split Reading Model (see Figure 1). Recall that the model asserts that in the RH of hearing readers, there is no direct link between orthographic and phonological representations of words, predicting no differences between heterophones and homophones in the LVF/RH. The fact that the deaf readers do not show an effect of phonology, and that their performance in the LVF does not differ from that of hearing readers, converges with the hypothesis that the hearing RH does not compute phonology from orthography.

The studies by Peleg and Eviatar with hearing participants revealed the ubiquitous right visual field advantage that is interpreted as reflecting LH specialization for the lexical decision task. However, our deaf participants reveal a significant left visual field advantage, indicating RH specialization for this task. A large number of divided visual field studies, over the last half century (see Willemin et al., 2016 for a review), together with many imaging studies from the last few decades (see Bookheimer 2002 for a review; see Willemin et al., 2016 for a large scale study) showed that the LH of hearing readers is more accurate and active in the identification of words than the RH. Research on deaf readers on the other hand, demonstrates that their RH plays a more significant role than the LH during reading (Corina, Lawyer, Hauser, & Hirshorn, 2013; Neville et al., 1998; Sanders et al., 1989). The findings reported by Morford et al. (2011) may suggest the mechanism by which this hemispheric change occurs: They report evidence that when deaf signers read English, the English words are automatically translated into their sign equivalents. Given that sign language relies on the RH more than oral language, it may be that the RH is more involved in reading in English among deaf signers than in hearing readers. Our findings converge with these reports and emphasize the involvement of the right hemisphere in visual word recognition in Hebrew in deaf individuals.

Corina and colleagues (Corina et al., 2013) examined what distinguishes proficient from less proficient deaf readers. They found greater RH involvement among the less proficient deaf readers group. On the other hand, the proficient deaf group showed a similar LH pattern to hearing readers. Differently, Emmorey (2020) suggests that although deaf readers usually show left hemisphere patterns of activation similar to those of hearing individuals, skilled deaf readers show more bilateral patterns, rather than a left hemisphere dominance. Emmorey suggests that hearing and deaf readers may differ in their reading process, and that it may well be that neural processes that are less efficient for hearing readers, will suit deaf readers.

One of the limitations of the present study is that we did not assess reading proficiency in the deaf participants. Doing so might have told us if the results found in the present study are, at least in part, due to reading proficiency. Whereas all deaf participants tested in the present study were at least high school graduates, it does not necessarily mean they had good reading skills. Such caution in drawing early conclusions is warranted, as some researchers failed to find significant correlations between deaf readers' level of the education and their reading comprehension skills (e.g., Miller et al., 2012).

Consistent with the lack of phonological effects found in the responses of the deaf participants in the lexical decision task, we replicated Miller (2010) and found that the deaf group had a greater orthographic awareness and rather poor phonological awareness. However, the present study did not find a significant correlation between orthographic awareness and performance in the lateralized decision task, as would be predicted by the hypothesis that deaf readers utilize compensatory orthographic strategies. In other words, orthographic awareness fails to explain the results found in the present study. As mentioned, Miller (2010) has suggested that this mechanism is used by good deaf readers. Given that we did not assess the reading level of our participants, we may not have tested this hypothesis fairly. Further research that divides deaf participants by reading level and mode of instruction may help clarify our findings. For example, it may well be that trying to teach deaf individuals using the same methods as for hearing individuals, forces them to rely on strategies that simply do not work for them. It also may prevent them from developing more adequate strategies that can compensate for their impoverished phonological skills. Beech and Harris (1997) found that prelingually deaf children were less affected by regularity and homophony than matching hearing children.

They suggested that deaf readers rely more on the direct lexical reading route than on the indirect phonological route in order to derive meaning from print.

The present results may indeed indicate that the hemispheres of deaf and hearing readers process words differently. The findings imply that whereas the RH of both hearing and deaf seems to process written words similarly, they differ in the way they process such words in their LH.

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No potential conflict of interest was reported by the author(s).

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Data availability statement

The data that support the findings of this study are available from the corresponding author (Haim Assor), upon reasonable request.

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