Neural Processing of Morphology During Reading in Children

Becor Barouch, a* Yael Weiss, b Tami Katzir c and Tali Bitan a,d

a Psychology Department and Institute for Information Processing and Decision Making, University of Haifa, 199 Aba Khoushy Ave., Mount Carmel, Haifa 3498838, Israel

b Institute for Learning and Brain Sciences, University of Washington, 1715 NE Columbia Road, Portage Bay Building, Box 357988, Seattle, WA 98195-7988 USA

c Department of Learning Disabilities, The E.J. Safra Brain Research Center for the Study of Learning Disabilities, University of Haifa, 199 Aba Khoushy Ave., Mount Carmel, Haifa 3498838, Israel

d Department of Speech Language Pathology, University of Toronto, Toronto, Canada

Abstract—The importance of morphological segmentation for reading has been shown in numerous behavioral studies in children and adults. However, little is known about developmental changes in the neural basis of morphological processing. In addition to effects of age and reading skill, morphological processing during reading may be affected by the morphological structure of the language and the transparency of its orthography. Hebrew provides a unique opportunity to study these factors, with its rich morphological structure, and two versions of script that differ in orthographic transparency. Two groups of children (2nd–3rd and 5th–6th graders) were scanned using fMRI while reading aloud Hebrew nouns. Half of the words were composed of roots and templates (bi-morphemic) and half were mono-morphemic. The words were presented at two levels of transparency: with or without diacritics. ROI analyses showed greater activation for mono over bi-morphemic words across groups in the anterior portions of bilateral middle and superior temporal gyri, especially for the transparent script. These results diverge from a previous finding in adults, showing left frontal activation in the non-transparent script with the same stimuli. These results support the early sensitivity of young Hebrew readers to the rich morphological structure of their language but suggest a developmental change in the role of morphological processes during reading. While in adults morpho-phonological segmentation during reading may compensate for orthographic opacity, morphological processes in children may rely more on semantic aspects, and are enhanced by orthographic transparency. © 2022 IBRO. Published by Elsevier Ltd. All rights reserved.

Key words: morphological decomposition, orthographic transparency, Hebrew, FMRI, reading acquisition.

INTRODUCTION

Morphological processes play a key role in reading (McBride-Chang et al., 2003; Deacon and Kirby, 2004; Kuo and Anderson, 2006; McBride-Chang et al., 2008; Rastle and Davis, 2008; Traficante et al., 2011; Amenta and Crepaldi, 2012; Nagy et al., 2014; Vaknin-Nusbaum et al., 2016b). For example, the identification of the morpheme ‘friend’ in the derived English word ‘friendship’ may facilitate its identification and access to its meaning. However, the contribution of morphological processes to reading may change throughout development, and the developmental trajectory of morphological processing during reading may depend not only on the reader’s age and reading skill, but also on the morphological properties of the language, affecting children’s sensitivity to the morphological structures (Duncan et al., 2009; Casalis et al., 2015; Smolka et al., 2015). While morphological segmentation during reading could facilitate access to lexical-semantic representations (Rastle, 2019; Dawson et al., 2021), it could also provide phonological cues that may facilitate word identification. Thus, another factor that may affect the reliance on morphological processes during reading is the availability of phonological information in the orthography. Hence, the consistency of sound-to-letter mapping of an orthography, creating transparent
or opaque scripts, may differentially affect the reliance on morphological processing during reading in different levels of reading proficiency (Katz and Frost, 1992; Ziegler and Goswami, 2005; Frost, 2012). The current study will examine readers’ reliance on morphological processing during reading acquisition in Hebrew, a Semitic language with a rich morphology and two versions of script. Using fMRI, we aim to address the following questions: (a) are children at various stages of reading acquisition sensitive to the structure of morphologically derived words, and are they processing it when reading single words; (b) are the neuro-cognitive mechanisms children use to process morphologically complex words similar to those used by adults; (c) how the processing of morphologically complex words is affected by reading in a transparent vs. an opaque script.

Morphological processing

Many neuroimaging studies in adults, examining morphological processing of inflected forms, found activation in left frontal cortices associated with the combinatorial process of morpho-phonological decomposition (Beretta et al., 2003; Tyler et al., 2004; Tyler et al., 2005; Desai et al., 2006; Lehtonen et al., 2006; Sahin et al., 2006; Neval et al., 2017). Unlike inflected forms, derived forms constitute new lexical representations, raising the question of whether they are stored and retrieved as whole lexical items or decomposed into their morphological units like inflected forms (Matthews, 1991; Kircik and Claissen, 2013). The Full decomposition model (Taft and Forster, 1975; Taft, 1979, 2004; Fruchter and Marantz, 2015) argues that all morphologically complex words are decomposed before lexical access. In contrast, Hybrid models (Bozic et al., 2013a,b; Klimovich-Gray et al., 2016) argue that, unlike inflected forms, derived words are stored and may undergo decomposition only after lexical access. Studies that investigated the neural basis of processing morphologically derived forms also show involvement of the left frontal system, found in inflectional morphology, in both spoken (Marangolo et al., 2006; Carota et al., 2016) and written words (Bozic et al., 2007; Meinzer et al., 2009; Pliatsikas et al., 2014). In Hebrew, a morphologically rich language, the left inferior and middle frontal gyri (IFG, MFG) were implicated in oral reading of words containing roots (vs. mono-morphemic words; Bitan et al., 2020), root priming in a lexical decision task (Bick et al., 2010), and an explicit judgment task of shared roots between words (Bick et al., 2008).

In addition to the left frontal system, studies of both derivational and inflectional morphology in adults have shown morphological effects in left middle and superior temporal gyri (MTG, STG; Devlin et al., 2004; Lehtonen et al., 2006; Meinzer et al., 2009) and in the occipito-temporal-cortex (OTC; Devlin et al., 2004; Fruchter and Marantz, 2015; Lehtonen et al., 2006; Meinzer et al., 2009; Neophytou et al., 2018; Solomyak and Marantz, 2010). Structural connectivity evidence from diffusion MRI shows that morphological skills measured in written words are correlated with microstructural properties of ventral, but not dorsal, white matter pathways connecting occipital and temporal areas (Yablonski et al., 2019). Evidence from MEG showing morphological effects in occipital and temporal areas during early-stages of processing written words suggest that they reflect pre-lexical form based decomposition (OTC) or semantic re-composition (MTS; Fruchter and Marantz, 2015; Hakala et al., 2018; Neophytou et al., 2018; Solomyak and Marantz, 2010). In contrast, other studies suggest that bilateral temporal activation in morphologically derived words reflects post-lexical competition between stored derived form and their stems (Bozic et al., 2013a,b; Klimovich-Gray et al., 2016).

Only a couple of studies examined the neural correlates of morphological processing in children, and they point to a similar set of regions as the adult studies. In children aged 6–12, an explicit auditory judgment task showed that processing of morphologically derived words activated the left IFG, left MFG, and left anterior STG (Arrendondo et al., 2015; Ip et al., 2017). Another study in Chinese readers aged 11–13 showed a morphological effect in semantic judgment of visually presented words in the left IFG (Liu et al., 2013). The paucity of neuroimaging studies on morphological processes in children notwithstanding, these results provide neural evidence for morphological processes in children in both spoken and written language.

Morphology in reading acquisition

While the contribution of phonological awareness to the early development of reading skills is widely agreed upon (Caravolas et al., 2001; Ehni et al., 2001; de Jong and van der Leij, 2002), age related changes in the role of morphological processing in reading acquisition is less clear. The conscious manipulation and perception of morphological structures (i.e. MA), was shown to predict reading skills and vocabulary in school age children beyond the effects of phonological awareness (McBride-Chang et al., 2003; Deacon and Kirby, 2004; Kuo and Anderson, 2006) in Chinese, English, Finnish, French, and Hebrew, among other languages (Mcbride-Chang et al., 2008; Nagy et al., 2014; Vaknin-Nusbaum et al., 2016b). Children acquire morphological ability and awareness in English spoken words gradually, starting at ages 4–5 and through the eighth grade (Clark and Cohen, 1984; Tyler and Nagy, 1989), along with increasing reliance on morphological segmentation during reading. This is probably due to the increase in the proportion of complex words in the lexicon (Anglin et al., 1993; Mahony et al., 2000; Singson et al., 2000; Kuo and Anderson, 2006; Rispens et al., 2008; Nagy et al., 2014). In English, learning to rely on morphology can enhance the direct link between orthography and semantics in skilled readers due to the high regularity of this connection as compared to the irregularity in the mapping between spelling and sound (Rastle, 2019). However, it is possible that this developmental trajectory differs between languages (Duncan et al., 2009; Vaknin-Nusbaum and Miller, 2011; Casalis et al., 2015). In French, children’s morphological abilities were suggested to develop at a faster rate than those of English-speaking children (Duncan et al., 2009; Casalis et al., 2015), ostensibly stemming from the
greater productivity, or richness, of the French morphological system compared to the English one.

Another factor that may interact with the effect of age and reading skill on the reader’s reliance on morphological segmentation is the orthographic transparency of the script, defined as the consistency in mapping between orthographic and phonological units. As indicated above, in the English script reliance on morphology may contribute to direct access from orthography to semantics, due to the high irregularity of the spelling-sound correspondence (Rastle, 2019). It has been hypothesized that in Hebrew the phonological information provided by morphemes can compensate for the missing phonological information in a non-transparent script (Katz and Frost, 1992; Ziegler and Goswami, 2005; Frost, 2012).

The Hebrew language and its orthography

Most words in Hebrew consist of a three-to-four letter consonantal root, interjected between vowels and other consonants that make up a morphological pattern. For example, the word rakdan ‘dancer’, is formed with a root, r-k-d ‘dance’, and a pattern CaCCan (where each C represents the root consonants). The root can combine with other patterns to form a variety of words referring to dancing: lirkod ‘to dance’, nkud ‘a dance’, etc. The pattern CaCCan also appears with other roots: kablan ‘contractor’, and kabitzan ‘beggar’, both referring to people with certain characteristics. This creates a complex morphological system, where one structure, the root, carries most of the semantic information and the other, the pattern, indicates the part of speech or general category of the word (e.g., person with certain characteristics).

Additionally, Hebrew orthography has two slight variations of the same script: (i) a transparent pointed version using diacritic marks to fully convey phonological information; and (ii) an opaque un-pointed version using diacritic marks to partially represent vowels. Starting in the 1st grade children are first taught the pointed script, and are gradually exposed to un-pointed script during the 2nd and 3rd grade until the pointed script is completely phased out in grade 4 (Shany et al., 2012), so skilled readers are not typically exposed to the pointed script. However, despite the use of the terms ‘opaque’ and ‘transparent’, which are often used to compare alphabetical orthographies such as English and Spanish, it should be noted that while the English opacity is due to inconsistency in mapping letters to sounds, the un-pointed Hebrew script is opaque due to the partial absence of vowel marks.

Morphology and orthographic transparency in Hebrew reading

Morphological segmentation has a prominent role in reading Hebrew words among adult readers (Bentin and Feldman, 1990; Frost et al., 1997; Deutch et al., 1998; Yablonski et al., 2017). It starts to develop in the early stages of acquiring spoken language, with evidence that 3-year-olds already possess knowledge of roots in speech (Berman, 1982), and mastery of accessing and processing roots is achieved as early as the end of kindergarten (Ravid and Malenky, 2001). Studies in Hebrew reading children show evidence of explicit knowledge of roots and morphemic patterns as early as 2nd grade (Ravid and Schiff, 2006), and children’s morphological awareness throughout elementary school was found to correlate with their reading skills (Cohen-Mimran, 2009; Vaknin-Nusbaum et al., 2016a,b; Haddad et al., 2018; Shechter et al., 2018). These findings are consistent with the Triplex model (Share and Bar-On, 2017) that suggests that reading acquisition in Hebrew evolves from sequential spelling-to-sound reading in Grade 1, to lexico-morpho-orthographic processing of written words in Grade 2, until it reaches supra-lexical contextual reading in the upper elementary grades. This model diverges from commonly believed development arcs in languages such as English and Dutch, which propose that children’s reliance on morphological segmentation during reading emerges only in later stages of acquisition (Carlisle, 1988; Tyler and Nagy, 1989; Mahony et al., 2000; Rispens et al., 2008; Kieffer and Lesaux, 2012; Nagy et al., 2014; Sparks and Deacon, 2015).

In addition to the rich morphology, the dual version of the Hebrew orthography provides an opportunity to study the effect of orthographic transparency on morphological processing during reading. Because in the non-transparent script the vowels are mostly un-represented, it has been suggested that the morphological pattern can fill this missing information, thus compensating for the orthographic depth (Katz and Frost, 1992; Ziegler and Goswami, 2005; Frost, 2012). A recent fMRI study with adults, using an identical paradigm to the current study (Bitan et al., 2020), has shown that this is indeed the case. Skilled adult Hebrew readers showed morphological effects in left IFG and left MFG, only in the non-transparent script. Nevertheless, in a recent behavioral study with children, using the same paradigm (Haddad et al., 2018), we found that morphological information improved reading accuracy in the transparent script, but interfered with reading accuracy in the non-transparent script. Additionally, a correlation between morpho-syntactic awareness and reading accuracy of morphologically complex words was found only for the younger group. These findings may suggest that the role of morphological processing during reading, and how it is affected by orthographic transparency, depends on age and reading skill.

The current study

The current study investigates the neural mechanisms underlying processing of morphological complexity and how they are affected by orthographic transparency in Hebrew reading children in early and intermediate stages of reading acquisition. Hebrew words at two levels of morphological complexity (mono-morphemic/bi-morphemic) were presented at two levels of orthographic transparency (pointed/un-pointed) to two groups of children (2–3rd graders/5–6th graders) during an fMRI scan. As the task does not require metalinguistic judgements the morphological processes tested are implicit ones. We examined regions that were previously associated with morphological processing
including left IFG (Lehtonen et al., 2006; Bick et al., 2010; Bitan et al., 2020), left MFG (Bick et al., 2010; Bitan et al., 2020), left MTG (Lehtonen et al., 2006; Meinzer et al., 2009), left STG (Lehtonen et al., 2006; Meinzer et al., 2009), and left OTC (Devlin et al., 2004; Lehtonen et al., 2006; Meinzer et al., 2009; Solomyak and Marantz, 2010; Frucht and Marantz, 2015; Neophytou et al., 2018). We also included the right hemisphere homologues of these regions to account for the possibility of bilateral cortical involvement in language processing in children (Holland et al., 2001; Turkeltaub et al., 2003; Szaflarski et al., 2006; Clahsen et al., 2007; Ressel et al., 2008; Everts et al., 2009; Olulade et al., 2020). We expect to find the following:

1. Based on the greater morphological effects for the 2nd grade group reported by Haddad et al. (2018), we expect that children from both age groups will show effects of morphological complexity on brain activation, but these will be stronger in the younger group. We expect to find these effects predominantly in the left MFG and left IFG, implicated in the adult processing of Hebrew root morphology (Bick et al., 2008; Bick et al., 2010; Bitan et al., 2020). However, these effects may also be evident in the right hemisphere homologues of these frontal regions, in bilateral temporal areas (STG and MTG), or in OTC, indicating differences between children and adults in processing morphologically complex words during reading.

2. While adults showed greater morphological effects in the un-pointed script (Bitan et al., 2020), a behavioral study with children (Haddad et al. 2018) showed that morphological information facilitated word processing only in the pointed script, and impeded the processing of un-pointed, opaque, words in the younger age group. This leads us to predict that an interaction between morphological complexity and diacritics will be found in the above regions, with stronger morphological effects in the pointed compared to the un-pointed script.

**EXPERIMENTAL PROCEDURES**

**Participants**

16 2nd and 3rd grade students (ages 7.33–9, M = 8.11, SD = 0.5, 8 girls) and 9 5th and 6th grade students (ages 10.5–12, M = 11.24, SD = 0.54, 3 girls) were recruited from a regular elementary school in Israel. Only 14 children from the younger group were included in the final analyses, as two participants were excluded due to excessive movement artifacts (see preprocessing section). Written informed consent was obtained from the parents of all participants, and oral consent from the children. The study was approved by the ethics committee of the Faculty of Social Welfare and Health Sciences at the University of Haifa, and by the IRB committee Ministry of Health. All participants were native Hebrew speakers, right-handed, with no neurological disorders, with normal (or corrected to normal) vision and no learning disabilities as reported by their teachers and confirmed by our assessment. Reading level was tested using the Word Recognition and the Pseudo Word Decoding Tests, from “Alef-Taf, Diagnostic test battery for written language disorders” (Shany et al., 2006) described below. The inclusion criterion was scoring no lower than one standard deviation below the norm in both tests and both measures: reading rate and accuracy (see Table 1 for average scores). No student was excluded based on this criterion. Children from both groups were also within the (1SD) norm for their age group on phonological awareness as measured by the Phoneme Omission Test (Shany et al., 2006).

**Stimuli**

The experimental stimuli are identical to those used in our behavioral study with children (Haddad et al., 2018) and in our fMRI study with adults (Bitan et al., 2020). The stimuli consist of 96 concrete Hebrew nouns in two levels of orthographic transparency and two levels of morphological complexity. Morphologically complex (bi-morphemic) words are composed of two morphemes: a root and a morphemic pattern. Examples of the stimuli can be seen in Table 2. All roots were tri-consonantal productive roots, which are also 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. In each morphological level, half of the words (24) were presented with diacritics and half without diacritics. None of the words in the experiment were homographs even when presented with no diacritics. Word lists were matched across conditions for the number of consonants (3–4), the number of vowel letters (0–2), the number of syllables (2–3), and for written frequency. At the time the study was executed no consensus.

**Table 1.** Average raw and z-scores (SD) on the Alef-Taf screening tests (Shani et al. 2006)

<table>
<thead>
<tr>
<th>Stimulus Type</th>
<th>Younger Group (n = 14)</th>
<th>Older Group (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reading words</td>
<td></td>
<td></td>
</tr>
<tr>
<td>number per minute raw score</td>
<td>33.8 (10.3)</td>
<td>48.3 (9.4)</td>
</tr>
<tr>
<td>number per minute z score</td>
<td>-0.05 (0.67)</td>
<td>-0.53 (0.40)</td>
</tr>
<tr>
<td>Reading pseudo-words</td>
<td></td>
<td></td>
</tr>
<tr>
<td>number per minute raw score</td>
<td>19.9 (3.8)</td>
<td>22.2 (6.6)</td>
</tr>
<tr>
<td>number per minute z score</td>
<td>0.14 (0.49)</td>
<td>-0.01 (0.41)</td>
</tr>
<tr>
<td>Phoneme omission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% errors raw score</td>
<td>27.7 (20.8)</td>
<td>12.5 (13.3)</td>
</tr>
<tr>
<td>% errors z score</td>
<td>-0.58 (0.78)</td>
<td>-0.40 (0.57)</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Bi-morphemic words</th>
<th>Mono-morphemic words</th>
</tr>
</thead>
<tbody>
<tr>
<td>With diacritics (pointed)</td>
<td>MXSOL/mixshol/ MXSOL (obstacle)</td>
</tr>
<tr>
<td>Without diacritics (un-pointed)</td>
<td>TLMID /talmid/ TLMID (student)</td>
</tr>
<tr>
<td>With diacritics &lt; SNTR &gt; / santer/ (chin)</td>
<td></td>
</tr>
<tr>
<td>Without diacritics SNTR&gt; / snapir/ (fin)</td>
<td></td>
</tr>
</tbody>
</table>
corpus for written Hebrew frequency was available, therefore we based the frequency ranking on the rating of 14 elementary school teachers on a Likert scale of 1–5. This scale represents a range of low to high frequency for second graders. For more details on the matching of the stimuli see Bitan et al. (2020).

Standardized tests
All participants underwent standardized screening tests in order to assess their reading and decoding abilities and vocabulary knowledge. The screening tasks were: (1) Word recognition ("Alef-Taf" battery; Shany et al., 2006): participants read aloud 38 nouns with diacritics which represent different levels of frequency, length, and phonological structure. Different age-appropriate lists are used for different age groups. The obtained scores indicate the number of accurately read words per minute and the percentage of errors. (2) Pseudo-word decoding ("Alef-Taf" battery; Shany et al., 2006): participants read aloud 33 pseudo-words with diacritics. 24 of these items represent familiar morpho-phonological structures in Hebrew and nine contained sound structures non-existent in Hebrew. Different age-appropriate lists are used for different age groups. The obtained scores indicate the number of accurately read pseudowords per minute. (3) Phonological awareness (from the "Alef-Taf " battery; Shany et al., 2006): includes 16 mono and bi-syllable words read aloud by the examiner. Participants produce pseudo-words obtained by omitting a designated phoneme positioned at the beginning, middle or end of the word. The score reflects the percentage of correctly produced items.

Experimental procedure
Each trial began with a 190 ms presentation of a fixation cross followed by the presentation of the stimulus word for 1500 ms and then a blank screen for 2300 ms. 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.). Stimuli were presented using E-Prime stimulus presentation software (v.2.0, Psychological Software Tools, Inc.). Pointed and un-pointed words were presented in separate runs to minimize interference which may arise from frequent shifting between versions. Each word appeared once, either pointed or un-pointed, and the lists were counterbalanced across participants so that each word was presented in the pointed version for half of the participants and in the un-pointed version to the other half. Runs of pointed words and of un-pointed words appeared in alternating order, and the order was counterbalanced across individuals. The 96 words were intermixed with 152 words from another experiment, as well as 48 baseline trials in which the participants saw a string of asterisks and were required to say the word ‘pass’. 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/). A total of 296 trials were acquired in four runs of 5:52 min each. All children participated in a practice session in the mock scanner, in which they were acclimatized to the scanner environment, practiced lying still and reading aloud. Different words were used for the practice.

fMRI data acquisition
FMRI scans were acquired in The Functional Brain Imaging Center, at the Tel-Aviv Sourasky Medical Center. Images were acquired using a 3.0T 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 ms, 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 ms. One hundred seventy-one images were acquired during each run. In addition, a high resolution, anatomical T1 weighted 3D structural images were acquired (AX SPGR, TR = 9.044 ms, TE = 3.0504 ms, 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 data preprocessing
Scanner images (DICOM) were converted to NIfTí format using MRicron software (http://www.sph.sc.edu/comd/rorden/mricron; Rorden et al., 2007). Data preprocessing was then performed, using the Statistical Parametric Mapping toolbox for MATLAB (SPM12-Welcome Trust Centre for Neuroimaging, University College London, www.fil.ion.ucl.ac.uk/spm), as well as the ArtRepair toolbox (Mazaika et al., 2009; http://cibs.ranford.edu/tools/human-brain-project/artrepair-software.html). Images were spatially realigned to the first volume in each run to correct for head movements. Spatially realigned images were then smoothed with a 4-mm isotropic gaussian kernel and underwent motion adjustment and volume artifact detection and correction at a threshold of 1.5% global intensity and 2 mm/TR (ArtRepair programs: Art Motion Regress, Art Global). Sync interpolation was used to minimize timing errors between slices. The functional images were then co-registered with the anatomical image and normalized to the standard T1 template volume (MNI). The data was then smoothed again with a 5-mm isotropic gaussian kernel. Runs which had more than 20% of volumes repaired by ArtRepair were discarded for the analysis. This resulted in the exclusion of two participants (for whom all runs exceeded this threshold) and ten of the runs of the remaining participants.

Statistical analysis
Behavioral analysis. Repeated measure GLM analyses of the in-scanner task was performed.
separately for RT and accuracy, with group (young/older children) as a between-subject variable, and morphological complexity (bi-morphemic/mono-morphemic) and diacritics (pointed/un-pointed) as within-subject factors. Analysis for RT was performed using only correct responses.

**Voxel-Wise whole brain analysis.** Statistical analyses at the first level were performed in each participant using the GLM analysis for event-related designs across all 4 runs. The model included two levels of diacritics (pointed/un-pointed), X two levels of morphological complexity (mono-morphemic/bi-morphemic) as well as the baseline condition. At the group level 2-sample t-tests comparing between groups were conducted using a first level contrast of all language conditions vs. baseline. In order to assess the interaction of group and morphology, we used the first level contrasts of mono-morphemic words vs. baseline and bi-morphemic words vs. baseline (across diacritics) to perform a flexible factorial analysis with a 2X2 model of group (young/older children) by morphology (mono/bi-morphemic). In order to examine the effect of morphology in different levels of orthographic transparency we also conducted separate analyses of morphology by group separately within pointed and un-pointed words. First level contrasts of mono-morphemic words vs. baseline and bi-morphemic words vs. baseline within each diacritic condition were taken to the second level to conduct a flexible factorial analysis of group (young/older children) by morphology (mono/bi-morphemic) in each diacritic condition.

Because there was no activation at FWE corrected we report voxels that met an uncorrected threshold of \( p < 0.001 \) and cluster size \( k > 10 \) for descriptive purposes. Brain coordinates were interpreted by using the WFU PickAtlas 3.0.5 (Maldjian et al., 2003) and the Yale MNI to Talairach atlas (http://sprout022.sprout.yale.edu/mni2tal/mni2tal.html, Yale Biolmage Suite Package).

**Region of interest analysis.** Our predictions were tested by region of interest (ROI) analysis. This was performed by extracting mean percent signal changes in five bilateral cortical areas for the contrast of every condition compared to baseline: (i) pointed mono-morphemic words, (ii) un-pointed mono-morphemic words, (iii) pointed bi-morphemic words, (iv) un-pointed bi-morphemic words. The cortical areas were defined using the Automated Anatomical Labeling atlas (AAL) (Tzourio-Mazoyer et al., 2002) and anatomical masks were created in the MarsBaR toolbox for SPM (Brett et al., 2002). While our selection of regions was based on previous studies showing activation in relevant contrasts mostly in the left hemisphere, we chose to look at bilateral activation to account for the possibility of greater involvement of the right hemisphere in language processing in younger children (Holland et al., 2001; Szafiarski et al., 2006; Clahsen et al., 2007; Ressel et al., 2008; Everts et al., 2009; Olulade et al., 2020). The following areas were included: (1) IFG (Beretta et al., 2003; Tyler et al., 2005; Desai et al., 2006; Lehtonen et al., 2006; Sahin et al., 2006; Bick et al., 2010; Platsikas et al., 2014; Nevat et al., 2017; Bitan et al., 2020) was defined based on the anatomical masks of the AAL atlas and includes all three sub-regions: (1a) pars opercularis (Op), (1b) pars orbitalis (Orb) and (1c) pars triangularis (Tr); (2) STG (Meinzer et al., 2009; Pugh et al., 2013; Arredondo et al., 2015; Holloway et al., 2015); (3) MTG (Lehtonen et al., 2006; Gold and Rastle, 2007). Because STG and MTG are large structures activation was extracted separately for their anterior and posterior halves based on the midline of the y axis. Two additional regions were defined based on specific coordinates from previous studies: (4) MFG (Bick et al., 2010) was defined as a 10 mm sphere centered around MNI coordinates \( x = -35, y = 7, z = 29 \) (for left MFG); (5) OTC (Lehtonen et al., 2006), defined as a 10 mm sphere surrounding the MNI coordinates \( x = -54, y = -57, z = -4 \) (for right OTC).

Repeated measures GLM analyses on the percent signal change as a dependent variable were performed using SPSS 22, separately for each of the five areas. Four within subject variables were defined: sub-region (for IFG, STG & MTG), hemisphere (left/right), diacritics (pointed/un-pointed), and morphology (mono-morphemic/bi-morphemic), with grade group as the between-subject variable, and separately for RT and accuracy, with group (young children/older children) as a between-subject variable, and morphological complexity (bi-morphemic/mono-morphemic) and diacritics (pointed/un-pointed) as within-subject factors. Analysis for RT was performed using only correct responses.

**RESULTS**

**Behavioral results**

GLM analysis was performed for the behavioral measures of participants in the scanner, separately for the reaction time (RT) and accuracy. The analysis for accuracy yielded main effects of group \([F_{1,21} = 6.787, p = 0.017]\), with older children showing higher accuracy than younger children, and diacritics \([F_{1,21} = 21.717, p < 0.001]\), with pointed words being read with higher accuracy than un-pointed words (see Fig. 1). However, a significant interaction of diacritics and group \([F_{1,21} = 8.245, p = 0.009]\) indicated that only younger children read pointed words more accurately than un-pointed words \([F_{1,21} = 26.014, p < 0.001]\). No significant effects were found for morphology.

The analysis for RT yielded a main effect of group \([F_{1,21} = 9.759, p = 0.005]\), with slower responses in the younger compared to the older children (See Fig. 2). We also found a significant interaction of diacritics and morphology \([F_{1,21} = 4.595, p = 0.044]\). Fig. 2 shows that this is due to opposite but non-significant trends in the simple effects of morphology in pointed and un-pointed words across groups.

**fMRI results**

**Voxel-Wise whole brain analysis.** Fig. 3a,b and Table 3a,b show the activation within each age group
across all conditions with \( p < 0.05 \) FWE corrected. No other analysis showed any significant differences at FWE corrected, and they are therefore reported at the uncorrected threshold \( (p < 0.001, k > 10) \) for descriptive purposes. The two-sample-T-test assessing group differences across all other conditions showed greater activation for older children in left MTG in (see Table 3c), and greater activation for younger children in left superior occipital gyrus and right MFG in (see Table 3d).

The flexible factorial analysis assessing the model of group (young/older children) by morphology (mono/bi-morphemic) across diacritic conditions showed greater activation for mono-morphemic than bi-morphemic words across groups in left IFG, left MTG and left STG (see Table 4 and Fig. 3C). There was no significant activation in the opposite direction.

The separate analysis of morphology by group within each level of diacritics showed in pointed words greater activation for mono-morphemic over bi-morphemic words in right STG and left MFG (see Table 4a) across groups, (with no activation for the opposite contrast). The analysis within un-pointed words showed greater activation in the hippocampus for mono-morphemic words (see Table 5b), and greater activation in the right calcaneal sulcus for bi-morphemic words (see Table 5c). Since the effects of morphological complexity yielded no results at the corrected level, our predictions were further examined in ROI analyses.

Region of interest analysis. GLM analyses were conducted on the ROIs in bilateral STG, MTG, IFG, MFG and OTC. Only the temporal areas, namely STG and MTG, showed significant effects of morphology, and are thus reported below.

Middle Temporal Gyri. The repeated measures GLM analysis of MTG (including the anterior [aMTG] and posterior [pMTG] sub-regions) across both hemispheres yielded a main effect of hemisphere \([F_{1,21} = 9.771, p = 0.005]\) and a significant interaction of hemisphere by group \([F_{1,21} = 6.552, p = 0.018]\). Follow-up analysis showed that this was due to a significant effect of hemisphere only in the older children \([F_{1,8} = 20.957, p = 0.002]\), with the right hemisphere (RH) showing more negative activation than the left hemisphere (LH). The main analysis also showed significant interactions of sub-region by group \([F_{1,21} = 4.52, p = 0.046]\), and a four-way interaction of sub-region, hemisphere, morphology, and group \([F_{1,21} = 4.964, p = 0.037]\).

To follow up these interactions separate analyses were conducted within each sub-region (aMTG, pMTG). The analysis for pMTG yielded only a main effect of hemisphere \([F_{1,21} = 6.255, p = 0.021]\) with the right...
hemisphere (RH) showing more negative activation than the left hemisphere (LH).

In aMTG we found a main effect of hemisphere \( [F_{1,21} = 4.449, p = 0.047] \) with left hemisphere (LH) showing more negative activation than right hemisphere (RH), and a two-way interaction of hemisphere and group \( [F_{1,21} = 4.93, p = 0.038] \), due to a significant asymmetry (LH more negative than RH) only in the older group \( [F_{1,8} = 8.478, p = 0.02] \). The analysis in aMTG also showed a significant effect of morphology \( [F_{1,21} = 6.838, p = 0.016] \) and a three-way interaction of morphology, diacritics, and hemisphere \( [F_{1,21} = 6.02, p = 0.023] \). To further understand this three-way interaction, we performed a follow-up analysis of aMTG split by diacritics. This analysis showed a significant effect of morphology only for pointed words \( [F_{1,21} = 6.171, p = 0.021] \) and no interaction with hemisphere or group. No effect of morphology was found for the un-pointed words \( [F_{1,21} = 0.388, p = 0.54, \text{NS}] \) (see Fig. 4).

Superior Temporal Gyrri. Repeated measures GLM analysis of STG (including the anterior [aSTG] and posterior [pSTG] sub-regions) across both hemispheres yielded a main effect of hemisphere \( [F_{1,21} = 13.338, p = 0.001] \) and a two-way interaction of hemisphere and group \( [F_{1,21} = 0.029] \), where follow-up analysis revealed that only the older children showed greater activation in the LH compared to the RH \( [F_{1,8} = 14.96, p = 0.005] \). The analysis in STG also showed a marginal effect of morphology \( [F_{1,21} = 4.208, p = 0.053] \), with mono-morphemic words showing higher activation than bi-morphemic words. Finally, there was a main effect of sub-region \( [F_{1,21} = 9.538, p = 0.006] \), two-way interactions of sub-region with group \( [F_{1,21} = 12.043, p = 0.002] \) and sub-region with hemisphere \( [F_{1,21} = 10.77, p = 0.004] \), and a three-way interaction of hemisphere, group and diacritics \( [F_{1,21} = 8.111, p = 0.001] \).

We therefore conducted separate analyses in each diacritics condition across sub-regions and across hemispheres. These analyses showed significantly greater activity for mono-morphemic over bi-morphemic words \( [F_{1,21} = 4.668, p = 0.042] \) only in pointed words.

We also conducted separate analyses in each sub-region across diacritics conditions and across hemispheres. The analysis of pSTG showed a main effect of hemisphere \( [F_{1,21} = 18.687, p < 0.001] \) with greater activation for LH over the RH. The analysis of aSTG yielded a main effect of morphology \( [F_{1,21} = 5.261, p = 0.032] \), with greater activation for mono-morphemic over bi-morphemic words (see Fig. 4). There was also a two-way interaction of hemisphere and group \( [F_{1,21} = 5.148, p = 0.034] \), due to a significant effect of hemisphere only in the older group \( [F_{1,8} = 5.513, p = 0.047] \), and a three-way interaction of hemisphere, group, and diacritics \( [F_{1,21} = 8.457, p = 0.008] \). A further analysis of aSTG separately in pointed and un-pointed words yielded a significant effect of morphology only in pointed words \( [F_{1,21} = 4.796, p = 0.04] \), (Fig. 5).

**DISCUSSION**

The current study investigated the interaction of morphological complexity and orthographic depth in the brains of Hebrew reading children in early and intermediate stages of reading acquisition. Hebrew words at two levels of morphological complexity (mono-morphemic/bi-morphemic) were presented at two levels of orthographic transparency (pointed/un-pointed) to two groups of children (2–3rd graders/5–6th graders) during an fMRI scan. We expected to find morphological effects in left IFG and MFG, which were implicated in the processing of Hebrew root morphology in adults (Bick et al., 2008; Bick et al., 2010; Bitan et al., 2020). Additional regions, namely bilateral STG, MTG and OTC were also included in the ROI analysis because of their documented role in adult and children readers’ morphological processes in other languages (Lehtonen et al., 2006; Gold and Rastle, 2007; Meinzer et al., 2009; Arredondo et al., 2015). We further predicted an interaction of morphology and diacritics in the above regions so that morphological effects would be stronger in pointed compared to un-pointed words based on our previous behavioral findings in Hebrew reading children (Haddad et al., 2018).
Children’s performance inside the scanner was faster and more accurate in older compared to younger children, with the younger children showing more accurate reading for pointed compared to un-pointed words. We also found an interaction of diacritics and morphology in RT due to opposite but non-significant trends showing a facilitation of morphological structure for pointed words, while the same structure hindered reading of un-pointed words. In the ROI analyses, the only regions showing morphological effects were bilateral MTG and STG. These regions, and more specifically their anterior portions, showed greater activation for mono-morphemic over bi-morphemic words across groups, especially in pointed words. These two regions also showed a developmental increase in lateralization, with only older children showing a significant difference in activation between the left and right hemispheres.

**Hemispheric asymmetry**

Our results show greater activation in the left hemisphere (LH) compared to the right hemisphere (RH) in STG and MTG only for the older children. The effect of age on LH lateralization of spoken and written language processing has been the focus of many studies and debates. Specifically for orthographic processing it has been suggested that literacy acquisition induces LH specialization of the Visual Word Form Area (Dehaene et al., 2008).

### Table 3. Regions showing activation in the whole brain analysis across diacritic conditions: for the contrasts of (a) young children only across morphological conditions, (b) old children only across morphological conditions, (c) greater activation for old compared to young children, and (d) greater activation for young compared to old children. Results for (a) and (b) are significant at threshold p < 0.05 FWE corrected, cluster extent k ≥ 50, and results for (c) and (d) are significant at threshold p < 0.001 uncorrected, with cluster extent k ≥ 10

<table>
<thead>
<tr>
<th>Area</th>
<th>BA</th>
<th>H</th>
<th>Z</th>
<th>Voxels</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inferior occipital</td>
<td>18</td>
<td>L</td>
<td>7.83</td>
<td>999</td>
<td>−22</td>
<td>−92</td>
<td>−8</td>
</tr>
<tr>
<td>Postcentral gyrus</td>
<td>6</td>
<td>L</td>
<td>7.03</td>
<td>689</td>
<td>−52</td>
<td>−6</td>
<td>26</td>
</tr>
<tr>
<td>Postcentral gyrus</td>
<td>4</td>
<td>R</td>
<td>6.84</td>
<td>315</td>
<td>60</td>
<td>−4</td>
<td>22</td>
</tr>
<tr>
<td>Cerebellum</td>
<td>N/A</td>
<td>R</td>
<td>6.12</td>
<td>209</td>
<td>20</td>
<td>−62</td>
<td>−20</td>
</tr>
<tr>
<td>Fusiform gyrus</td>
<td>37</td>
<td>R</td>
<td>6.1</td>
<td>83</td>
<td>38</td>
<td>−52</td>
<td>−18</td>
</tr>
<tr>
<td>Precuneus</td>
<td>19</td>
<td>R</td>
<td>5.78</td>
<td>108</td>
<td>−46</td>
<td>0</td>
<td>−8</td>
</tr>
<tr>
<td>Lingual gyrus</td>
<td>18</td>
<td>R</td>
<td>5.54</td>
<td>66</td>
<td>26</td>
<td>−90</td>
<td>−8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area</th>
<th>BA</th>
<th>H</th>
<th>Z</th>
<th>Voxels</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precentral gyrus</td>
<td>6</td>
<td>L</td>
<td>Inf</td>
<td>2866</td>
<td>−52</td>
<td>−4</td>
<td>24</td>
</tr>
<tr>
<td>Insula</td>
<td>4</td>
<td>R</td>
<td>Inf</td>
<td>2662</td>
<td>50</td>
<td>−12</td>
<td>22</td>
</tr>
<tr>
<td>Inferior occipital</td>
<td>19</td>
<td>L</td>
<td>7.74</td>
<td>1216</td>
<td>−42</td>
<td>−68</td>
<td>−10</td>
</tr>
<tr>
<td>Inferior occipital</td>
<td>18</td>
<td>R</td>
<td>6.33</td>
<td>126</td>
<td>28</td>
<td>−92</td>
<td>−10</td>
</tr>
<tr>
<td>Posterior cingulum</td>
<td>N/A</td>
<td>R</td>
<td>6.31</td>
<td>165</td>
<td>−18</td>
<td>−44</td>
<td>8</td>
</tr>
<tr>
<td>Cerebellum</td>
<td>N/A</td>
<td>R</td>
<td>6.23</td>
<td>117</td>
<td>14</td>
<td>−62</td>
<td>−20</td>
</tr>
<tr>
<td>Cerebellum</td>
<td>N/A</td>
<td>L</td>
<td>6.06</td>
<td>76</td>
<td>−12</td>
<td>−62</td>
<td>−18</td>
</tr>
<tr>
<td>Fusiform gyrus</td>
<td>36</td>
<td>R</td>
<td>5.64</td>
<td>54</td>
<td>38</td>
<td>−28</td>
<td>−18</td>
</tr>
<tr>
<td>Precuneus</td>
<td>30</td>
<td>R</td>
<td>5.23</td>
<td>50</td>
<td>22</td>
<td>−40</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area</th>
<th>BA</th>
<th>H</th>
<th>Z</th>
<th>Voxels</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thalamus</td>
<td>50</td>
<td>L</td>
<td>3.51</td>
<td>25</td>
<td>−16</td>
<td>−20</td>
<td>0</td>
</tr>
<tr>
<td>Middle temporal gyrus</td>
<td>22</td>
<td>L</td>
<td>3.5</td>
<td>18</td>
<td>−48</td>
<td>−36</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area</th>
<th>BA</th>
<th>H</th>
<th>Z</th>
<th>Voxels</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superior occipital</td>
<td>18</td>
<td>L</td>
<td>3.97</td>
<td>23</td>
<td>−10</td>
<td>−98</td>
<td>6</td>
</tr>
<tr>
<td>Middle frontal gyrus</td>
<td>8</td>
<td>R</td>
<td>3.95</td>
<td>223</td>
<td>32</td>
<td>22</td>
<td>46</td>
</tr>
<tr>
<td>Superior frontal gyrus</td>
<td>10</td>
<td>R</td>
<td>3.85</td>
<td>35</td>
<td>28</td>
<td>64</td>
<td>18</td>
</tr>
<tr>
<td>Superior occipital</td>
<td>18</td>
<td>L</td>
<td>3.56</td>
<td>10</td>
<td>−14</td>
<td>−96</td>
<td>12</td>
</tr>
<tr>
<td>Middle frontal gyrus</td>
<td>9</td>
<td>R</td>
<td>3.51</td>
<td>18</td>
<td>32</td>
<td>44</td>
<td>38</td>
</tr>
</tbody>
</table>

### Table 4. Regions showing activation in the whole brain analysis across diacritic conditions for the contrast of mono-morphemic compared to bi-morphemic words across groups. Results are significant at threshold p < 0.001 uncorrected, with cluster extent k ≥ 10

<table>
<thead>
<tr>
<th>Area</th>
<th>BA</th>
<th>H</th>
<th>Z</th>
<th>Voxels</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superior temporal gyrus</td>
<td>22</td>
<td>L</td>
<td>4.12</td>
<td>18</td>
<td>−52</td>
<td>2</td>
<td>−8</td>
</tr>
<tr>
<td>Inferior frontal gyrus</td>
<td>47</td>
<td>L</td>
<td>3.65</td>
<td>15</td>
<td>−28</td>
<td>28</td>
<td>−18</td>
</tr>
<tr>
<td>Middle temporal gyrus</td>
<td>21</td>
<td>L</td>
<td>3.61</td>
<td>19</td>
<td>−60</td>
<td>−18</td>
<td>−8</td>
</tr>
<tr>
<td>Precuneus</td>
<td>4</td>
<td>L</td>
<td>3.29</td>
<td>18</td>
<td>−54</td>
<td>−12</td>
<td>36</td>
</tr>
<tr>
<td>Medial frontal gyrus</td>
<td>10</td>
<td>L</td>
<td>3.2</td>
<td>12</td>
<td>−8</td>
<td>50</td>
<td>12</td>
</tr>
</tbody>
</table>
et al., 2015). However, for anterior-temporal and frontal regions there is an ongoing debate on whether the LH specialization changes with age, with some accounts claiming it is a pre-determined result of brain maturation (Groen et al., 2012), and others positing that it can be more directly attributed to the acquisition of improved language skills (Holland et al., 2007; Everts et al., 2009). Several studies, finding no association between language-related lateralization and age (Gaillard et al., 2003; Wood et al., 2004; Balsamo et al., 2006; Groen et al., 2012), argue that LH specialization is constant from the very beginning of language acquisition. However, neuroimaging studies in English and German speaking children, teens, and adults have found age related increases in LH lateralization of brain activation during various language tasks (Holland et al., 2001; Szaflarski et al., 2006; Clahsen et al., 2007; Ressel et al., 2008; Everts et al., 2009). Recently, Olulade et al., (2020) looked at patterns of activation in the LH and RH during an auditory judgement task in 53 participants between ages 4–29 and found a negative correlation between age and activation in RH language areas, with no correlation in the LH. Similarly, reading ability was positively correlated with activation in LH regions and negatively correlated with activation in RH regions in subjects aged 6–22 (Turkeltaub et al., 2003). Participants’ performance in the scanner, showing higher accuracy and faster RT for older children, are consistent with the expected developmental trajectory and with the evidence for increase in LH lateralization. Although the findings of the current study cannot distinguish between maturational and skill acquisition accounts, they are consistent with the view of a developmental increase in LH specialization, and they consist of the first neuroimaging evidence for this developmental change in Hebrew readers.

Sensitivity to morphology in early reading development

Our ROI analyses showed significant effects of morphological complexity across groups in the anterior portions of MTG and STG for pointed words, with no interaction between morphology and age group. The morphological effects found across both age groups are not consistent with our prediction based on our previous behavioral study (Haddad et al., 2018) that morphological effects would be larger in the young children compared to

Table 5. Regions showing the effect of morphological complexity across groups separately for each level of diacritics. (a) Greater activation for mono-morphemic compared to bi-morphemic words in pointed words, (b) greater activation for mono-morphemic compared to bi-morphemic words in un-pointed words, and (c) greater activation for bi-morphemic compared to mono-morphemic words in un-pointed words. Results are significant at threshold \( p < 0.001 \) uncorrected, with cluster extent \( k \geq 10 \)

(a) Mono-Morphemic > Bi-Morphemic words across groups in pointed words

<table>
<thead>
<tr>
<th>Area</th>
<th>BA</th>
<th>H</th>
<th>Z</th>
<th>Voxels</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superior temporal gyrus</td>
<td>22</td>
<td>R</td>
<td>4.58</td>
<td>43</td>
<td>62</td>
<td>-32</td>
<td>16</td>
</tr>
<tr>
<td>Cerebellar vermis</td>
<td>N/A</td>
<td>N/A</td>
<td>3.77</td>
<td>25</td>
<td>-2</td>
<td>-44</td>
<td>-12</td>
</tr>
<tr>
<td>Cingulate gyrus</td>
<td>24</td>
<td>L</td>
<td>3.71</td>
<td>63</td>
<td>-4</td>
<td>-20</td>
<td>38</td>
</tr>
<tr>
<td>Medial frontal gyrus</td>
<td>10</td>
<td>L</td>
<td>3.67</td>
<td>96</td>
<td>-2</td>
<td>54</td>
<td>16</td>
</tr>
</tbody>
</table>

(b) Mono-Morphemic > Bi-Morphemic words across groups in un-pointed words

<table>
<thead>
<tr>
<th>Area</th>
<th>BA</th>
<th>H</th>
<th>Z</th>
<th>Voxels</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Postcentral gyrus</td>
<td>4</td>
<td>L</td>
<td>4.29</td>
<td>153</td>
<td>-52</td>
<td>-12</td>
<td>40</td>
</tr>
<tr>
<td>Pallidum</td>
<td>N/A</td>
<td>R</td>
<td>4.08</td>
<td>17</td>
<td>24</td>
<td>-12</td>
<td>-6</td>
</tr>
<tr>
<td>Hippocampus</td>
<td>N/A</td>
<td>R</td>
<td>3.63</td>
<td>20</td>
<td>40</td>
<td>-16</td>
<td>-14</td>
</tr>
</tbody>
</table>

(c) Bi-Morphemic > Mono-Morphemic words across groups in un-pointed words

<table>
<thead>
<tr>
<th>Area</th>
<th>BA</th>
<th>H</th>
<th>Z</th>
<th>Voxels</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcarine sulcus</td>
<td>N/A</td>
<td>R</td>
<td>3.41</td>
<td>12</td>
<td>24</td>
<td>-62</td>
<td>16</td>
</tr>
</tbody>
</table>
the older children group. Nevertheless, the results are partially consistent with these findings since morphological effects in Hebrew speaking children are seen as early as the second grade. These findings also appear to be in contrast with the suggested developmental increase in the reliance on morphological segmentation skills during the elementary school years in English speaking children (Carlisle, 1988; Tyler and Nagy, 1989; Kieffer and Lesaux, 2012; Nagy et al., 2014; Sparks and Deacon, 2015). This increase is attributed to the regularity of mapping morphemes to meaning in English, providing efficient direct access from orthography to meaning in older children (Rastie, 2019). The discrepancy with the results of the current study may be related to cross linguistic differences in morphological structure.

The prominent role of the root morpheme in the structure of most words in Hebrew results in pervasive morphological decomposition during lexical access in skilled Hebrew readers (Bentin and Feldman, 1990; Frost et al., 1997; Deutsch et al., 1998, 2000; 2003; 2005), which is suggested to be different than morphological processing in adult English readers (Bick et al., 2011). For younger Hebrew readers studies have found explicit knowledge of roots and patterns as early as the second grade (Ravid and Schiff, 2006). Morphological Awareness (MA) in Hebrew, assessed by written language tests of inflectional and derivational morphology, has been shown to correlate with children's word reading as early as 2nd or 3rd grade (Vaknin-Nusbaum et al., 2016b; Shechter et al., 2018). Furthermore, written word MA explained significant variance in 3rd graders reading of Hebrew pointed and un-pointed single words (Bar-Kochva and Breznitz, 2014), and Hebrew reading children are able to rely on their knowledge of morphological patterns to correctly read pseudo-words (Bar-On and Ravid, 2011). Together with our behavioral findings (Haddad et al., 2018) the results of our current neuroimaging study are the first to directly show evidence of morphological processing during oral reading of real words, indicating that Hebrew reading children in early stages of reading acquisition engage in morphological processing while reading familiar words.

Morphological effects in bilateral temporal areas

Our findings, localizing the morphological effects to bilateral anterior temporal regions, differ from our predictions, which were based on Hebrew speaking adults showing morphological effects in left IFG and left MFG using identical stimuli (Bitan et al., 2020). These frontal areas were also shown in Hebrew speaking adults during a root-priming task (Bick et al., 2008, 2010). This discrepancy may suggest age-related differences in the neurocognitive processes involved in morphological decomposition during reading. Very few neuroimaging studies investigated children's morphological processing of written or spoken words in any language. Two previous studies used an auditory morphological judgment task in which English-speaking children aged 6–13 judged the grammaticality of morphologically derived pseudowords (Arredondo et al., 2015; Ip et al., 2017). Both studies found activation for this explicit morphological judgment task in frontal and temporal areas including: bilateral superior frontal gyri, left MFG, left IFG, left Inferior Parietal Lobule, bilateral anterior STG, and bilateral posterior MTG (Arredondo et al., 2015; Ip et al., 2017). Children's performance on a morphological test outside the scanner was correlated with stronger activation in both left superior temporal and inferior parietal regions during these tasks (Arredondo et al., 2015). Activation in this wider fronto-temporal network in the above studies may be due to the explicit nature of the task, the use of pseudowords, and the use of spoken language, which is much more proficient than written language during the early school years. The only previous neuroimaging study showing evidence for children's morphological processing during reading comes from Chinese reading children aged 11–13. In this study participants judged the semantic relatedness of visually presented words, which contained morphologically congruent or incongruent features (Liu et al., 2013). An effect for morphological incongruency was seen in left IFG (BA 9, 47). The difference between these effects and the ones seen in the current study may be due to differences between languages (Perfetti et al., 2013), or due to maturational changes in frontal areas (Bitan et al., 2006, 2009; Friederici et al., 2011; Brauer et al., 2013) that occurred in the older participants in the Liu et al. (2013) study.

Neuroimaging studies in adults implicate both left frontal and bilateral temporal areas in morphological processing across languages. Left IFG, including pars opercularis and pars triangularis, have been implicated in morphological decomposition of inflected (Beretta et al., 2003; Tyler et al., 2005; Sahin et al., 2006; Bozic et al., 2013b; Platsikas et al., 2014; Nevat et al., 2017) and derived words (Marangolo et al., 2006; Bozic et al., 2007) in different modalities and languages. MEG studies suggest that morphological effects in these frontal regions represent late morpho-phonological segmentation processes at around 350–495 ms. following the visual presentation of the word (Whiting et al., 2014; Cavalli et al., 2016). Left temporal areas, including STG and MTG, were also found to be involved in morphological processing of derived words in adults (Vannest et al., 2011; Cavalli et al., 2016). Studies showing morphological effects in derived German adjectives (Bölte et al., 2010), and semantically transparent compound English words (Brooks and Cid de Garcia, 2015), in anterior temporal regions in adult readers suggest these regions are involved in morpho-semantic processing. This interpretation is supported by the key role anterior temporal regions play in the semantic processing network across modalities (Patterson et al., 2007; Visser et al., 2009; Friederici, 2011; Ralph et al., 2017). Findings from MEG studies, showing these morphological effects in temporal regions in early stages of word reading (Solomyak and Marantz, 2009; Fruchter and Marantz, 2015), are taken as supporting the Full Decomposition model that argues for pre-lexical decomposition of all morphologically complex words (Taft and Forster, 1975; Taft, 1979, 2004; Fruchter and Marantz, 2015). These findings are also consistent with eye tracking studies in Italian reading children showing sensitivity to the morphological structure of
derived words in early stages of processing a written word (Traficante et al., 2018).

However, other researchers have different interpretations for the activation in anterior temporal cortices in morphologically complex words that do not support the notion of morphological decomposition of derived words. A series of studies by Bozic and Marslen-Wilson et al. (Bozic et al., 2013a,b; Klimovich-Gray et al., 2016), examined the processing of morphologically complex spoken words in English, Polish and Russian. The authors suggest that left IFG activation reflects decomposition of inflected words only, while derived words producing activation in bilateral temporal regions reflect whole word processing. According to this approach, greater activation in bilateral temporal areas for derived words reflects lexical competition between the meaning of derived words and the meaning of their embedded base stem (Bozic et al., 2013a,b; Klimovich-Gray et al., 2016). While the authors suggest that this finding supports the notion that derived words are processed as stored forms, such competition is itself an indication of sensitivity to the morphological units (Traficante et al., 2018). Whether the temporal activation while reading derived words represents full decomposition or semantic competition, it indicates that children are sensitive to the morpho-semantic similarity between derived words and their stem.

Altogether these results suggest that the differences between children showing morphological effects in bilateral temporal regions, and adults showing morphological effects in left frontal regions (Bitan et al., 2020) may reflect differences in morphological processing between children and adults. While adults may process derived words, like inflected forms, using morphophonological decomposition processes associated with left frontal areas, children may be more sensitive to the morpho-semantic aspects of the shared morpheme, activating bilateral anterior temporal areas instead. This difference between children and adults in reliance on frontal vs. posterior language areas may also be related to the late maturation of frontal cortical areas during development (Holland et al., 2001; Gaillard et al., 2003; Gogtay et al., 2004; Bitan et al., 2006, 2009).

This interpretation is consistent with ERP studies of German inflected words, showing a developmental shift from posterior to anterior regions and from bilateral to left lateralized processing. During the production of inflected German verbs researchers found posterior distribution of enhanced negativity in children aged 8–13, compared to an anterior distribution in adults (Jessen et al., 2017). Moreover, auditory processing of inflected German nouns has also shown a shift from right to bilateral to left lateralized processing (Olahsen et al., 2007).

The effect of orthographic transparency on morphological segmentation

The morphological effect found in aMTG and aSTG was significant only in pointed words. This finding is consistent with our prediction, and with our previous behavioral findings in Hebrew reading children (Haddad et al., 2018), showing that the morphological structure was beneficial for reading pointed words, across groups. It is also consistent with the significant interaction between morphology and diacritics found in the current study’s in-scanner reaction times, and a trend for facilitatory effect of morphology only in pointed words. Our previous behavioral study (Haddad et al., 2018) also showed that morphological structure hindered word recognition for un-pointed words in younger children, while in the current study this was evident in a non-significant trend in RT. The missing vowels in the un-pointed script may enhance the competition between bi-morphemic words and other words sharing the same root, especially in younger readers. Such competition between morphologically related words has been suggested in previous studies in children (Traficante et al., 2018). These results differ from the findings in typically reading adults, showing greater morphological effects in un-pointed words, perhaps reflecting the compensation for the missing vowel information (Bitan et al., 2020). Nonetheless, the current results in children are similar to those of adults with dyslexia showing morphological effects only for pointed words in Occipito-Temporal cortex (Bitan et al., 2020).

While the specific way in which orthographic transparency interacts with morphological structure is unique to the Semitic script and morphology, our findings are generally consistent with findings from French, English, and Spanish. One study that compared French and English speaking 8–9 year old children performing a visual lexical decision task found greater morphological effects in French, which has a richer morphology and a more transparent letter-to-sound correspondence, than English (Casalis et al., 2015). Studies in English, Spanish and French also suggest that the morpho-phonological transparency of morphologically complex words modulates morphological effects in children during reading (Carlisle, 2000; Carlisle et al., 2001; Duncan et al., 2009; Lázaro et al., 2015). These findings support the importance of transparent phonological cues for morphological segmentation.

The findings of the current study, together with our previous behavioral results (Haddad et al., 2018), shed light on the developmental trajectory of morphological processing, and provide direct evidence for the early sensitivity of Hebrew reading children to morphological structure while reading real words. Unlike adult readers, who can utilize morphological segmentation as compensation for reading un-pointed words, children rely on the phonological information provided in the pointed, transparent script to facilitate morphological processing.

These findings are in line with the Triplex Model of reading Hebrew (Share and Bar-On, 2017), suggesting that around the second grade Hebrew readers utilize lexico-morpho-orthographic processes to read words. However, these findings diverge from findings in English and Dutch suggesting that children’s reliance on morphological segmentation for reading emerges only in later stages of reading acquisition (Carlisle, 1988; Tyler and Nagy, 1989; Adams, 1990; Anglin et al., 1993; Mahony et al., 2000; Rispens et al., 2008; Kieffer and Lesaux, 2012; Nagy et al., 2014; Sparks and Deacon, 2015;
These discrepancies can be explained by the unique properties of each language and orthography. The early reliance on morphological segmentation while reading Hebrew may be related to its rich morphological structure and the prominence of the root morpheme at the core of its lexical representations (Ravid and Tolchinsky, 2002; Frost et al., 2005). Even so, the question of whether reliance on morphological segmentation indeed develops differently depending on the structure of the language can only be answered by a cross-linguistic study using comparable stimuli and procedures (Rastle, 2019).

Need for further study notwithstanding, as this study is one of the first neuroimaging studies of morphological processing in children in any language, its findings go beyond those of behavioral evidence. Our results, showing morphological effects in bilateral anterior temporal regions, stand in contrast to adults showing such effects in left frontal regions with identical stimuli. These morphological effects in bilateral anterior temporal cortices may reflect pre-lexical morpho-semantic decomposition (Taft, 2004; Fruchter and Marantz, 2015), or alternatively, semantic competition between whole derived words and their stems (Bozic et al., 2013a,b; Klimovich-Gray et al., 2016). As an fMRI study, our results lack the temporal resolution to distinguish between pre and post lexical access to morphological representations, but still clearly show that while young children are sensitive to the morphological structure of written derived words, they process them differently from adults. While Hebrew reading adults decompose derived words using the same morpho-phonological mechanisms as for inflected words, children rely more strongly on morpho-semantic processes.

### LIMITATIONS

The main limitation of the current study is the small sample size, especially in the older children’s group. The difficulty in recruiting children has also resulted in a large age range within each group of children. The small sample size may have also led to the absence of significant morphological effects at the whole brain level. It should be noted that while the ROI analysis did not show any age differences in morphological effects, the finding of developmental changes in hemispheric asymmetry suggests that the absence of age differences in morphological processing was not due to the small sample size. Together with our behavioral findings (Haddad et al., 2018), collected from larger samples, these results support the conclusion that there was no difference between the younger and older children in processing morphology.

### FUNDING

The study was funded by the Israel Foundation Trustees, grant 34/2011 to Tali Bitan, and by the ISF under grant 1142/11 to Tali Bitan and Tami Katzir.

### DECLARATIONS OF INTEREST

None.

### REFERENCES


