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Morphological decomposition compensates for imperfections in phonological decoding. Neural evidence from typical and dyslexic readers of an opaque orthography

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ABSTRACT

The current study examined the widely held, but un-tested, assumption that morphological decomposition can compensate for missing phonological information in reading opaque orthographies. In addition, we tested whether morphological decomposition can compensate for the phonological decoding deficits in readers with dyslexia. Hebrew provides a unique opportunity to test these questions as it has a rich Semitic morphology, and two versions of script: a transparent orthography (with diacritic marks, ‘pointed’) and an opaque orthography (without diacritic marks, ‘un-pointed’). In two experiments, one behavioral and one fMRI, skilled and dyslexic readers read aloud Hebrew nouns: half bi-morphemic (root + pattern) and half mono-morphemic (non-decomposable). Each word was presented both in the transparent orthography (pointed), and in the opaque orthography (un-pointed). While skilled readers were faster, and showed no effects of diacritics or morphology, dyslexic readers read pointed words more slowly than un-pointed words and bi-morphemic words faster than mono-morphemic words. The imaging results showed: 1) In both groups a morphological effect was found in un-pointed words, in left inferior and middle frontal gyri, associated with morpho-phonological decomposition. 2) Only readers with dyslexia showed a morphological effect in pointed words in the left occipito-temporal cortex, associated with orthographic processing. 3) Dyslexic readers also showed a positive association between morphological awareness and activation in the left occipito-temporal cortex during reading of all words, and activation in inferior frontal cortex during reading of un-pointed bi-morphemic words. Altogether, these findings suggest that in both typical and dyslexic readers morphological decomposition can compensate for the missing phonological information in an opaque orthography. The results also show that readers with dyslexia can rely on morphological decomposition to compensate for their deficits in

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phonological decoding. Finally, these results highlight the way in which unique language specific properties shape the neural mechanisms underlying typical and atypical reading.

1. Introduction

The critical contribution of morphological processing abilities to reading has been the focus of growing interest for researchers in the last two decades (Deacon & Kirby, 2004; Kieffer & Lesaux, 2012; McBride-Chang, Shu, Zhou, Wat, & Wagner, 2003; Treiman & Cassar, 1996). Despite the strong links between morphological and phonological segmentation processes, it is not yet clear how these processes interact during reading (Carlisle & Nomanbhoy, 1993; Fowler & Liberman, 1995). One open question is to what extent morphological decomposition during reading is affected by the orthographic transparency (i.e., the consistency of the mapping between orthography and phonology, aka orthographic depth). A common hypothesis is that morphological decomposition can facilitate visual word recognition, especially in opaque orthographies, because recognition of morphemes can compensate for the missing information when mapping graphemes to phonemes (Bar-On & Ravid, 2011; Casalis, Quemart, & Duncan, 2015; Frost 2006, 2012; Vaknin-Nusbaum & Miller, 2011). Nevertheless, to the best of our knowledge this question has not been tackled by any empirical study.

Another open question related to the interaction between morphological and phonological processes during reading is the extent to which dyslexic readers with phonological deficits rely on morphological decomposition in reading. While some evidence suggests that individuals with phonological deficits perform poorly on morphological awareness tasks (Bendror, Bentin, & Frost, 1995; Mahony, Singson, & Mann, 2000; Schiff & Ravid, 2007), other studies suggest that readers with dyslexia rely on morphological decomposition during reading more than typical readers to compensate for their phonological decoding difficulties (Burani, Marcolini, De Luca, & Zoccolotti, 2008; Cavalli et al., 2017; Elbro & Arnbak, 1996; Vellutino, Fletcher, Snowling, & Scanlon, 2004). However, the answer to this last question may depend not only on the skills of the readers but also on the specific morphological and orthographic properties of the language. Thus, a language with a rich morphology and words with salient morphological structures may facilitate morphological decomposition and enhance reliance on morphological segmentation during reading, even in readers with weaker phonological skills.

Hebrew has two interesting properties: a rich Semitic morphological system, in which most words are composed of a root and a morphemic pattern, and two versions of script, a transparent (pointed) and an opaque (un-pointed) orthography. These characteristics provide an opportunity to examine the interaction between orthographic transparency and morphological complexity in a within language design.

The goal of the current study is to examine the effect of the phonological information present in the script on readers' tendency to engage in morphological segmentation, in typical readers and in dyslexic readers with a phonological deficit. We will use behavioral measures as well as brain activation measures in fMRI in adult Hebrew speakers to determine the contribution of regions involved in orthographic, phonological and semantic processing to the morphological segmentation of Hebrew derived words composed of roots and morphemic patterns. Specifically, we aim to determine (a) what is the contribution of each of these linguistic processes to morphological segmentation of single words during reading in skilled adult readers, in a language with a rich morphology; (b) are these processes enhanced in the non-transparent orthography; and (c) is any aspect of the morphological decomposition process impaired or enhanced in dyslexic readers with phonological deficits.

1.1. *The role of morphological processing in reading*

A central question in many behavioral and neuroimaging studies of morphological processing is whether inflected and derived words are decomposed into their smaller units, or stored and retrieved as whole lexical items. The models range from endorsing Full Decomposition of all inflected and derived words prior to lexical access (Fruchter & Marantz, 2015; Lewis, Solomyak, & Marantz, 2011), to hybrid models that suggest decomposing of some complex words into discrete morphemes while other complex words are stored as whole lexical units (Bertram, Schreuder, & Baayen, 2000; Marslen-Wilson, Tyler, Waksler, & Older, 1994; Ullman, 2013). In contrast, connectionist models, which disagree with the view of morphemes as distinct units and with a dichotomy between decomposable and non-decomposable words, suggest that access to morphemic representations is distributed, and that sensitivity to morphological regularities reflects the interaction between form and semantics (Gonnerman, Seidenberg, & Andersen, 2007; Rumelhart & McClelland, 1986).

Regardless of whether morphemic representations are discrete units or distributed entities, morphemes have the potential to serve as the elementary building blocks of word representations, supporting an economical body of lexical knowledge that facilitates the learning of novel forms and morphological variants of known words (e.g., Merkx, Rastle, & Davis, 2011; Rastle & Davis, 2008). The notion is that readers' ability to recognize familiar morphemes embedded in morphologically derived and inflected words facilitates their recognition of written words. This potential facilitation depends on several properties of the language and the orthography (Bertram, Laine, & Karvinen, 1999; Duncan, Casalis, & Cole, 2009; Marslen-Wilson et al., 1994; Rispens, McBride-Chang, & Reitsma, 2008; Tolchinsky, Levin, Aram, &

McBride-Chang, 2012). These properties include the morphemes' semantic, phonological and orthographic transparency (i.e., the degree to which morphologically related words share similar meaning, phonology and orthography. Marslen-Wilson et al., 1994; Clahsen, Eisenbeiss, & Sonnenstuhl-Henning, 1997; Carlisle & Stone, 2005; Carota, Bozic, & Marslen-Wilson, 2016). Other properties include the word's surface and stem frequency (Deacon, Whalen, & Kirby, 2011; Solomyak & Marantz, 2010; Verhoeven & Schreuder, 2011), and the morpheme productivity (Bertram et al., 1999; Carota et al., 2016).

Neuroimaging studies that examined morphological processing of derivationally complex words showed the involvement of the left fronto-striatal system including the inferior frontal gyrus (IFG) and the caudate nucleus in both spoken (Carota et al., 2016; Marangolo, Piras, Galati, & Burani, 2006) and written words (Bozic, Marslen-Wilson, Stamatakis, Davis, & Tyler, 2007; Meinzer, Lahiri, Flaisch, Hannemann, & Eulitz, 2009; Pliatsikas, Wheeldon et al., 2014). These findings are similar to findings in inflectional morphology (Beretta, Campbell et al., 2003; Desai, Conant, Waldron, & Binder, 2006; Lehtonen, Vorobyev, Hugdahl, Tuokkola, & Laine, 2006; Nevat, Ullman, Eviatar, & Bitan, 2017; Tyler, Stamatakis, Post, Randall, & Marslen-Wilson, 2005) indicating the involvement of these regions in the combinatorial process associated with morphological decomposition and recomposition (Carota et al., 2016).

More specifically for written words, many neuroimaging studies have shown morphological effects already in regions associated with orthographic processing, namely the occipito-temporal-cortex (OTC) (Devlin, Jamison, Matthews, & Gonnerman, 2004; Fruchter & Marantz, 2015; Lehtonen et al., 2006; Meinzer et al., 2009; Neophytou, Manouilidou, Stockall, & Marantz, 2018; Solomyak & Marantz, 2010). MEG studies (Fruchter & Marantz, 2015; Neophytou et al., 2018; Solomyak & Marantz, 2010) show that these morphological effects in left OTC are evident as early as 170 msec following word presentation. These findings suggest that form-based decomposition of morphologically derived words begins very early in the process of visual word recognition. Finally, studies with written derived words also show morphological effects in left middle temporal cortex (Devlin et al., 2004; Meinzer et al., 2009). These effects are evident around 350–400 msec after word presentation, as shown by MEG finding (Fruchter & Marantz, 2015; Hakala, Hulten, Lehtonen, Lagus, & Salmelin, 2018; Neophytou et al., 2018; Solomyak & Marantz, 2010) and hence are attributed to semantic re-composition of morphologically derived words.

1.2. *Morphological processing in readers with dyslexia*

The tendency to decompose written words depends not only on linguistic properties of the words but also on the readers' language and reading skills. Specifically, readers' reliance on morphological segmentation may depend on their sensitivity to morphological regularities on the one hand, and on other abilities that contribute to their reading skills on the other hand. Many developmental studies suggest that morphological processing is deficient in readers with dyslexia (Kaminsky, Eviatar, & Norman, 2002; Leong, 1989), and that poor morphological sensitivity in reading and spelling continues into adulthood (Deacon, Parrila, & Kirby, 2008; Leong, 1989; Fischer, Shankweiler, & Liberman, 1985). While some studies suggest that the morphological deficit is secondary to impaired phonological awareness (Fowler & Liberman, 1995; Shankweiler, Crain, & Katz, 1995), in others, morphological awareness explains a unique portion of the variance in reading achievements in English, French and Chinese children (Casalis & Louis-Alexandre, 2000; Mahony et al., 2000; Nagy, Berninger, Abbott, Vaughan, & Vermeulen, 2003; Nagy, Carlisle, & Goodwin, 2014). Some neuroimaging studies in Chinese reading children with dyslexia support this dissociation by showing differential association of morphological and phonological abilities with functional (Liu et al., 2013) and structural measures (Su et al., 2018). The common notion across these studies is a deficit in morphological processing in individuals with dyslexia.

In contrast to the above findings, other studies suggest that readers with dyslexia rely on morphological information in reading *more* than typical readers to compensate for their phonological deficits, especially when the morphological structure is transparent (Vellutino et al., 2004). For example, Danish adult readers with dyslexia read compound words with a transparent morphological structure (e.g., sunburn) better than words with an opaque structure (e.g., window), an advantage not found for the typical readers group (Elbro & Arnbak, 1996). In a series of studies in Italian, adult readers with dyslexia benefited from the morphological structure of bi-morphemic words more than skilled readers (Burani et al., 2008). The authors suggested that morphological decomposition is beneficial in cases where whole-word processing is less likely such as pseudowords, low frequency or very long words, or among young or dyslexic readers (Burani, 2010). In French too, the morphological status of silent letters facilitated spelling in children with dyslexia, suggesting that morphological segmentation can compensate for readers' phonological deficit (Quemart & Casalis, 2017). Similarly, a study with English speaking university students showed that among readers with dyslexia, morphological awareness predicted word reading and spelling as well as academic achievements more than among controls (Law, Wouters, & Ghesquière, 2015), suggesting that dyslexic readers relied on morphological processes as a compensatory strategy for their reading deficits. Similar conclusions were drawn by recent meta-analyses in dyslexic reading children (Bowers, Kirby, & Deacon, 2010; Goodwin and Ahn 2010, 2013) showing that morphology based interventions can help these children compensate for some of their reading deficits.

These apparently contradictory findings, showing on the one hand morphological deficits in readers with dyslexia, and on the other hand compensatory reliance on morphological segmentation in these readers (Deacone, Parilla, & Kirby, 2008) suggest that one needs to examine the different components of morphological processing more deeply. Behavioral and MEG studies from French speaking children and adults suggest that morphological processing in readers with dyslexia were mainly influenced by the semantic properties of morphemes, whereas typical readers relied more on the morphemes' form (Cavalli et al., 2017; Quemart & Casalis, 2015). They further show earlier morphological effects in frontal areas that dyslexic readers (Cavalli et al., 2017). In the current study we will examine the neural correlates of morphological processing in dyslexic and typical readers, to identify more specifically differences between the two groups in brain regions associated with phonological, orthographic and semantic processing.

1.3. *Hebrew morphology and orthography*

The Hebrew language is characterized by high morphological density in both its inflectional and derivational word formation. In the Hebrew derivational system, as in other Semitic languages, most words are morphologically complex as they are composed of at least two abstract morphemes: the root and the word pattern (Mishkal/Binyan). All verbs and the majority of nouns and adjectives in Hebrew are derived via nonlinear formation in which a consonantal root is interleaved with a vocal pattern which adds the vowels in between the root consonants (i.e., “GIDUL”, “גידול”, (*growth*) root – G.D.L. (*associated with growing*) pattern CiCuC) (Ravid & Malenky, 2001). The root that provides the basic meaning to the word is not an independent word. It typically consists of three (but sometimes four) consonants. The morphemic pattern consists of the vowels, and can also include consonants, but only at the beginning (e.g., “MIGDAL”, “מגדל” (*tower*) root – G.D.L. pattern miCCaC), and/or at the end (e.g., “MAGDELET”, “מגדלת”, (*magnifying (glass)*) root – G.D.L. pattern maCCeCet) of the word. Thus, the orthographic representation of the root is an almost continuous sequence, which is only interrupted occasionally by narrow vowel letters (ו,י; Ravid & Malenky, 2001; Vaknin-Nusbaum, Sarid, & Shimron, 2015).

The Hebrew orthography consists of one script with two versions that differ in their orthographic transparency. The opaque version is the un-pointed “Abjad” orthography that represents mostly consonants, and partially represents vowels using vowel letters. Vowel letters provide only ambiguous vowel information because they denote both consonants and vowels, and some of them represent more than one vowel, creating extensive phonological underspecification (Bar-On, 2010). The transparent version is pointed, with diacritic marks superimposed under or above the letters, providing full representation of words' phonology. Children learn to read the transparent (pointed) version first, and are only exposed to the un-pointed version around 2nd or 3rd grade, with the transformation to the un-pointed script completed around 4th grade (Bar-On & Ravid, 2011). Adult texts are almost entirely un-pointed. Our previous behavioral and fMRI studies showed that while skilled Hebrew readers flexibly switch to decoding smaller orthographic and phonological units, when the less familiar pointed script is presented (Weiss, Katzir, & Bitan, 2015a, b), the cost is higher for readers with dyslexia, who read pointed words slower than un-pointed words, and do not show the expected activation in left temporo-parietal junction when reading pointed words (Weiss, Katzir, & Bitan, 2016).

1.4. *Morphological processing in reading Hebrew*

Morphological segmentation has a prominent role in processing Hebrew words. Hebrew speaking toddlers are already sensitive to the root of spoken words and can manipulate it to create new words (Berman, 1982). Studies in Hebrew reading children show evidence for explicit knowledge of roots and morphemic patterns as early as 2nd grade (Ravid & Schiff, 2006), and children's morphological awareness throughout elementary school was found to correlate with their reading skills (Cohen-Mimran, 2009; Haddad, Weiss, Katzir, & Bitan, 2018; Vaknin-Nusbaum et al., 2015; Vaknin-Nusbaum, Sarid, Raveh, et al., 2016; Vaknin-Nusbaum, Sarid, Shimron, et al., 2016). In a recent study, using the same stimuli as the current one, we found that children in 2nd and 5th grade were sensitive to the presence of a root + morphemic pattern when reading aloud single Hebrew words (Haddad et al., 2018). Evidence for the processing of roots and morphemic patterns in skilled Hebrew readers comes from studies of masked morphological priming of single words (Bentin & Feldman, 1990; Deutsch, Frost, & Forster, 1998; Frost, Forster, & Deutsch, 1997), eye-movements tracking in sentence reading (Deutsch, Frost et al. 2000, 2003, 2005) and other paradigms (Velan & Frost, 2011). Evidence from measurement of microsaccades suggests that root structure information is extracted automatically in the process of word recognition in Hebrew (Yablonski, Polat, Bonneh, & Ben-Shachar, 2017). The neural mechanisms involved in processing the root morpheme in Hebrew reading adults were identified in the left middle frontal gyrus (LMFG) which was active in both an explicit morphological relatedness judgment task (Bick, Goelman, & Frost, 2008), as well as an implicit morphological priming task (Bick, Frost, & Goelman, 2010), and the left IFG, which was active only in the implicit task. The left inferior parietal lobule (LIPL) has also shown morphological priming effects specific to words that were semantically un-related (Bick et al., 2010), presumably related to its involvement in interactions between orthography and phonology.

Similar to other languages, studies on the role of morphological decomposition in Hebrew readers with dyslexia provide mixed evidence. Several studies show that dyslexic adult Hebrew readers, with phonological deficits, fail to show long term morphological priming effects for written words (Raveh & Schiff, 2008; Schiff & Raveh, 2007). Similarly, both children and adult Hebrew readers with dyslexia showed deficient morphological awareness in spoken words (Bendror et al., 1995; Schiff & Ravid, 2007). However, another study showed that although dyslexic Hebrew speakers performed poorly on morphological awareness tasks, they showed greater morphological priming effects than controls in a visual lexical decision masked priming task (Leikin & Even Zur, 2006). This together with recent training studies (Bar-Kochva, 2016; Kimel & Ahissar, 2019) suggest that while dyslexic Hebrew readers may be impaired on metalinguistic morphological awareness tasks, they have intact sensitivity to the morphological structure of words evident in implicit tasks.

1.5. *Current study*

The current study examined the effect of orthographic transparency on morphological decomposition in reading single words among typical readers and dyslexic readers with a phonological deficit. We conducted one behavioral and one fMRI experiment, in which typical and dyslexic adult Hebrew readers read aloud words. Both experiments used the same set of words in which half of them were bi-morphemic (containing a root + morphemic pattern) and half were mono-morphemic (non-decomposable). The words were presented with and without diacritic marks, resulting in two levels of orthographic transparency. We examined five left hemisphere regions of interest, which were previously shown to be sensitive to morphological decomposition of written words: left OTC associated with orthographic processing (Devlin et al., 2004; Fruchter & Marantz, 2015; Lehtonen et al., 2006; Leminen, Smolka, Duñabeitia, & Pliatsikas, 2019; Meinzer et al., 2009; Neophytou et al., 2018; Solomyak & Marantz, 2010); left IFG (Bozic et al., 2007; Leminen, Smolka, Duñabeitia, & Pliatsikas, 2019; Meinzer et al., 2009; Pliatsikas, Wheeldon et al., 2014) and left MFG (Bick et al., 2010; Bick et al., 2008) associated with late morpho-phonological segmentation; left IPL associated with non-semantic morphological effects in Hebrew (Bick et al., 2010), and left middle temporal gyrus (MTG) (Devlin et al., 2004; Meinzer et al., 2009) associated with semantic re-composition.

We tested three main predictions: 1) Due to the prominent role of the root morpheme in identifying Hebrew words, we expect to find evidence for morphological decomposition in *all* adult readers. Although behavioral RT measures in oral reading of single words may be at ceiling in skilled readers, and thus may not be sensitive enough, we expect to find morphological effects in brain activation in all the tested regions; namely, left OTC, left IFG, left MFG, left IPL and left MTG. 2) Because the morphemic pattern contains information about vowels, and because this information is often missing in the un-pointed script, morphological decomposition can compensate for this missing vowel information and facilitate word identification, especially when reading the un-pointed non-transparent script. We therefore expect, at least for skilled readers, to show stronger morphological effects in brain activation in the un-pointed compared to the pointed script. 3) Based on the mixed results in the literature, it is not clear whether dyslexic readers would benefit from the morphemic structure more or less than typical readers and how this would interact with orthographic transparency. On the one hand, morphological decomposition may be recruited more for reading the un-pointed script to compensate for the missing vowels (as predicted above for skilled readers). However, on the other hand, because dyslexic readers have more difficulty with reading the pointed compared to the un-pointed script (Weiss et al., 2015; Weiss et al., 2016), they could show stronger morphological effects when reading pointed words to compensate for their deficient phonological decoding skills.

2. Experiment 1 - behavior

2.1. *Methods*

2.1.1. *Participants*

21 Adult readers with developmental dyslexia (8 males; age range 22:07–38 years, M = 27:09, SD = 4:01) and 19 typical readers (9 males; age range 23–34:09 years, M = 27:01, SD = 3.1) participated in the behavioral experiment. The number of participants was determined based on sample sizes in previous studies. They have also taken part in our previously published behavioral study (Weiss et al., 2015), which described their selection in details. All participants were university or college students in Israel, native Hebrew speakers, right-handed, and displayed normal (or corrected to normal) vision in both eyes. None of them had a history of neurological, attention or psychiatric disorders.

Dyslexic readers were diagnosed in childhood and again by the university student support services, and matched the definition of 'compensated' dyslexics (Miller-Shaul, 2005). In addition to current and childhood diagnosis of dyslexia inclusion criteria were a score lower than one standard deviation below the average of the local norms (Weiss et al., 2015), in at least one of the two phonological tests: In the phonological decoding test (one minute pseudoword test; Shatil, 1997) participants read lists of pointed pseudowords as quickly and accurately as possible within one minute, and the number of correctly read items is counted. In the phonological awareness test (phoneme deletion test for pseudowords; Ben Dror & Shani, 1996) participants hear 25 pseudowords and repeat them by omitting a specified phoneme. These criteria were established before data analysis. We also administer a speeded reading test in which participants read as many real words per minute (Shatil, 1997). These tests were administered on a separate session, before the experiment. Table 1 shows the mean and SD of the two groups in the screening tests.

2.1.2. *Stimuli*

The stimuli for the current study have been used in our previous behavioral study with children (Haddad et al., 2018). It consists of 96 Hebrew concrete nouns in 4 conditions (24 words each): two levels of diacritics (orthographic transparency: with or without diacritic marks) and two morphological conditions. Morphologically rich (bi-morphemic) words are composed of two morphemes: a root + pattern. All roots were three consonant productive roots, which are also

Table 1 – Means and SD of screening and phonological tests for participants in the behavioral experiment.

Tests	Units of measure	Dyslexic Readers (N = 21)	Typical Readers (N = 19)	Sig.
Phoneme Deletion Test	Total time (sec)	212.67 (49.54)	100.31 (12.37)	$p < .001$
	Number of correct answers	20.15 (5.75)	22.47 (2.98)	N.S.
One Minute Pseudoword Test	Number of correct pseudowords per minute	30.63 (10.44)	61.47 (13.49)	$p < .001$
One Minute Word Test	Number of correct words per minute	70.75 (19.90)	102.78 (19.75)	$p < .001$

Note. SD are given in parenthesis.

Table 2 – Examples of bi-morphemic and mono-morphemic words presented either with or without diacritic marks (letters in bold constitute the root morpheme).

	Bi-morphemic words (with root + pattern)	Mono-morphemic words
With diacritics (pointed)	מִכְשׁוֹל M**XS**OL /mixshol/(obstacle)	סַנְטֵר <SNTR> /santer/(chin)
Without diacritics (un-pointed)	תלמיד T**LM**ID /talmid/(student)	סנפיר SNPIR /snapir/(fin)

used in existing Hebrew verbs, as judged by a linguist. Morphologically simple (mono-morphemic) words cannot be decomposed into smaller morphemes. We did not include words that can be decomposed into base + suffix (e.g., /gagon//gag/+/on/'small roof') even if they did not include a root (See Table 2). In order to avoid lexical ambiguity of both pointed and un-pointed word forms, we avoided the inclusion of homographic words. Words in all conditions had an identical number of letters, consonants and syllables (See Table 3). As there is no available consensus corpus for written Hebrew frequency, our frequency ranking was based on subjective rating of 14 elementary school teachers on a 1–5 Likert scale, that represent a range of average to high frequency in adult texts. In order to verify that our morphological conditions do not differ in frequency we compared their subjective frequency measure, as well as a measure of frequency that was recently published (https://chengafni.wordpress.com/resources/heblex). Because the distributions of these measures were not normal (significant Shapiro–Wilk's test for normality as well as non-zero skewness and kurtosis) we used the Mann–Whitney U tests, which showed non-significant differences in frequency between mono-morphemic and bi-morphemic words (See Table 3). Orthographic neighborhood was tested using the Language Resources for Hebrew Corpus (Itai & Wintner, 2008), which was used in our previous study (Weiss et al., 2015). The size of the orthographic neighborhood of a given word is defined as the number of words of the same length created by replacing a single letter in the target word (Coltheart 1977). It should be noted that the degree to which this measure is relevant for the Hebrew orthography is debated, since unlike Indo-European languages, orthographic neighborhood was not found to affect visual form-priming in Hebrew (Frost, Kugler, Deutsch, & Forster, 2005). Because this measure is based on the specific position of letters within words, while root letters can appear in different positions in words sharing the same root, this measure may be less relevant to Hebrew than morphological relatedness. Nevertheless, we still expect words containing roots to have a larger orthographic neighborhood than mono-morphemic words. Because this measure was not normally distributed we compared it using the Mann–Whitney *U* test. Indeed, this comparison showed a significantly larger orthographic neighborhood for bi-morphemic compared to mono-morphemic words (see Table 3).

2.1.3. *Experimental procedure*

We employed an oral naming task because it has a high ecological validity for testing reliance on phonological representations during word recognition (Burani et al., 2008; Koriat, 1984). Stimuli from the current experiment were presented together with words from another experiment (Weiss et al., 2015) which includes 192 words, with 40 words overlapping between the two experiments. Hence, the total number of trials for both experiments together was 248. Pointed and un-pointed words were presented in separate blocks of 124 words each, to minimize interference from frequent switching between strategies associated with reading pointed and un-pointed words. Block order was counter-balanced across individuals, while mono-morphemic and bi-morphemic words were randomly intermixed.

Stimuli were presented on a computer monitor and participants were required to read them aloud, while oral responses and reaction times were recorded using a voice-activated-key (E-prime, Serial Response Box, PST, script is available on https://doi.org/10.5281/zenodo.3873360). The words disappeared 1200 msec after the onset of the vocal response, and were replaced by a fixation cross. Reaction times were collected from the stimulus presentation to the onset of vocalization. The presentation of the subsequent word was triggered by the participants when they were ready in order to make sure they were attentive.

2.1.4. *Analysis of data*

Response times shorter than 154 msec. (−2 SD), and longer than 1,570 msec (+3 SD) (i.e., 1.55% of total responses) were excluded from the analysis. Participants mean response time

Table 3 – Properties of stimuli in the two morphological conditions.

		Bi-morphemic	Mono-morphemic	Statistic	P (diff)
No. of letters	mean	4.33 ± .48	4.33 ± .48	*identical*	
	range	4–5	4–5		
No. of consonants	mean	3.58 ± .5	3.58 ± .5	*identical*	
	range	3–4	3–4		
No. of syllables	mean	2.08 ± .28	2.08 ± .28	*identical*	
	range	2–3	2–3		
Freq. subjective	median	3.46	3.33	Mann Whitney U	.803
	range	1.33–4.92	1.25–4.88		
Freq. Gafni	median	576	350.5	Mann Whitney U	.245
	range	21–51386	15–17435		
Orthographic neighborhood	median	17	12.5	Mann Whitney U	.04*
	range	3–45	0–51		

on correct responses and percentage of pronunciation errors for the different factors were calculated. Repeated measures GLM analyses were conducted separately for RT and accuracy as dependent measures, with group (dyslexic *vs* typical readers) as a between-subject variable, and morphological complexity (bi-morphemic *vs* mono-morphemic) and diacritics (pointed *vs* un-pointed) as within-subject factors. Planned separate analyses within each group and within pointed and un-pointed words were conducted to test our specific hypotheses, even if there were no significant interactions of experimental factors and group. No part of the study procedures or analysis was pre-registered prior to the research being conducted.

2.2. Results

2.2.1. Behavioral experiment

Participant mean response time on correct responses and proportion of correct responses are presented in Figs. 1 and 2. The raw data is also available on https://doi.org/10.5281/zenodo.3873360.

2.2.1.1. Reaction time. A GLM repeated measures analysis with group as a between subject factor, and diacritics and morphological complexity as within subject factors showed that dyslexic readers' performance was significantly slower than typical readers (F(1,38) = 22.439, $p < .001$). In addition, we found a significant effect of diacritics (F(1,38) = 7.33, $p = .01$) and a two way interaction of group and diacritics (F(1,38) = 4.33, $p = .044$). To follow-up this interaction separate GLM analyses were conducted within each group, with diacritics and morphological complexity as within subject factors. No significant effects were found for typical readers. Dyslexic readers, on the other hand, showed significantly slower performance in pointed compared to un-pointed words (F(1,20) = 12.919, $p = .002$), and a significant effect of morphology (F(1,20) = 5.242, $p = .033$) with faster response time for bi-morphemic compared to mono-morphemic words (see Fig. 1).

2.2.1.2. Accuracy. A GLM repeated measures analysis, with group as a between subject factor, showed that typical readers were significantly more accurate than dyslexic readers (F(1,38) = 9.997, $p = .003$). In separate analyses within each group there were no significant main effects or interactions (see Fig. 2).

2.3. Discussion

In the behavioral experiment we examined the accuracy and reaction time of reading aloud mono-morphemic and bi-morphemic words presented with or without diacritic marks among typical and dyslexic adult Hebrew readers. We predicted that due to the prominent role of morphological decomposition in Hebrew, both typical and dyslexic readers would benefit from the morphological structure of words. For skilled readers we expected that this benefit would be stronger in the non-transparent orthography (un-pointed words), to compensate for the missing phonological information. For dyslexic readers, we expected to either find a similar pattern to typical readers (i.e., stronger morphological effect in the un-pointed script to compensate for the missing vowels) or an opposite pattern, with stronger morphological effects in the transparent orthography (pointed words), because it requires phonological decoding which is impaired in this group.

Our behavioral results showed that dyslexic readers read all words less accurately and more slowly than typical readers. Furthermore, only dyslexic readers read pointed words more slowly than un-pointed words. Interestingly only dyslexic readers read bi-morphemic words faster than mono-morphemic words, irrespective of orthographic transparency. These results suggest that dyslexic readers are sensitive to the morphological structure of words, and benefit from it during word recognition. The lack of any morphological effect in typical readers may be due to their high reading proficiency, and the insensitivity of the behavioral measures for this group.

In contrast to our predictions, we didn't find an interaction between morphological complexity and orthographic

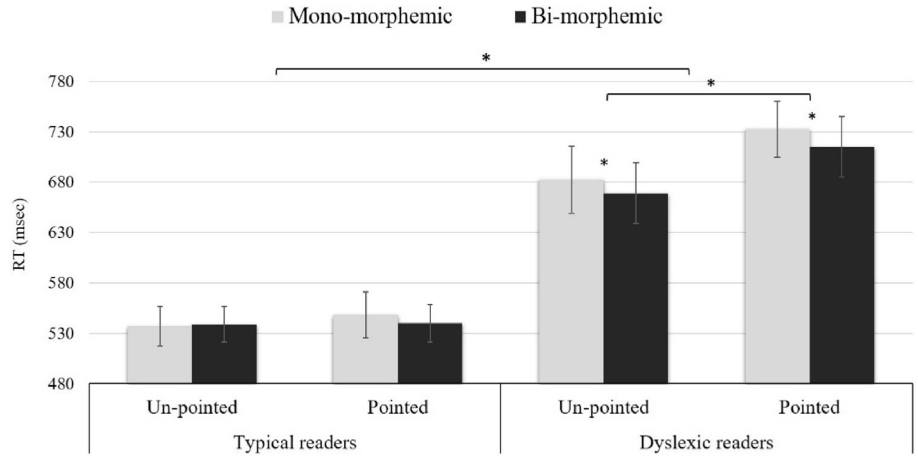

Fig. 1 – Latencies of oral naming of mono-morphemic and bi-morphemic words presented with and without diacritic marks to typical and dyslexic readers in the behavioral experiment. * indicates significance at $p < .05$, error bars represent standard error.

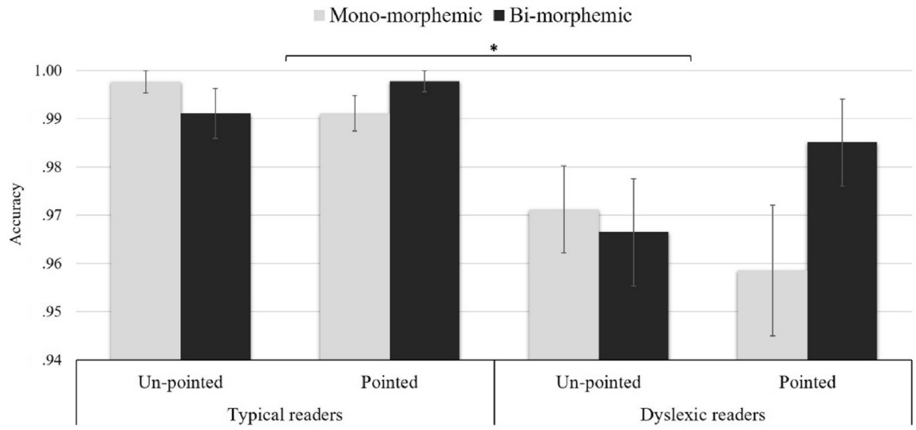

Fig. 2 – **Oral naming accuracy in the behavioral experiment for typical and dyslexic readers. * indicates significance at $p < .05$, error bars represent standard error.**

transparency in any group, and the advantage for bi-morphemic words in dyslexic readers was similar for the pointed and un-pointed conditions. For dyslexic readers this may suggest that the morphological structure can compensate for different kinds of difficulties when reading pointed and un-pointed words. When reading un-pointed words, the morphological structure can compensate for the missing vowel information. However, when reading pointed words, the morphological structure can compensate for the low orthographic familiarity. Our results showing that dyslexic readers read pointed words more slowly than un-pointed words are consistent with the results from our partly overlapping behavioral and fMRI studies (Weiss et al., 2015; Weiss et al., 2016). By manipulating word length and the presence of vowel letters, in addition to diacritic marks, these studies showed that diacritic marks reduce the familiarity of the orthographic form of words. Unlike typical readers, dyslexic readers cannot compensate for this reduced familiarity with reliance on decoding of smaller units, and are thus more hindered by it. This may explain why the morphological structure of words would benefit recognition of both pointed and un-pointed words, each for a different reason. While behavioral measures cannot distinguish between these different sources of benefit, this may be achieved by measuring brain activation in fMRI.

3. Experiment 2 – FMRI

3.1. *Method*

3.1.1. *Participants*

21 readers with developmental dyslexia (9 males, age range 19:11–32:06 years, M = 26:10, SD = 3:05) and 22 typical readers (11 males, age range 22:03 - 33:07 years, M = 28:03, SD = 2:07) participated in the fMRI experiment. The sample size was determined based on previous studies. None of the participants in the fMRI experiment took part in the behavioral experiment, but the same selection criteria were applied. These criteria were established before data analysis. All of the fMRI participants have also participated in our previously published fMRI study (Weiss et al., 2016). In addition to the screening tests (which were similar to those performed in the behavioral experiment) the dyslexic readers group also performed a Morphological Relatedness test (Leikin & Even Zur, 2006), that served to examine correlations with brain activation. In this test participants hear 20 pairs of words and judge whether they share the same root. All word pairs are semantically un-related. Maximum score is 20. These tests were administered on a separate session, before the scanning session. Means and SD of all measures for the two groups are presented in Table 4. Readers with dyslexia performed significantly worse than typical readers in all measures.

3.1.2. *Stimuli*

The same oral naming task and 96 words used in the behavioral experiment and in our previous behavioral study in children (Haddad et al., 2018), were also used for this FMRI experiment.

3.1.3. *Experimental procedure*

The experimental procedure, fMRI data acquisition and preprocessing steps are identical to our previous fMRI study (Weiss et al., 2016). In the fMRI experiment all 96 words were presented twice, once in the pointed and once in the un-pointed version (total of 192 trials) to increase the power. Each trial began with a 200 msec presentation of a fixation cross followed by the presentation of the stimulus word for 1500 msec and then a blank screen for 2300 msec. Participants were required to read the word aloud as soon as it appears on the screen, and their responses and reaction times were monitored by an MRI compatible microphone with noise cancellation (FOMRI™ III system, Optoacoustics Ltd.). The use of this microphone which enables participants to hear themselves easily above the scanner noise, reduces large jaw and head movements associated with speaking loudly.

Stimuli were presented using E-Prime stimulus presentation software (v.2.0, Psychological Software Tools, Inc.). Bi-morphemic and mono-morphemic words and baseline trials were intermixed in an event-related design. Pointed and un-pointed words were presented in separate runs to minimize interference which may arise from frequent shifting between versions. Half of the words in the list appeared first in their pointed version and half appeared first in their un-pointed

Table 4 – Means and SD of screening and phonological tests for participants in the fMRI experiment.

	Units of measure	Dyslexic Readers (N = 21)	Typical Readers (N = 22)	Sig.
Phoneme Deletion Test	Total time (sec)	177.23 (45.63)	84.62 (7.65)	$p < .001$
	Number of correct answers	15.19 (6.36)	23.72 (1.51)	$p < .001$
One Minute Pseudoword Test	Number of correct pseudowords per minute	27.04 (10.29)	60.45 (8.26)	$p < .001$
One Minute Word Tests	Number of correct words per minute	60.04 (18.33)	95.18 (18.26)	$p < .001$
Morphological Relatedness	Number of correct pairs	14.65 (.62)	NA	

Note. SD are given in parenthesis.

version. Four runs of pointed words and four runs of un-pointed words appeared in alternating order, and the order was counterbalanced across individuals. Stimuli from the current experiment were presented together with words from another experiment (Weiss et al., 2016) which includes 192 words, with 40 words overlapping between the two experiments. As indicated above all experimental stimuli were presented twice, resulting in 496 trials, and were intermixed with 96 baseline trials, in which participants saw a string of asterisks and were required to say the word 'pass'. The production of a word in the baseline condition was used to control for the articulation and motor component in the comparison of the experimental conditions. Trial interval was jittered with 30% time of null and the sequence of trials was optimized using Optseq (Dale, 1999; http://surfer.nmr.mgh.harvard.edu/optseq/). The total of 592 trials were acquired in eight runs of 5:42 min each. A practice list of ten different words was presented to participants immediately prior to the first experimental run.

3.1.4. *FMRI data acquisition*

Images were acquired using a 3.0 T GE scanner with a standard head coil. The stimuli were projected onto a screen, and viewed through a mirror attached to the inside of the head coil. Participant's oral reading was monitored, to ensure their compliance with the task requirements. Functional images were acquired with a susceptibility weighted single-shot EPI (echo planar imaging) with BOLD (blood oxygenation level-dependent) with the following parameters: TE = 35 msec., flip angle = 78°, matrix size = 96 × 96, field of view = 20 cm, slice thickness = 3 mm +1 mm gap, number of slices = 26 in a sequential ascending order, TR = 2000 msec. 171 images were acquired during each run. In addition, a high resolution, anatomical T1 weighted 3D structural images were acquired (AX SPGR, TR = 9.044 msec., TE = 3.0504 msec., flip angle = 13°, matrix size = 256 × 256, field of view = 25.6 cm, slice thickness = 1 mm) using an identical orientation as the functional images. FMRI scans were performed in The Functional Brain Imaging Center, at the Tel-Aviv Sourasky Medical Center.

3.1.5. *FMRI data preprocessing and statistical analysis*

Data were analyzed using the Statistical Parametric Mapping toolbox for Matlab (SPM12- Welcome Trust Centre for Neuroimaging, University College London, www.fil.ion.ucl.ac.uk/spm). The images were spatially realigned to the first volume in each run to correct for head movements. Average displacement in x, y or z dimensions across runs and across subjects is .8 mm (range = .1–3.5 mm). Sinc interpolation was used to minimize timing errors between slices (Henson, Buchel, Josephs, & Friston, 1999). The functional images were co-registered with the anatomical image and normalized to the standard T1 volume (MNI). The data were then smoothed with a 5-mm isotropic Gaussian kernel.

Statistical analyses at the first level were done in each participant using the GLM analysis for event-related designs. A high-pass filter with a cutoff period of 128 s was applied. Movement parameters calculated during realignment were included as regressors of no interest. The model included two levels of morphological complexity (bi-morphemic *vs* mono-morphemic), and two levels of diacritics (pointed *vs* un-pointed) as well as the baseline condition, resulting in four basic condition. The contrasts of the four basic conditions *vs* the baseline were carried into the second level analysis. To avoid a possible effect of reduced brain response due to repetition of words across conditions (pointed and un-pointed), we conducted a preliminary analysis restricted to the first occurrence of each word. No differences were found between this analysis and the analysis with the two occurrences in the effects of experimental condition. Thus, we decided to include both occurrences in the analysis to increase statistical power.

3.1.6. *Whole brain group analyses*

For each participant four basic contrasts were carried from the first level into the second level analysis. These include the four basic conditions (bi-morphemic and mono-morphemic words presented in the pointed and un-pointed versions) versus baseline. The data is available in: https://doi.org/10.5281/zenodo.3873360. In order to identify brain regions associated with sensitivity to the morphological structure in words with and without diacritic marks, second level whole brain analyses were conducted separately for pointed and un-pointed words. These flexible factorial design models included group (dyslexic *vs* typical readers), as the between subject factor and morphological complexity (mono-morphemic *vs* bi-morphemic words) as a within subject factor. Statistical maps showing the effect of morphological complexity within group and within pointed and un-pointed words are depicted for descriptive purpose at significance level of $p < .001$ uncorrected for multiple comparisons, using a cluster extent threshold of $k \geq 20$.

3.1.7. *ROI analyses*

Five regions of interest were defined in the left hemisphere based on brain areas showing sensitivity to morphological complexity in previous studies. 1) Left inferior frontal gyrus (IFG) was identified in numerous studies with both inflectional and derivational morphology (Bozic, Szlachta, & Marslen-Wilson, 2013; Marangolo et al., 2006; Meinzer et al., 2009; Pliatsikas, Wheeldon et al., 2014). It was therefore defined anatomically, based on the Automated Anatomical Labeling atlas (AAL) (Tzourio-Mazoyer, Landeau, Papathanassiou, Crivello, & Etard, 2002) and included all three sub-regions: 1a) pars opercularis (oper), 1b) pars triangularis (tri) and 1c) pars orbitalis (orb); 2) The left middle frontal gyrus (MFG) was defined as an 8 mm sphere centered around MNI coordinates $x = -35$, $y = 7$, $z = 29$, showing morphological priming in Hebrew (Bick, Goelman, & Frost, 2011); 3) The left occipito-temporal cortex (OTC) was defined as a 10 mm sphere centered around MNI coordinates: $x = -54$, $y = -57$, $z = -4$, showing sensitivity to morphological inflections at an orthographic level (Lehtonen et al., 2006)); 4) The left middle temporal gyrus (MTG) was defined as a 10 mm sphere centered around MNI coordinates: $x = -70$, $y = -42$, and $z = 4$, which showed morpho-semantic priming effects for visual words (Devlin et al., 2004); and 5) The left IPL was defined as an anatomical mask based on the AAL atlas. Changes in signal intensity during word reading were extracted using the MarsBaR toolbox for SPM (MARSeille Boîte À Région d'Intérêt, v.0.43- (Brett, Anton, Valabregue, & Poline, 2002)). For each ROI we extracted the betas for each of 4 experimental conditions (2 levels of diacritics X 2 levels of morphological complexity) and the baseline. We then calculated the differences between each condition and the baseline's beta values. These difference values served as the dependent variable in the statistical analysis. Statistical analysis was done using IBM SPSS Statistics software (v. 19).

Data from all ROIs was approximately normally distributed, with Shapiro–Wilk's tests >.05, and skewness and kurtosis close to 0 in all conditions. The statistical analysis was carried out separately for each of the five ROIs, using GLM analysis with group as a between subject factor, and morphological complexity and diacritics as within subject factors. For IFG we included all three sub-regions in the same analysis, as a third within-subject factor. Follow-up analyses for interactions with sub-region applied Bonferroni correction for multiple comparisons. Because we have specific predictions for the morphological effect in dyslexic readers, we conducted follow-up analyses within each group even when the interaction with group was not significant. In order to test whether brain activity in the ROIs was associated with participants' morphological and phonological awareness, we used performance scores on the 'morphological relatedness' test (that was only administered to dyslexic readers) and 'non-words per minute' test. Both measures were normally distributed (Shapiro–Wilk's test >.05, skewness and kurtosis close to 0). We have included these test scores together as covariates in GLM analyses conducted separately for each ROI. When these covariates showed a significant interaction with one of the experimental variables Pearson correlations were computed with each individual condition, and the *p* value was corrected for the 4 experimental conditions. No part of the study procedures or analysis was pre-registered prior to the research being conducted.

3.2. Results

3.2.1. Whole brain analysis

Whole brain activation maps from the second level analysis, for all reading conditions versus baseline are presented in Fig. 3 and Table 5 separately for typical and dyslexic readers.

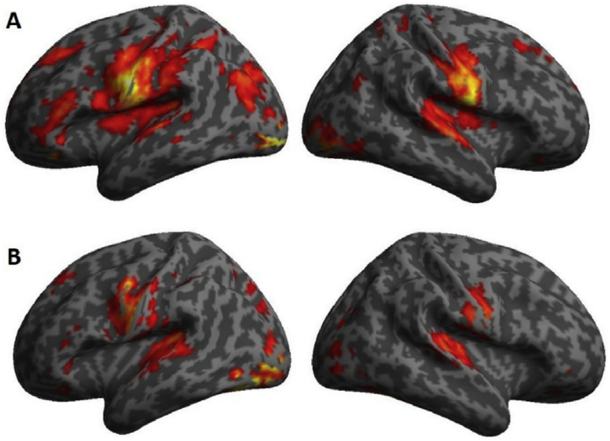

Fig. 3 – Activation map for all reading conditions versus baseline in typical (A) and dyslexic (B) readers. FWE corrected $p<.05$, k>50. Brighter (yellow) colors indicate stronger activation.

Morphological effects at the whole brain level were assessed in the second level group analysis by means of the flexible factorial design with the factors subject, group and morphological complexity, separately in the pointed and un-pointed conditions. There were no significant effects at the FWE corrected level. However, the analysis in un-pointed words showed greater activation for mono-morphemic compared to bi-morphemic words in left IFG with a threshold of $p < .001$ uncorrected. This cluster was only evident among typical readers (See Fig. 4). No activation was found for the dyslexic readers in this contrast, nor for bi- versus mono-morphemic words in either group. No morphological effect was evident for pointed words.

3.2.2. ROI analysis

The following sections describe the analyses conducted in each ROI. The significant effects are also summarized in Table 6.

3.2.2.1. INFERIOR FRONTAL GYRUS. A four-way GLM analysis was conducted on the percent signal change in the left IFG, with group (typical *vs* dyslexic readers) as between subject factor,

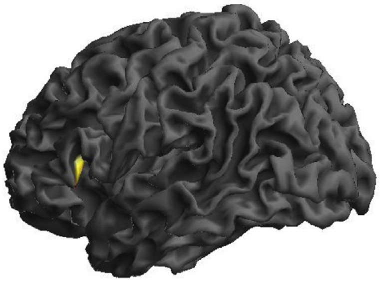

Fig. 4 – Greater activation in mono-morphemic compared to bi-morphemic words in the un-pointed script for typical readers. Activation in left IFG (BA 47/13), MNI coordinates: −44, 22, −2, Z score = 4.23, extent = 118 voxels, was significant at a threshold of $p < .001$ uncorrected, $k \geq 20$.

Table 5 – Activation in the contrast of all reading conditions versus baseline, FWE corrected $p < .05$, k>50.

Area	BA	H	Z score	voxels	x	y	z
Typical readers							
Postcentral gy.	3	L	Inf	16,028	58-	12-	26
Middle/Inferior occipital gy.	18	L	Inf	2019	32-	88-	4-
Rolandic operculum/Postcentral gy.	43	R	Inf	4574	62	6-	12
Inferior frontal gy. Orbitalis/ Tringularis	11	L	Inf	1208	36-	34	12-
Inferior occipital gy./Cerebellum	18	R	Inf	1491	34	92-	8-
Middle occipital/Angular gy.	39	R	6.63	107	52	70-	26
Superior frontal gy.	8	R	6.55	131	24	22	48
Dyslexic readers							
Inferior/Middle occipital gy.	19	L	Inf	9769	40-	78-	12-
Superior temporal/Postcentral gy.	41	R	Inf	1895	56	26-	12
Middle/Superior frontal gy.	10	L	Inf	293	8-	56	4-
Supplementary motor area	6	L	Inf	503	4-	14	52
Inferior frontal gy. Orbitalis	47	L	Inf	378	30-	36	10-
Inferior frontal gy. orbitalis	47	R	7.34	76	36	38	8-
Mid cingulum	32	R	7.04	76	14	14	38
Inferior parietal lobule	32	L	6.9	131	44-	40-	42
Middle/Superior occipital gy.	19	L	6.85	301	26-	76-	22
Superior frontal gy.	8	L	6.65	124	20-	28	48
Caudate	25	R	6.24	101	8	8	8-
Superior frontal gy.	9	L	6.22	51	14-	52	40
Superior/Medial frontal gy.	10	R + L	5.64	68	0	60	30

and IFG sub-region (opercularis, triangularis, orbitalis), morphological complexity (bi-morphemic *vs* mono-morphemic) and diacritics (pointed *vs* un-pointed) as within subject factors. The analysis revealed a main effect of morphological complexity ($F(1, 41) = 5.552$, $p = .023$). A significant two way interaction between sub-region and group ($F(2, 82) = 7.307$, $p = .001$) was due to dyslexic readers showing stronger activation in IFG pars orbitalis compared to IFG pars opercularis ($p = .007$). Finally, the IFG analysis also showed a three-way interaction between sub-region, diacritics and morphological complexity ($F(1.304, 53.459) = 7.095$, $p = .006$), which was followed-up by separate analyses within each sub-region. This revealed no significant effects in IFG pars orbitalis.

The analysis within IFG pars opercularis revealed more activation for mono-morphemic compared to bi-morphemic words ($F(1,41) = 4.97$, $p = .031$), and an interaction between diacritics and morphological complexity ($F(1,41) = 4.617$, $p = .038$). Paired *t*-tests showed a significantly stronger activation for mono-morphemic compared to bi-morphemic words, only in the un-pointed condition ($t(42) = -3.425$, $p = .001$) across both groups (see Table 6). Although the interaction with ‘group’ was not significant, in order to examine our prediction for morphological effects specifically within dyslexic readers, we conducted paired-t-tests between mono-morphemic and bi-morphemic un-pointed words, separately for each group. This morphological effect in un-pointed words was significant in typical readers ($T(21) = 2.836$, $p = .01$), and marginally significant in dyslexic readers ($T(20) = 1.951$, $p = .065$) (See Fig. 5a).

The analysis within IFG pars triangularis also showed a significant main effect of morphological complexity ($F(1,41) = 6.938$, $p = .012$). Although the interactions with group or diacritics were not significant, Fig. 5b shows a similar pattern to

Table 6 – Summary of significant main effects and interactions in the ROI analyses.

ROI	Effect	dfn	dfd	F/T	*p*
L.IFG	Mono-morphemic > bi-morphemic	1	41	5.552	.023
	sub-region x group	2	82	7.307	.023
	IFG orbitalis > IFG opercularis only in dyslexic readers				*.007*
	sub-region x diacritics x morphological complexity[1]	1.304	53.459	7.095	.006
L. Oper	Mono-morphemic > bi-morphemic	1	41	4.97	.031
	Diacritic x morphological complexity	1	41	4.617	.038
	Mono-morphemic > bi-morphemic only in un-pointed words		42	$t = 3.425$	.001
L. Tri	Mono-morphemic > bi-morphemic	1	41	6.938	.012
MFG	Diacritic x morphological complexity	1	41	6.358	.016
	Mono-morphemic > bi-morphemic only in un-pointed words		42	$t = 3.221$	.002
OTC	Group x diacritics x morphological complexity	1	41	9.75	.003
	Diacritic x Morphology only in dyslexic readers	1	20	9.439	.006
	Bi-morphemic > mono-morphemic only in pointed words in dyslexic readers		20	$t = 2.448$	.024

dfn-degrees of freedom in the numerator. dfd-degrees of freedom in the denominator. Post-hoc analyses for simple effects are in italic letters.
[1] Greenhous-Geisser correction was applied for violation of sphericity.

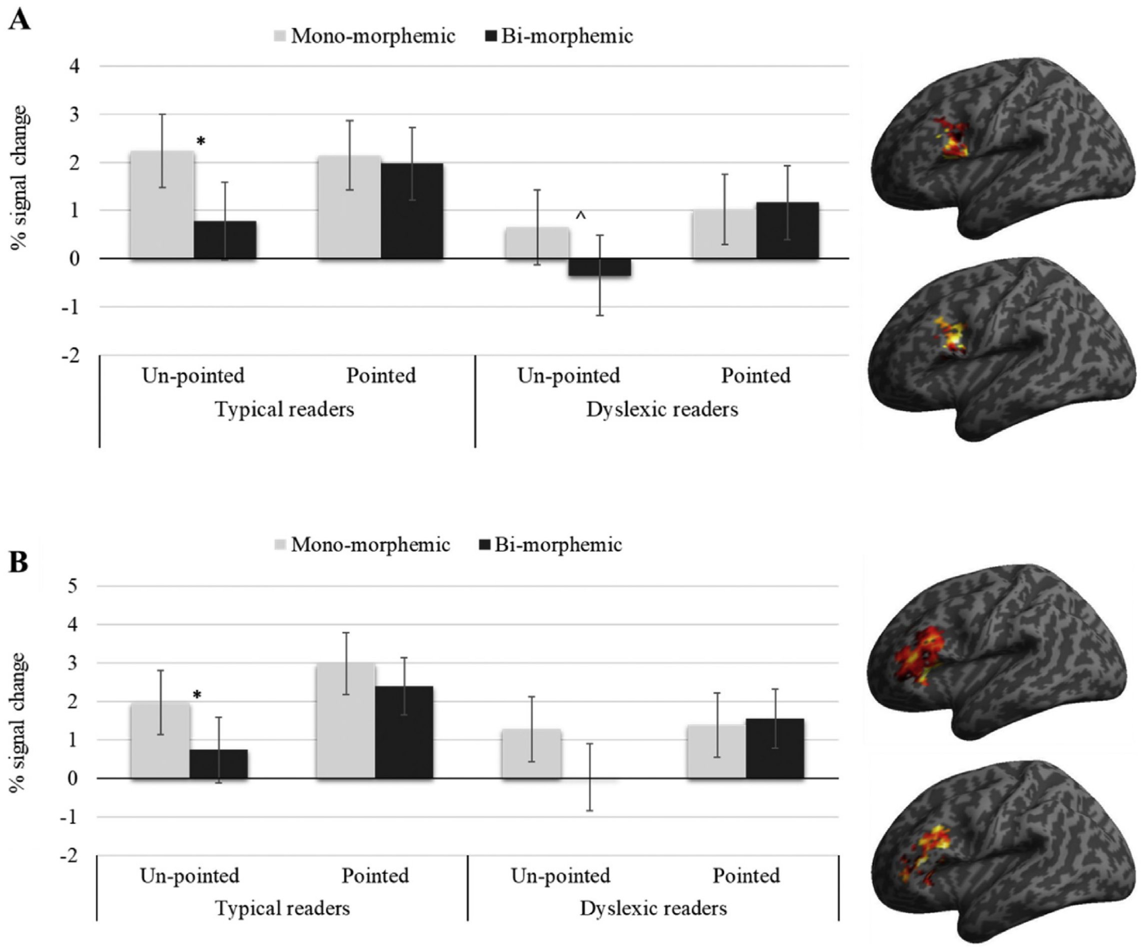

Fig. 5 – Left inferior frontal gyrus. Percent signal change in IFG pars opercularis (A) and IFG pars triangularis (B). *-Significant effects ($p < .05$); ^-marginally significant effects. Brain images on the right present un-thresholded maps of activation in the contrast of mono-morphemic versus bi-morphemic words in the un-pointed script, within the anatomical mask (based on the AAL atlas) used to extract the ROIs, separately for typical (top) and dyslexic (bottom) readers. Brighter (yellow) colors indicate stronger activation

pars opercularis, with a morphological effect only in un-pointed words. Paired *t*-tests show a significant morphological effect in un-pointed words only in typical readers (T(21) = 2.361, $p = .028$) and a non-significant trend in dyslexic readers (T(20) = 1.793, $p = .088$) (See Fig. 5b).

3.2.2.2. Middle frontal gyrus. A three-way GLM analysis conducted for left MFG revealed a two way interaction between Diacritic and morphological complexity (F(1,41) = 6.358, $p = .016$). Paired t-tests across groups revealed that this interaction was due to a significantly stronger activation for mono-morphemic words compared to bi-morphemic words, only in the un-pointed condition (t(42) = −3.221, $p = .002$). Although the interaction with group was not significant, in order to examine the prediction for an effect of morphology specifically within dyslexic readers we conducted paired-t-tests between mono-morphemic and bi-morphemic un-pointed words, separately for each group. This morphological effect in un-pointed words was significant in dyslexic readers (T(20) = 2.535, $p = .02$), and marginally significant in typical readers (T(20) = 1.969, $p = .062$) (See Fig. 6).

3.2.2.3. Occipito-temporal cortex. A three-way GLM analysis conducted on left OTC, revealed a three-way interaction between diacritics, morphological complexity and group (F(1,41) = 9.75, $p = .003$). This interaction was followed-up by a separate GLM analyses within each group. The analysis revealed an interaction between diacritics and morphological complexity (F(1,20) = 9.439, $p = .006$) only for the dyslexic readers. Paired t-tests revealed that this interaction was due to a significantly less negative activation for bi-morphemic compared to mono-morphemic words, but only in pointed words (t(20) = 2.448, $p = .024$) (See Fig. 7).

3.2.2.4. Middle temporal gyrus and inferior parietal lobule. Three-way GLM analyses were conducted separately on the percent signal change in left MTG and in left IPL, with group as between-subject factor and morphological complexity and

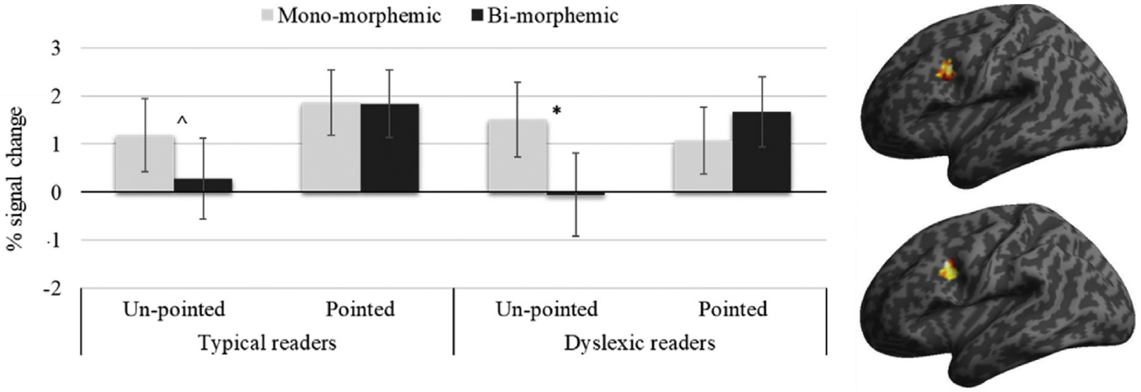

Fig. 6 – Left middle frontal gyrus. Percent signal change in ROI. *-Significant effects ($p < .05$); ^-marginally significant effects. Brain images on the right present un-thresholded maps of activation in the contrast of mono-morphemic versus bi-morphemic words in the un-pointed script, within a sphere around x = −35, y = 7, z = 29 (Bick et al., 2011) used to extract the ROIs, separately for typical (top) and dyslexic (bottom) readers. Brighter (yellow) colors indicate stronger activation.

diacritics as within-subject factors showed no significant main effects or interaction among the conditions.

3.2.3. *Effects of meta-linguistic abilities*

In order to test whether brain activity in these regions was associated with participants' morphological and phonological abilities, we included the scores of the 'morphological relatedness' test and the 'non-words per minute' test together, as between-subject covariates, in the GLM analyses conducted separately for each ROI. Because the morphological relatedness score was not available for typical readers, this analysis was only carried out only for dyslexic readers. Scores of the 'morphological relatedness' test had a significant main effect on activation in OTC (F(1,17) = 6.179, $p = .024$). Fig. 8a shows the correlation between performance on morphological relatedness test and the average activation in OTC across conditions. There was also significant interaction of the morphological relatedness test scores with morphological complexity in left pars triangularis (F(1,17) = 6.161, $p = .024$) and left pars opercularis (F(1,17) = 5.463, $p = .032$) and a significant interaction with diacritics in left pars opercularis (F(1,17) = 5.121, $p = .037$). Pearson correlations were computed between the morphological relatedness scores and activation in these regions in each of the 4 conditions (correcting for 4 comparisons). A significant correlation was found between scores in the morphological relatedness test and activation in *un-pointed bi-morphemic* words in pars triangularis (r = .539, $p = 0.012$). See Fig. 8b. For the pars-opercularis the correlation with activation in *un-pointed bi-morphemic* words (r = .455, r = .038) did not survive the correction for multiple comparison. No main effects or interactions were found for the phonological decoding measure (non-words per minute score).

3.3. Discussion

In this fMRI experiment, as in the behavioral experiment we predicted that both typical and dyslexic readers would show morphological effects in brain regions associated with early and late morpho-phonological processing. We also predicted

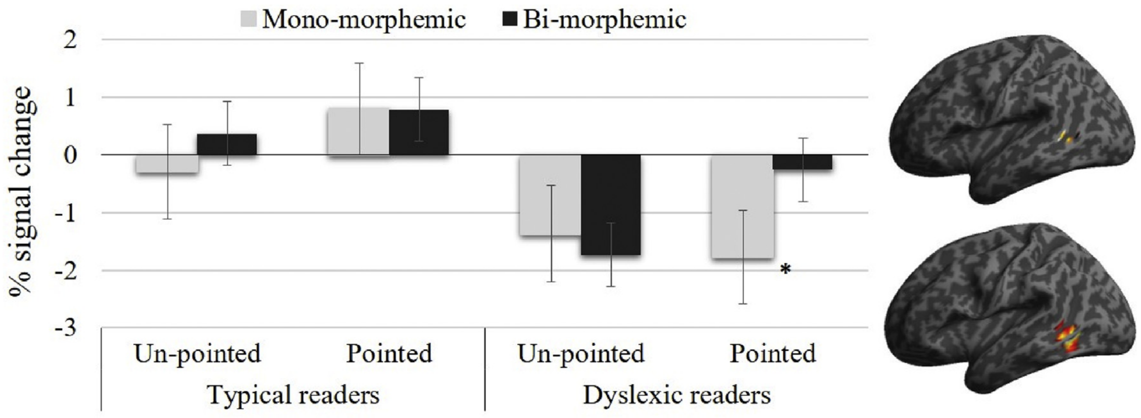

Fig. 7 – Left Occipito-temporal cortex. Percent signal change in ROI. *- Significant effects ($p < .05$). Brain image on the right present un-thresholded maps of activation in the contrast of bi-morphemic versus mono-morphemic words in the pointed script, within a sphere around: x = −54, y = −57, z = −4 (Lehtonen et al., 2006); used to extract the ROI data separately for typical (top) and dyslexic (bottom) readers. Brighter (yellow) colors indicate stronger activation.

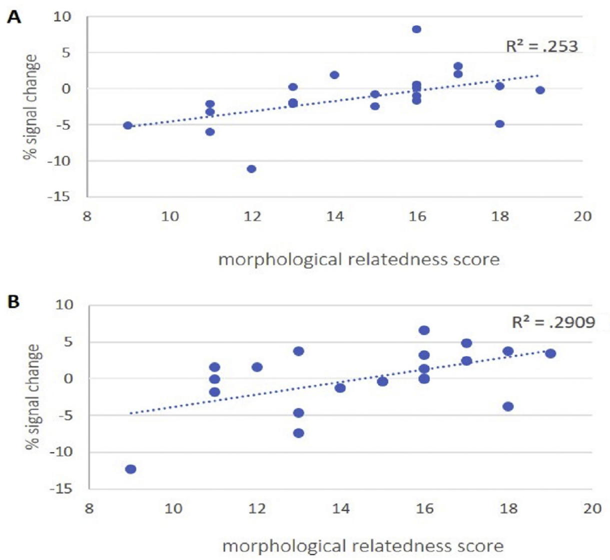

Fig. 8 – Correlation with morphological awareness test in dyslexic readers. Correlation between morphological relatedness test performed outside the scanner and activation in the left occipito-temporal cortex ROI across all conditions (A) and activation in left IFG pars triangularis ROI in un-pointed bi-morphemic words (B).

that for typical readers these effects would be stronger in the non-transparent orthography (un-pointed words), to compensate for the missing phonological information. For dyslexic readers, we expected to either find a similar pattern to typical readers or an opposite pattern, with stronger morphological effects in the transparent orthography, because the behavioral experiment showed that pointed words were more difficult than un-pointed words for this group.

Our fMRI study showed three main findings: 1) Both dyslexic and typical readers showed greater activation for mono-morphemic compared to bi-morphemic words, specifically in the un-pointed script, in left inferior frontal gyrus (IFG) pars opercularis and pars triangularis, and in left middle frontal gyrus (MFG). 2) Only dyslexic readers showed a morphological effect in pointed words in the left occipito-temporal cortex (OTC). 3) Morphological awareness in dyslexic readers was positively associated with activation in the occipito-temporal cortex for all words, and in frontal areas for *un-pointed bi-morphemic* words. No significant effects were found in left MTG or left IPL. These findings are partially consistent with our predictions, and we will discuss them in the following sections.

3.3.1. *Brain regions sensitive to the Hebrew morphological structure*

Two clusters of brain regions showed sensitivity to the morphological structure in our study, demonstrating distinct patterns of effects. The frontal cluster of regions, including left MFG and left IFG pars opercularis and pars triangularis, showed a morphological effect (greater for mono-morphemic words) in the non-transparent script across all participants. In contrast, the OTC showed a morphological effect (greater for bi-morphemic words) in the transparent script, and only for dyslexic readers.

The left IFG, including pars opercularis and pars triangularis, has been implicated in morphological decomposition of inflected (Beretta, Campbell et al., 2003; Nevat et al., 2017; Pliatsikas, Johnstone et al., 2014; Sahin, Pinker, & Halgren, 2006; Tyler et al., 2005) and derived words (Bozic et al., 2007; Bozic et al., 2013; Marangolo et al., 2006) in different modalities and languages in a vast number of studies. The pars opercularis has also been involved in phonological segmentation during reading (Burton, Small, & Blumstein, 2000; Twomey et al., 2015) while the pars triangularis is typically associated with lexical retrieval and semantic selection (Binder, Desai, Graves, & Conant, 2009; Fiebach, Friederici, Muller, & von Cramon, 2002; Kircher, Sass, Sachs, & Krach, 2009). MEG studies suggest that morphological effects in these frontal regions represent late morpho-phonological segmentation processes at around 350–495 msec following the visual presentation of the word (Cavalli et al., 2016; Whiting, Shtyrov, & Marslen-Wilson, 2015). These regions as well as left MFG have previously shown morphological effects in Hebrew, in morphological judgment (Bick et al., 2008) and morphological priming (Bick et al., 2010) tasks of words sharing the same roots. The current results are consistent with these previous findings and show these “late” morpho-phonological segmentation processes also in an oral reading task. The direction of the morphological effect (greater activation for mono-morphemic words) suggests a greater load due to the unsuccessful attempts to decompose mono-morphemic words. Alternatively, it may reflect the readers’ expectance to encounter a root. In accordance with predictive coding approaches (Wacongne, Changeux, & Dehaene, 2012), the absence of roots may result in high predictive error and thus higher activation in regions associated with morphological decomposition. Furthermore, the positive correlation found between participants’ morphological awareness and activation in *bi-morphemic* (un-pointed) words in this area supports this conclusion.

The second area showing a morphological effect, is left OTC. Activation in this area was also correlated with participants’ awareness to the root, measured outside the scanner in the morphological relatedness test. This area is part of the occipito-temporal ventral stream which has been associated with orthographic processing (Dehaene & Cohen, 2011; Dehaene, Le Clec, Poline, Le Bihan, & Cohen, 2002). The ventral stream is organized along a posterior-anterior gradient, with anterior regions showing growing selectivity to larger sub-lexical familiar orthographic units (Dehaene, Cohen, Sigman, & Vinckier, 2005; Vinckier et al., 2007). More specifically, the region of interest in the current study (centered around coordinates: −54, −57, −4) closely corresponds to the anterior-posterior location of the mid-fusiform (−48 −56 −16) showing selective activation not only for real words but also for pseudo-words with high frequency quadrigrams as compared to letter strings with smaller or no familiar chunks of letters (Vinckier et al., 2007). This selectivity to large familiar chunks of letters can underlie the sensitivity of this region to the orthographic representation of morphemes. The specific location in the current study was selected based on its sensitivity to morphologically inflected written words in Finnish (Lehtonen et al., 2006), and this finding is consistent with other fMRI studies showing evidence of morphological decomposition in the ventral occipito-temporal stream (Devlin et al., 2004; Meinzer et al., 2009). Moreover, evidence from MEG studies (Fruchter & Marantz, 2015; Lehtonen, Monahan, & Poeppel, 2011; Neophytou et al., 2018; Solomyak & Marantz, 2010; Zweig & Pylkkanen, 2009), shows that these morphological effects in visually presented derived words appear as early as 170 msec following word presentation. Altogether these findings support the notion of early form-based morpho-orthographic decomposition of written words (Leminen, Smolka, Duñabeitia, & Pliatsikas, 2019; Rastle & Davis, 2008).

One previous study showed evidence for morpho-orthographic decomposition in the ventral occipito-temporal stream in Hebrew readers using form-based root priming (Bick et al., 2011). Our study is the first to show a morphological effect in OTC in a simple reading aloud task, and it shows morpho-orthographic effects in Hebrew words in similar brain regions to those involved in morpho-orthographic effects in other languages. While morphological decomposition in Indo-European languages is mostly linear, with the affixes typically located in the beginning or end of the word, Hebrew derivational morphology is interleaved, with no fixed position for the root letters, so the extraction of the root consonants from the letters of the word-pattern relies on statistical learning of conditional probabilities of letter positions (Frost, 2012; Velan & Frost, 2011). These findings are consistent with studies showing morphological effects in Hebrew readers with neglect dyslexia and letter position dyslexia, supporting the conclusion that morphological decomposition in Hebrew starts in the orthographic visual analysis stage (Friedmann, Gvion, & Nisim, 2015; Reznick & Friedmann, 2015). Nevertheless, it should also be noted that this morpho-orthographic effect was not found for skilled readers or for un-pointed words, but only in very specific conditions that will be discussed below.

In contrast to our hypothesis we did not find evidence for morphological sensitivity in MTG, previously associated with morpho-semantic recomposition (Devlin et al., 2004; Fruchter & Marantz, 2015; Hakala et al., 2018; Meinzer et al., 2009; Neophytou et al., 2018; Solomyak & Marantz, 2010). We also didn't find morphological effects in left IPL, previously found to show morphological priming effects in Hebrew (Bick et al., 2010).

4. General discussion

4.1. *Morphological segmentation in dyslexic readers*

Our results show similar morphological effects between dyslexic and typical readers in the frontal cluster of regions, and a morphological effect in OTC only for dyslexic readers. This finding is consistent with our behavioral results showing that the morphological structure facilitated reading only in dyslexic readers. Together these findings show that dyslexic readers with phonological deficits engage in morphological decomposition of derived words not less, and perhaps more, than typical readers. More specifically, while their late morpho-phonological decomposition processes are similar to those of typical readers, their early reliance on morpho-orthographic segmentation may help them compensate in conditions where their reading deficits are most disturbing, namely reading the less familiar pointed script. These findings are generally consistent with our prediction (#1) that all participants will engage in morphological decomposition in Hebrew, and they further show that dyslexic readers benefit from it more, as compensation for their phonological deficits.

Several previous studies point to impairments in morphological processing in dyslexic English readers (Fischer, Shankweiler, & Liberman, 1985; Leong, 1989), as well as failed morphological priming effects among impaired Hebrew readers (Bendror et al., 1995; Raveh & Schiff, 2008; Schiff & Raveh, 2007; Schiff & Ravid, 2007). However, despite these impairments it was shown that dyslexic readers can benefit from morphological interventions to facilitate reading (Bowers et al., 2010; Goodwin & Ahn, 2013). Our results are consistent with behavioral findings from Hebrew and other languages showing that when the morphological structure is salient (i.e., has high orthographic or semantic transparency or high frequency) impaired readers rely on morphological information in reading *more* than unimpaired readers (Burani, 2010; Burani et al., 2008; Cavalli et al., 2017; Elbro & Arnbak, 1996; Leikin & Even Zur, 2006; Vellutino et al., 2004). Interestingly, mixed results were found in a recent study (Kimel & Ahissar, 2019) that examined dyslexic Hebrew readers learning novel verbs with or without a familiar morphological structure. Dyslexic readers showed a facilitating effect of the morphological structure in recognition and fast reading tasks, while their morphological benefits were weaker than that of controls in recall of the novel verbs and their root. Another training study in dyslexic Hebrew readers (Bar-Kochva, 2016) found some benefit from an implicit morpheme-based training, which emphasized the root morpheme of written words, for spelling of untrained words. Together with these results, our findings may suggest that the sensitivity of dyslexic readers to morphological regularities are evident more in implicit tasks that do not require explicit manipulation of morphological units and metalinguistic morphological awareness.

Our findings are amongst the first neuroimaging evidence for morphological sensitivity in readers with dyslexia. The one functional imaging study that tested this question before (Cavalli et al., 2017) used MEG in a morphological priming task in French speaking adults with dyslexia. Consistent with our findings, Cavalli et al. (2017) found morphological effects in dyslexic readers in left inferior frontal gyrus and left occipito-temporal cortex, supporting the conclusion that dyslexic adult readers are engaged in morphological decomposition and may rely on it during reading. In contrast to the current study the morphological effects in the frontal areas in Cavalli et al. were localized to ventral aspects of IFG, associated with semantic processing, and its earlier latency compared to controls lead to the conclusion of greater reliance on the semantic aspects of morphology in dyslexic readers. In the current study the morphological effects in both groups of readers were in dorsal frontal areas (MFG, and IFG pars opercularis and pars triangularis) associated with morpho-phonological segmentation. This difference may stem from the different paradigms used in the two studies (oral reading that emphasized phonological processes in the current study *vs* priming in lexical decision in Cavalli et al.). Alternatively it may stem from the role of the root morpheme in word recognition in Hebrew, which is very prominent regardless of its semantic meaning (Bick et al., 2011).

Our conclusion, that dyslexic readers are sensitive to the morphological structure of words, in both orthographic and phonological levels, is also supported by our findings on morphological awareness. These findings show that performance on a test measuring participants' awareness to the form of the root, performed outside the scanner, was positively associated with activation in the occipito-temporal area when reading all words, and activation in frontal areas during reading of bi-morphemic un-pointed words. While we cannot compare this finding to typical readers (due to missing data), it further supports the conclusion that dyslexic readers rely on the morphological structure when reading morphologically derived words.

4.2. The effect of orthographic transparency on morphological segmentation

The two clusters of regions identified in the current study showed distinct patterns of interaction between orthographic transparency and morphological segmentation. Regions in frontal areas showed a morphological effect only in the unpointed script, consistent with our prediction (#2) that at least for typical readers, morphological segmentation may compensate for the missing vowels in the non-transparent script. This finding was true for both groups. On the other hand, the morphological effect in OTC for dyslexic readers was only found in pointed words. This finding is consistent with our prediction (#3) that specifically for dyslexic readers, morphological segmentation may compensate for the particular impairment in phonological decoding of pointed words.

Our prediction (#2) for more reliance on morphological segmentation in the non-transparent script was based on the common, but un-tested, assumption that the extraction of the root and identification of the template can compensate for the missing vowels and facilitate word recognition (Bar-On & Ravid, 2011; Frost, 2006; Ziegler, Stone, & Jacobs, 1997). While the behavioral measure of response time in oral reading was not sensitive enough to reveal this effect, the neuroimaging findings in the frontal areas support this prediction. Thus, our findings are the first to show that the morpho-phonological decomposition of derived words facilitates reading specifically in the non-transparent script.

The findings in OTC, showing a stronger morphological effect in pointed compared to un-pointed words for dyslexic readers is consistent with the behavioral results, showing that reading pointed words is harder than un-pointed words for dyslexic readers. These findings, together with those of our previous behavioral and fMRI results (Weiss et al., 2015; Weiss et al., 2016) suggest that when reading pointed words dyslexic readers' deficit in temporo-parietal regions, leading to impaired mapping of small orthographic to phonological units, may lead to greater reliance on form-based morphological segmentation in early orthographic stages of processing. They also suggest that the benefit that the morphological structure provides for dyslexic readers in the recognition of pointed and un-pointed words may be due to distinct neurocognitive mechanisms.

Another study that showed an interaction between orthographic transparency and morphological segmentation is our behavioral study in 2nd and 5th grade children (Haddad et al., 2018), that used the same stimuli as the current study. In that study children benefited from the morphological structure of words only in the transparent script (pointed words). In the younger children group, the presence of roots in the non-transparent script (un-pointed words) impeded reading. This is presumably due to competition with other words containing the same root, when the vowels that constitute the morphemic pattern are not fully represented. These results showing that morphological segmentation does not compensate for the opacity of the script in children stand in contrast to the conclusions from the current study in skilled adult readers. Altogether these results suggest that the interaction between morphological decomposition and orthographic transparency depend on reading skill. While skilled adult readers, with numerous exposures to un-pointed words and roots can decompose them and rely on them for word recognition, children are sensitive to the morphemes but they benefit from them only when presented with full phonological information in the transparent script.

4.3. Limitations

Our study has some methodological limitations that should be taken into account when drawing conclusions. One limitation is the rather small sample sizes, that may have reduced the power and prevented us from finding morphological effects in left MTG and left IPL. Another limitation is the selection criteria for dyslexic readers, that included only "compensated" dyslexic readers, all of whom were university or college students. While this was done in order to reduce heterogeneity in the sample, this may have biased the sample of dyslexic readers towards those with more reading experience, and thus the results may not generalize to dyslexic readers with poor academic achievements. Finally, due to technical reasons we do not have information about the morphological awareness in typical readers, and thus we cannot draw any conclusions about the specificity of its effect to dyslexic readers.

4.4. Conclusions

The results of our study are the first to show that skilled readers rely on morphological decomposition more when reading the non-transparent script, presumably to compensate for the missing vowel information. Our findings are among the first functional neuroimaging evidence showing that dyslexic readers are sensitive to the morphological structure of derived words and rely on it during reading. They further show that while morpho-phonological segmentation processes in dyslexic readers are comparable to typical readers, they show stronger reliance on early morpho-orthographic segmentation. While similar conclusions were drawn from both behavioral and imaging studies in a number of languages, the strength of the morphological effect in a simple oral reading task may be related to the prominent role of the morphological structure in Hebrew. Overall, these findings demonstrate how the unique properties of each language and its orthography may determine the specific neural mechanisms involved in typical and atypical reading.

Open practices

The study in this article earned Open Materials and Open Data badges for transparent practices. Materials and data for the study are available at https://doi.org/10.5281/zenodo.3711555.

Author contribution

Tali Bitan: Conceptualization, Methodology, Formal analysis, Supervision, Funding acquisition, Writing; **Yael Weiss:** Conceptualization, Methodology, Investigation, Formal analysis; **Tami Katzir:** Conceptualization, Methodology, Funding acquisition, Supervision; **Tammar Truzman:** Formal analysis, Visualization, Writing

Statement

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

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