NEUROSCIENCE
RESEARCH ARTICLE

B. Barouch et al. / Neuroscience 485 (2022) 37–52

# Neural Processing of Morphology During Reading in Children

**Bechor 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.** 

**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

*Corresponding author.
E-mail addresses: becbarouch@gmail.com (B. Barouch), tbitan@research.haifa.ac.il (T. Bitan).
*Abbreviations:* aMTG, Anterior middle temporal gyri; aSTG, Anterior superior temporal gyri; BA, Brodmann area; ERP, Event-related potential; FEW, Family-wise error rate; fMRI, Functional magnetic resonance imaging; GLM, General linear model; IFG, Inferior frontal gyri; IRB, Institutional review board; LH, Left hemisphere; MA, Morphological awareness; MEG, Magnetoencephalography; MFG, Middle frontal gyri; mm, Millimeter; MNI, Montreal Neurological Institute and Hospital (coordinate system); MRI, Magnetic resonance imaging; Ms, Millisecond; MTG, Middle temporal gyri; Oper, Pars opercularis; Orb, Pars orbitalis; OTC, Occipito-temporal-cortex; pMTG, Posterior middle temporal gyri; pSTG, Posterior superior temporal gyri; RH, Right hemisphere; ROI, Region of interest; RT, Reaction time; SD, Standard deviation; STG, Superior temporal gyri; Tri, Pars triangularis.

https://doi.org/10.1016/j.neuroscience.2021.12.025
0306-4522/

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; Nevat 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; Kirkici and Clahsen, 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 words, 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 (MTG; 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 (Arredondo et al., 2015; Ip et al., 2017). Another study in Chinese readers aged 11–13 showed a morphological effect in semantic judgement 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; Ehri 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 represent the root consonants). The root can combine with other patterns to form a variety of words referring to dancing: *lirkod* 'to dance', *rikud* 'a dance', etc. The pattern *CaCCan* also appears with other roots: *kablan* 'contractor', and *kabtzan* '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 with no diacritics, which only partially represents 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; Deutsch 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; Fruchter 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)

| | Younger group ($n$ = 14) | Older group ($n$ = 9) |
|---|---|---|
| Reading words33.8 (10.3) | | |
| number per minute raw score | 33.8 (10.3) | 48.3 (9.4) |
| number per minute z score | −0.05 (0.67) | −0.53 (0.40) |
| Reading pseudo-words | | |
| number per minute raw score | 19.9 (3.8) | 22.2 (6.6) |
| number per minute z score | 0.14 (0.49) | −0.01 (0.41) |
| Phoneme omission | | |
| % errors raw score | 27.7 (20.8) | 12.5 (13.3) |
| % errors z score | −0.58 (0.78) | −0.40 (0.57) |

**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)

| | Bi-morphemic words (with root + pattern) | Mono-morphemic words |
|---|---|---|
| With diacritics (pointed) | מִכְשׁוֹל MXSOL/mixshol/ (obstacle) | סַנְטֵר <SNTR> / santer/(chin) |
| Without diacritics (un-pointed) | תלמיד TLMID /talmid/ (student) | סנפיר SNPIR / snapir/ (fin) |

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 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 NifTi 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://cibsr.stanford.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 BioImage 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; Szaflarski 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; Pliatsikas 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 (Oper), (1b) pars orbitalis (Orb) and (1c) pars triangularis (Tri); (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 $x = -35$, $y = 7$, $z = 29$ ($x = 45$, $y = 13$, $z = 30$ for right MFG); (5) OTC(Lehtonen et al., 2006), defined as a 10 mm sphere surrounding the MNI coordinates $x = -54$, $y = -57$, $z = -4$ ($x = 54$, $y = -57$, $z = -4$ 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 factor (young children/older children). We report the results only for areas showing a significant main effect or interaction with morphology, namely STG and MTG.

## 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

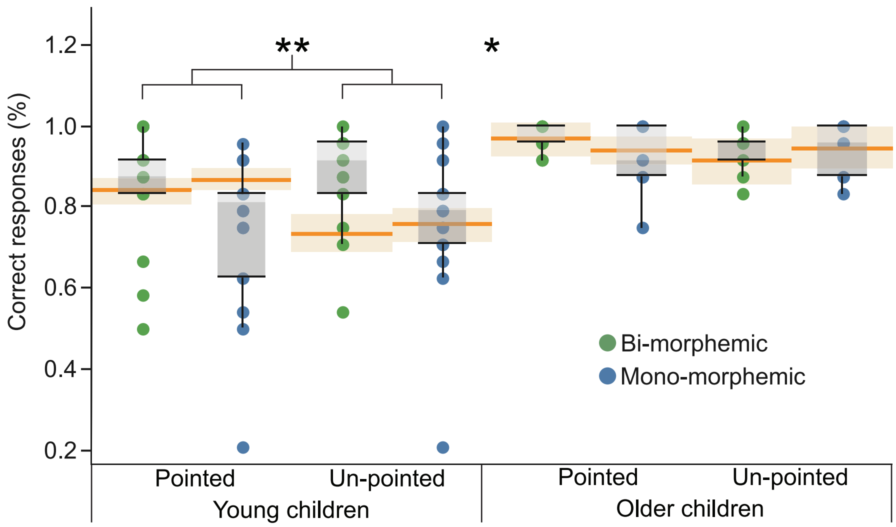


**Fig. 1.** Reading accuracy in the scanner. * Indicates significance of $p < 0.05$, ** indicate significance of $p < 0.001$, box plots indicate four quartiles and median, orange bars indicate estimated marginal mean, light orange bands indicate standard error.

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 5a) 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 calcarine 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

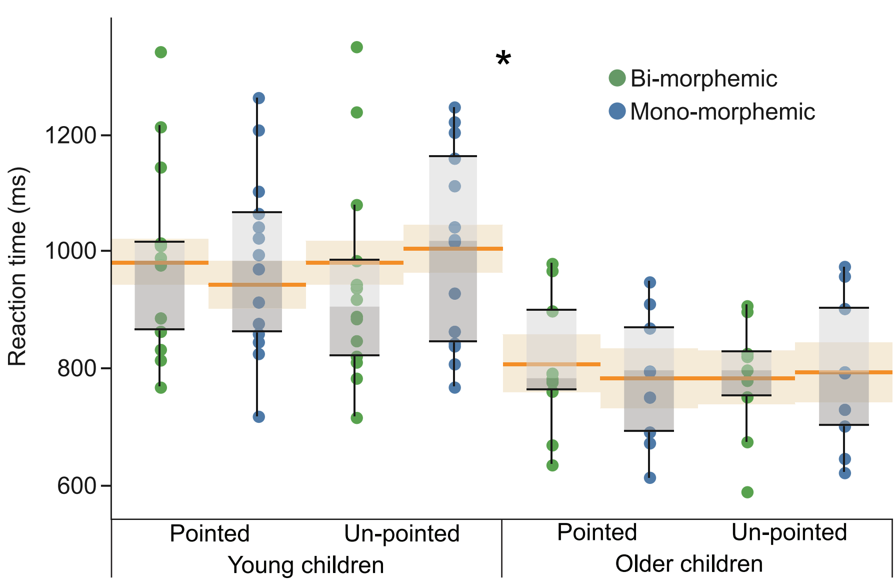


**Fig. 2.** Reaction time in the scanner. * Indicates significance of $p < 0.05$, box plots indicate four quartiles and median, orange bars indicate estimated marginal mean, light orange bands indicate standard error.

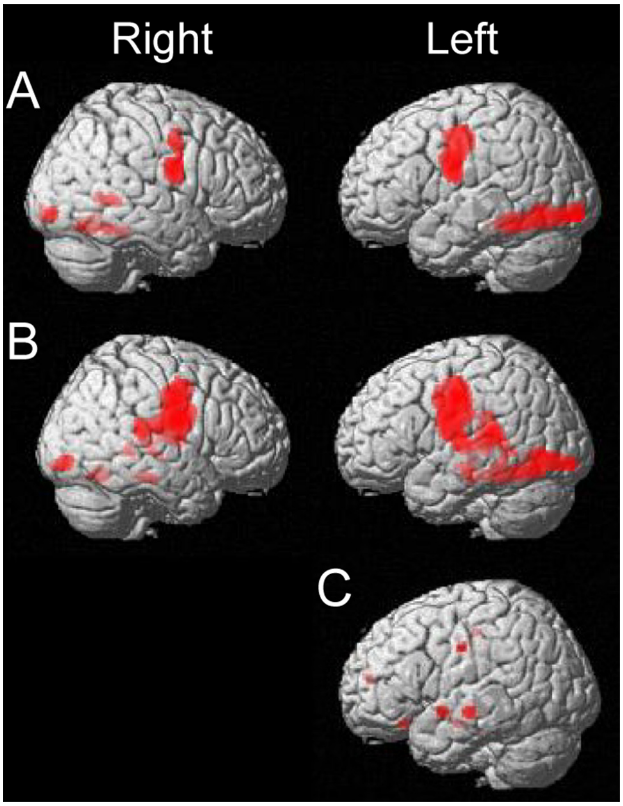


**Fig. 3.** Whole brain image panel. Regions showing activation in the whole brain analysis: for the contrasts of **(A)** young children: all words vs. baseline, **(B)** older children: all words vs. baseline, and **(C)** Greater activation in mono-morphemic compared to bi-morphemic words across groups. Results for **(A)** and **(B)** are significant at threshold $p < 0.05$ FWE corrected, cluster extent $k \geq 50$, and results for **(C)** are significant at threshold $p < 0.001$ uncorrected, cluster extent $k \geq 10$.

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 [$F_{1,21} = 0.388$, $p = 0.54$, NS] (see Fig. 4).

*Superior Temporal Gyri.* 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 [$F_{1,21} =$ , $p = 0.029$], 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).

**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 $k \geq 50$, and results for (c) and (d) are significant at threshold $p < 0.001$ uncorrected, with cluster extent $k \geq 10$

| Area | BA | H | Z | Voxels | X | Y | Z |
|---|---|---|---|---|---|---|---|
| (a) Young children | | | | | | | |
| Area | BA | H | Z | Voxels | X | Y | Z |
| Inferior occipital gyrus | 18 | L | 7.83 | 999 | −22 | −92 | −8 |
| Postcentral gyrus | 6 | L | 7.03 | 689 | −52 | −6 | 26 |
| Postcentral gyrus | 4 | R | 6.84 | 315 | 60 | −4 | 22 |
| Cerebellum | N/A | R | 6.12 | 209 | 20 | −62 | −20 |
| Fusiform gyrus | 37 | R | 6.1 | 83 | 38 | −52 | −18 |
| Precuneus | 19 | R | 5.78 | 108 | 30 | −46 | 0 |
| Lingual gyrus | 18 | R | 5.54 | 66 | 26 | −90 | −8 |
| (b) Older children | | | | | | | |
| Area | BA | H | Z | Voxels | X | Y | Z |
| Precentral gyrus | 6 | L | Inf | 2866 | −52 | −4 | 24 |
| Insula | 4 | R | Inf | 2662 | 50 | −12 | 22 |
| Inferior occipital gyrus | 19 | L | 7.74 | 1216 | −42 | −68 | −10 |
| Inferior occipital gyrus | 18 | R | 6.33 | 126 | 28 | −92 | −10 |
| Posterior cingulum | N/A | L | 6.31 | 165 | −18 | −44 | 8 |
| Cerebellum | N/A | R | 6.23 | 117 | 14 | −62 | −20 |
| Cerebellum | N/A | L | 6.06 | 76 | −12 | −62 | −18 |
| Fusiform gyrus | 36 | R | 5.64 | 54 | 38 | −28 | −18 |
| Precuneus | 30 | R | 5.23 | 50 | 22 | −40 | 2 |
| (c) Two-sample T-test, Older > Young children across language conditions | | | | | | | |
| Area | BA | H | Z | Voxels | X | Y | Z |
| Thalamus | 50 | L | 3.51 | 25 | −16 | −20 | 0 |
| Middle temporal gyrus | 22 | L | 3.5 | 18 | −48 | −36 | 8 |
| (d) Two-sample T-test, Young > Older children across language conditions | | | | | | | |
| Area | BA | H | Z | Voxels | X | Y | Z |
| Superior occipital gyrus | 18 | L | 3.97 | 23 | −10 | −98 | 6 |
| Middle frontal gyrus | 8 | R | 3.95 | 223 | 32 | 22 | 46 |
| Superior frontal gyrus | 10 | R | 3.85 | 35 | 28 | 64 | 18 |
| Superior occipital gyrus | 18 | L | 3.56 | 10 | −14 | −96 | 12 |
| Middle frontal gyrus | 9 | R | 3.51 | 18 | 32 | 44 | 38 |

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

**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, cluster extent $k \geq 10$

| Area | BA | H | Z | Voxels | X | Y | Z |
|---|---|---|---|---|---|---|---|
| Mono-Morphemic > Bi-Morphemic words across groups | | | | | | | |
| Area | BA | H | Z | Voxels | X | Y | Z |
| Superior temporal gyrus | 22 | L | 4.12 | 18 | −52 | 2 | −8 |
| Inferior frontal gyrus | 47 | L | 3.65 | 15 | −28 | 28 | −18 |
| Middle temporal gyrus | 21 | L | 3.61 | 19 | −60 | −18 | −8 |
| Precentral gyrus | 4 | L | 3.29 | 18 | −54 | −12 | 36 |
| Medial frontal gyrus | 10 | L | 3.2 | 12 | −8 | 50 | 12 |

**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 | | | | | | | |
|---|---|---|---|---|---|---|---|
| Area | BA | H | Z | Voxels | X | Y | Z |
| Superior temporal gyrus | 22 | R | 4.58 | 43 | 62 | −32 | 16 |
| Cerebellar vermis | N/A | N/A | 3.77 | 25 | −2 | −44 | −12 |
| Cingulate gyrus | 24 | L | 3.71 | 63 | −4 | −20 | 38 |
| Medial frontal gyrus | 10 | L | 3.67 | 96 | −2 | 54 | 16 |
| (b) Mono-Morphemic > Bi-Morphemic words across groups in un-pointed words | | | | | | | |
| Area | BA | H | Z | Voxels | X | Y | Z |
| Postcentral gyrus | 4 | L | 4.29 | 153 | −52 | −12 | 40 |
| Pallidum | N/A | R | 4.08 | 17 | 24 | −12 | −6 |
| Hippocampus | N/A | R | 3.63 | 20 | 40 | −16 | −14 |
| (c) Bi-Morphemic > Mono-Morphemic words across groups in un-pointed words | | | | | | | |
| Area | BA | H | Z | Voxels | X | Y | Z |
| Calcarine sulcus | N/A | R | 3.41 | 12 | 24 | −62 | 16 |

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, Oluladе 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

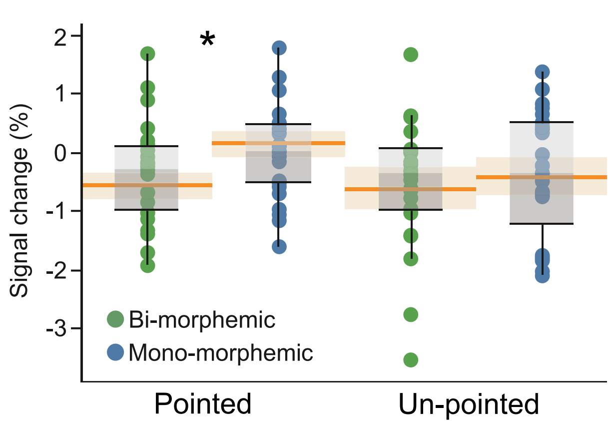


**Fig. 4.** Effect of morphology in aMTG: Significant effect of morphology in pointed words. * Indicates significance of < 0.05, box plots indicate four quartiles and median, orange bars indicate estimated marginal mean, light orange bands indicate standard error.

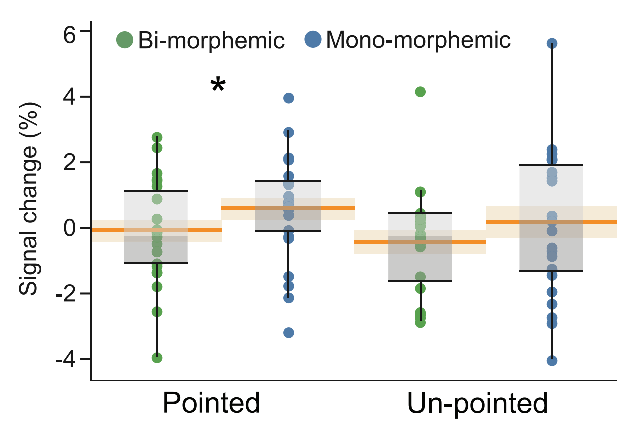


**Fig. 5.** Effect of morphology in aSTG: Beyond the main effect of morphology in aSTG, greater activation for mono-morphemic over bi-morphemic words is seen in the pointed condition. * Indicates significance of $p < 0.05$, box plots indicate four quartiles and median, orange bars indicate estimated marginal mean, light orange bands indicate standard error.

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 (Rastle, 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; Pliatsikas 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 morpho-phonological 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 (Clahsen 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;

Rastle, 2019). 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

Adams MJ (1990) Beginning to read. Cambrdige, MA: MIT Press.

Amenta S, Crepaldi D (2012) Morphological processing as we know it: an analytical review of morphological effects in visual word identification. Front Psychol 3. https://doi.org/10.3389/fpsyg.2012.00232.

Anglin JM, Miller GA, Wakefield PC (1993) Vocabulary development: a morphological analysis. Monogr Soc Res Child 58(10):1–186. https://doi.org/10.2307/1166112.

Arredondo MM, Ip KI, Shih Ju Hsu L, Tardif T, Kovelman I (2015) Brain bases of morphological processing in young children: Brain Bases of Morphological Abilities. Hum Brain Mapp 36 (8):2890–2900. https://doi.org/10.1002/hbm.22815.

Balsamo LM, Xu B, Gaillard WD (2006) Language lateralization and the role of the fusiform gyrus in semantic processing in young children. Neuroimage 31(3):1306–1314. https://doi.org/10.1016/j.neuroimage.2006.01.027.

Bar-Kochva I, Breznitz Z (2014) Reading scripts that differ in orthographic transparency: a within-participant-and-language investigation of underlying skills. J Exp Child Psychol 121:12–27. https://doi.org/10.1016/j.jecp.2013.07.011.

Bar-On A, Ravid D (2011) Morphological analysis in learning to read pseudowords in Hebrew. Appl Psycholinguist 32(03):553–581. https://doi.org/10.1017/S014271641100021X.

Bentin S, Feldman LB (1990) The contribution of morphological and semantic relatedness to repetition priming at short and long lags: evidence from hebrew. Q J Exp Psychol-A 42(4):693–711. https://doi.org/10.1080/14640749008401245.

Beretta A, Campbell C, Carr TH, Huang J, Schmitt LM, Christianson K, Cao Y (2003) An ER-fMRI investigation of morphological inflection in German reveals that the brain makes a distinction between regular and irregular forms. Brain Lang 85(1):67–92. https://doi.org/10.1016/S0093-934X(02)00560-6.

Berman RA (1982) Verb-pattern alternation: the interface of morphology, syntax, and semantics in Hebrew child language. J Child Lang 9(1):169–191. https://doi.org/10.1017/S030500090000369X.

Bick A, Goelman G, Frost R (2008) Neural correlates of morphological processes in Hebrew. J Cognitive Neurosci 20 (3):406–420. https://doi.org/10.1162/jocn.2008.20028.

Bick AS, Frost R, Goelman G (2010) Imaging implicit morphological processing: evidence from Hebrew. J Cognitive Neurosci 22 (9):1955–1969.

Bick AS, Goelman G, Frost R (2011) Hebrew brain vs. English brain: language modulates the way it is processed. J Cognitive Neurosci 23(9):2280–2290.

Bitan T, Burman DD, Lu D, Cone NE, Gitelman DR, Mesulam M-M, Booth JR (2006) Weaker top–down modulation from the left inferior frontal gyrus in children. Neuroimage 33(3):991–998. https://doi.org/10.1016/j.neuroimage.2006.07.007.

Bitan T, Cheon J, Lu D, Burman DD, Booth JR (2009) Developmental increase in top-down and bottom–up processing in a phonological task: an effective connectivity, fMRI study. J Cognitive Neurosci 21(6):1135–1145. https://doi.org/10.1162/jocn.2009.21065.

Bitan T, Weiss Y, Katzir T, Truzman T (2020) Morphological decomposition compensates for imperfections in phonological decoding. Neural evidence from typical and dyslexic readers of an opaque orthography. Cortex 130:172–191. https://doi.org/10.1016/j.cortex.2020.05.014.

Bölte J, Schulz C, Dobel C (2010) Processing of existing, synonymous, and anomalous German derived adjectives: an MEG study. Neurosci Lett 469(1):107–111. https://doi.org/10.1016/j.neulet.2009.11.054.

Bozic M, Marslen-Wilson WD, Stamatakis EA, Davis MH, Tyler LK (2007) Differentiating morphology, form, and meaning: neural

correlates of morphological complexity. J Cognitive Neurosci 19 (9):1464–1475. https://doi.org/10.1162/jocn.2007.19.9.1464.
Bozic M, Szlachta Z, Marslen-Wilson WD (2013a) Cross-linguistic parallels in processing derivational morphology: evidence from Polish. Brain Lang 127(3):533–538. https://doi.org/10.1016/j.bandl.2013.09.001.
Bozic M, Tyler LK, Su L, Wingfield C, Marslen-Wilson WD (2013b) Neurobiological systems for lexical representation and analysis in english. J Cognitive Neurosci 25(10):1678–1691. https://doi.org/10.1162/jocn_a_00420.
Brauer J, Anwander A, Perani D, Friederici AD (2013) Dorsal and ventral pathways in language development. Brain Lang 127 (2):289–295. https://doi.org/10.1016/j.bandl.2013.03.001.
Brett, M., Anton, J.-L., Valabregue, R., Poline, J.-B. (2002). Region of interest analysis using an SPM toolbox.
Brooks TL, Cid de Garcia D (2015) Evidence for morphological composition in compound words using MEG. Front Hum Neurosc I:9. https://doi.org/10.3389/fnhum.2015.00215.
Caravolas M, Hulme C, Snowling MJ (2001) The foundations of spelling ability: evidence from a 3-year longitudinal study. J Mem Lang 45(4):751–774. https://doi.org/10.1006/jmla.2000.2785.
Carlisle JF (1988) Knowledge of derivational morphology and spelling ability in fourth, sixth, and eighth graders. Appl Psycholinguist 9 (3):247–266. https://doi.org/10.1017/S0142716400007839.
Carlisle JF (2000) Awareness of the structure and meaning of morphologically complex words: impact on reading. Read Writ 12 (3):169–190. https://doi.org/10.1023/A:1008131926604.
Carlisle JF, Stone CA, Katz LA (2001) The effects of phonological transparency on reading derived words. Ann Dyslexia 51 (1):249–274. https://doi.org/10.1007/s11881-001-0013-2.
Carota F, Bozic M, Marslen-Wilson W (2016) Decompositional representation of morphological complexity: multivariate fMRI evidence from Italian. J Cognitive Neurosci 28(12):1878–1896. https://doi.org/10.1162/jocn_a_01009.
Casalis S, Quémart P, Duncan LG (2015) How language affects children's use of derivational morphology in visual word and pseudoword processing: evidence from a cross-language study. Front Psycholfront Psychol 6. https://doi.org/10.3389/fpsyg.2015.00452.
Cavalli E, Colé P, Badier J-M, Zielinski C, Chanoine V, Ziegler JC (2016) Spatiotemporal dynamics of morphological processing in visual word recognition. J Cognitive Neurosci 28(8):1228–1242. https://doi.org/10.1162/jocn_a_00959.
Clahsen H, Lück M, Hahne A (2007) How children process over-regularizations: evidence from event-related brain potentials. J Child Lang 34(3):601–622. https://doi.org/10.1017/S0305000907008082.
Clark EV, Cohen SR (1984) Productivity and memory for newly formed words. J Child Lang 11(3):611–625. https://doi.org/10.1017/S0305000900005985.
Cohen-mimran R (2009) The contribution of language skills to reading fluency: a comparison of two orthographies for Hebrew. J Child Lang 36(3):657–672. https://doi.org/10.1017/S0305000908009148.
Dale AM (1999) Optimal experimental design for event-related fMRI. Hum Brain Mapp 8(2–3):109–114. https://doi.org/10.1002/(SICI)1097-0193(1999)8:2/3 < 109::AID-HBM7 > 3.0.CO;2-W.
Dawson N, Rastle K, Ricketts J (2021) Bridging form and meaning: support from derivational suffixes in word learning. J Res Read 44 (1):27–50. https://doi.org/10.1111/1467-9817.12338.
de Jong PF, van der Leij A (2002) Effects of phonological abilities and linguistic comprehension on the development of reading. Sci Stud Read 6(1):51–77. https://doi.org/10.1207/S1532799XSSR0601_03.
Deacon SH, Kirby JR (2004) Morphological awareness: Just "more phonological"? The roles of morphological and phonological awareness in reading development. Appl Psycholinguist 25 (2):223–238. https://doi.org/10.1017/S0142716404001110.
Dehaene S, Cohen L, Morais J, Kolinsky R (2015) Illiterate to literate: behavioural and cerebral changes induced by reading acquisition. Nat Rev Neurosci 16(4):234–244.
Desai R, Conant LL, Waldron E, Binder JR (2006) fMRI of past tense processing: the effects of phonological complexity and task difficulty. J Cognitive Neurosci 18(2):278–297. https://doi.org/10.1162/jocn.2006.18.2.278.
Deutsch A, Frost R, Forster KI (1998) Verbs and nouns are organized and accessed differently in the mental lexicon: evidence from Hebrew. J Exp Psychol Learn 24(5):1238–1255. https://doi.org/10.1037/0278-7393.24.5.1238.
Deutsch A, Frost R, Pelleg S, Pollatsek A, Rayner K (2003) Early morphological effects in reading: evidence from parafoveal preview benefit in Hebrew. Psychon B Rev 10(2):415–422. https://doi.org/10.3758/BF03196500.
Deutsch A, Frost R, Pollatsek A, Rayner K (2000) Early morphological effects in word recognition in Hebrew: evidence from parafoveal preview benefit. Lang Cognitive Proc 15(4–5):487–506. https://doi.org/10.1080/01690960050119670.
Devlin JT, Jamison HL, Matthews PM, Gonnerman LM (2004) Morphology and the internal structure of words. P Natl Acad Sci USA 101(41):14984–14988.
Duncan LG, Casalis S, Colé P (2009) Early metalinguistic awareness of derivational morphology: observations from a comparison of English and French. Appl Psycholinguist 30(3):405–440. https://doi.org/10.1017/S0142716409090213.
Ehri LC, Nunes SR, Willows DM, Schuster BV, Yaghoub-Zadeh Z, Shanahan T (2001) Phonemic awareness instruction helps children learn to read: evidence from the National Reading Panel's meta-analysis. Read Res Quart 36(3):250–287.
Everts R, Lidzba K, Wilke M, Kiefer C, Mordasini M, Schroth G, Perrig W, Steinlin M (2009) Strengthening of laterality of verbal and visuospatial functions during childhood and adolescence. Hum Brain Mapp 30(2):473–483. https://doi.org/10.1002/hbm.20523.
Friederici AD (2011) The brain basis of language processing: from structure to function. Physiol Rev 91(4):1357–1392. https://doi.org/10.1152/physrev.00006.2011.
Friederici AD, Brauer J, Lohmann G, Rodriguez-Fornells A (2011) Maturation of the language network: from inter- to intrahemispheric connectivities. PLOS ONE 6(6):e20726. https://doi.org/10.1371/journal.pone.0020726.
Frost R (2012) A universal approach to modeling visual word recognition and reading: not only possible, but also inevitable. Behav Brain Sci 35(5):310–329. https://doi.org/10.1017/S0140525X12000635.
Frost R, Forster KI, Deutsch A (1997) What can we learn from the morphology of Hebrew? A masked-priming investigation of morphological representation. J Exp Psychol Learn 23 (4):829–856.
Frost R, Kugler T, Deutsch A, Forster KI (2005) Orthographic structure versus morphological structure: principles of lexical organization in a given language. J Exp Psychol Learn 31 (6):1293–1326. https://doi.org/10.1037/0278-7393.31.6.1293.
Fruchter J, Marantz A (2015) Decomposition, lookup, and recombination: MEG evidence for the Full Decomposition model of complex visual word recognition. Brain Lang 143:81–96. https://doi.org/10.1016/j.bandl.2015.03.001.
Gaillard WD, Sachs BC, Whitnah JR, Ahmad Z, Balsamo LM, Petrella JR, Braniecki SH, McKinney CM, Hunter K, Xu B, Grandin CB (2003) Developmental aspects of language processing: FMRI of verbal fluency in children and adults. Hum Brain Mapp 18 (3):176–185. https://doi.org/10.1002/hbm.10091.
Gogtay N, Giedd JN, Lusk L, Hayashi KM, Greenstein D, Vaituzis AC, Nugent TF, Herman DH, Clasen LS, Toga AW, Rapoport JL, Thompson PM (2004) Dynamic mapping of human cortical development during childhood through early adulthood. P Natl Acad Sci USA 101(21):8174–8179. https://doi.org/10.1073/pnas.0402680101.
Gold BT, Rastle K (2007) Neural correlates of morphological decomposition during visual word recognition. J Cognitive Neurosci 19(12):1983–1993.
Groen MA, Whitehouse AJO, Badcock NA, Bishop DVM (2012) Does cerebral lateralization develop? A study using functional transcranial Doppler ultrasound assessing lateralization for

language production and visuospatial memory. Brain Behav 2 (3):256–269. https://doi.org/10.1002/brb3.56.
Haddad L, Weiss Y, Katzir T, Bitan T (2018) Orthographic transparency enhances morphological segmentation in children reading Hebrew words. Front Psychol 8. https://doi.org/10.3389/fpsyg.2017.02369.
Hakala T, Hultén A, Lehtonen M, Lagus K, Salmelin R (2018) Information properties of morphologically complex words modulate brain activity during word reading. Hum Brain Mapp 39(6):2583–2595. https://doi.org/10.1002/hbm.24025.
Holland SK, Plante E, Weber Byars A, Strawsburg RH, Schmithorst VJ, Ball WS (2001) Normal fMRI brain activation patterns in children performing a verb generation task. Neuroimage 14 (4):837–843. https://doi.org/10.1006/nimg.2001.0875.
Holland SK, Vannest J, Mecoli M, Jacola LM, Tillema J-M, Karunanayaka PR, Schmithorst VJ, Yuan W, Plante E, Byars AW (2007) Functional MRI of language lateralization during development in children. Int J Audiol 46(9):533–551. https://doi.org/10.1080/14992020701448994.
Holloway ID, van Atteveldt N, Blomert L, Ansari D (2015) Orthographic dependency in the neural correlates of reading: evidence from audiovisual integration in English readers. Cereb Cortex 25(6):1544–1553. https://doi.org/10.1093/cercor/bht347.
Ip KI, Hsu LS-J, Arredondo MM, Tardif T, Kovelman I (2017) Brain bases of morphological processing in Chinese-English bilingual children. Developmental Sci 20(5):e12449. https://doi.org/10.1111/desc.12449.
Jessen A, Fleischhauer E, Clahsen H (2017) Morphological encoding in German children's language production: evidence from event-related brain potentials*. J Child Lang 44(2):427–456. https://doi.org/10.1017/S0305000916000118.
Katz, L., & Frost, R. (1992). Chapter 4 The Reading Process is Different for Different Orthographies: The Orthographic Depth Hypothesis. Adv Psychol (Vol. 94, pp. 67–84). Elsevier. https://doi.org/10.1016/S0166-4115(08)62789-2.
Kieffer MJ, Lesaux NK (2012) Direct and indirect roles of morphological awareness in the English reading comprehension of native English, Spanish, Filipino, and Vietnamese speakers. Lang Learn 62(4):1170–1204. https://doi.org/10.1111/j.1467-9922.2012.00722.x.
Kirkici B, Clahsen H (2013) Inflection and derivation in native and non-native language processing: masked priming experiments on Turkish. Biling-Lang Cogn 16(4):776–791. https://doi.org/10.1017/S1366728912000648.
Klimovich-Gray A, Bozic M, Marslen-Wilson WD (2016) Domain-specific and domain-general processing in left Perisylvian cortex: evidence from Russian. J Cognitive Neurosci 29(2):382–397. https://doi.org/10.1162/jocn_a_01047.
Kuo L, Anderson RC (2006) Morphological awareness and learning to read: a cross-language perspective. Educ Psychol 41 (3):161–180. https://doi.org/10.1207/s15326985ep4103_3.
Lázaro M, García L, Burani C (2015) How orthographic transparency affects morphological processing in young readers with and without reading disability. Scand J Psychol 56(5):498–507. https://doi.org/10.1111/sjop.12213.
Lehtonen M, Vorobyev VA, Hugdahl K, Tuokkola T, Laine M (2006) Neural correlates of morphological decomposition in a morphologically rich language: an fMRI study. Brain Lang 98 (2):182–193. https://doi.org/10.1016/j.bandl.2006.04.011.
Liu L, Tao R, Wang W, You W, Peng D, Booth JR (2013) Chinese dyslexics show neural differences in morphological processing. Dev Cogn Neuros-Neth 6(Supplement C):40–50. https://doi.org/10.1016/j.dcn.2013.06.004.
Mahony D, Singson M, Mann V (2000) Reading ability and sensitivity to morphological relations. Read Writ 12(3):191–218. https://doi.org/10.1023/A:1008136012492.
Maldjian JA, Laurienti PJ, Kraft RA, Burdette JH (2003) An automated method for neuroanatomic and cytoarchitectonic atlas-based interrogation of fMRI data sets. Neuroimage 19(3):1233–1239. https://doi.org/10.1016/S1053-8119(03)00169-1.
Marangolo P, Piras F, Galati G, Burani C (2006) Functional anatomy of derivational morphology. Cortex 42(8):1093–1106. https://doi.org/10.1016/S0010-9452(08)70221-1.
Matthews PH (1991) Morphology. Cambridge: Cambridge University Press.
McBride-Chang C, Shu H, Zhou A, Wat CP, Wagner RK (2003) Morphological awareness uniquely predicts young children's Chinese character recognition. J Educ Psychol 95(4):743–751. https://doi.org/10.1037/0022-0663.95.4.743.
Mcbride-chang C, Tardif T, Cho J-R, Shu H, Fletcher P, Stokes SF, Wong A, Leung K (2008) What's in a word? Morphological awareness and vocabulary knowledge in three languages. Appl Psycholinguist 29(3):437–462. https://doi.org/10.1017/S014271640808020X.
Meinzer M, Lahiri A, Flaisch T, Hannemann R, Eulitz C (2009) Opaque for the reader but transparent for the brain: neural signatures of morphological complexity. Neuropsychologia 47(8–9):1964–1971. https://doi.org/10.1016/j.neuropsychologia.2009.03.008.
Nagy WE, Carlisle JF, Goodwin AP (2014) Morphological knowledge and literacy acquisition. J Learn Disabilities 47(1):3–12. https://doi.org/10.1177/0022219413509967.
Neophytou K, Manouilidou C, Stockall L, Marantz A (2018) Syntactic and semantic restrictions on morphological recomposition: MEG evidence from Greek. Brain Lang 183:11–20. https://doi.org/10.1016/j.bandl.2018.05.003.
Nevat M, Ullman MT, Eviatar Z, Bitan T (2017) The neural bases of the learning and generalization of morphological inflection. Neuropsychologia 98:139–155. https://doi.org/10.1016/j.neuropsychologia.2016.08.026.
Olulade OA, Seydell-Greenwald A, Chambers CE, Turkeltaub PE, Dromerick AW, Berl MM, Gaillard WD, Newport EL (2020) The neural basis of language development: changes in lateralization over age. P Natl Acad Sci USA 117(38):23477–23483. https://doi.org/10.1073/pnas.1905590117.
Patterson K, Nestor PJ, Rogers TT (2007) Where do you know what you know? The representation of semantic knowledge in the human brain. Nat Rev Neurosci 8(12):976–987. https://doi.org/10.1038/nrn2277.
Perfetti C, Cao F, Booth J (2013) Specialization and universals in the development of reading skill: how Chinese research informs a universal science of reading. Sci Stud Read 17(1):5–21. https://doi.org/10.1080/10888438.2012.689786.
Pliatsikas C, Wheeldon L, Lahiri A, Hansen PC (2014) Processing of zero-derived words in English: an fMRI investigation. Neuropsychologia 53:47–53. https://doi.org/10.1016/j.neuropsychologia.2013.11.003.
Pugh KR, Landi N, Preston JL, Mencl WE, Austin AC, Sibley D, Fulbright RK, Seidenberg MS, Grigorenko EL, Constable RT, Molfese P, Frost SJ (2013) The relationship between phonological and auditory processing and brain organization in beginning readers. Brain Lang 125(2):173–183. https://doi.org/10.1016/j.bandl.2012.04.004.
Ralph MAL, Jefferies E, Patterson K, Rogers TT (2017) The neural and computational bases of semantic cognition. Nat Rev Neurosci 18(1):42–55. https://doi.org/10.1038/nrn.2016.150.
Rastle K (2019) The place of morphology in learning to read in English. Cortex 116:45–54. https://doi.org/10.1016/j.cortex.2018.02.008.
Rastle K, Davis MH (2008) Morphological decomposition based on the analysis of orthography. Lang Cognitive Proc 23(7–8):942–971. https://doi.org/10.1080/01690960802069730.
Ravid D, Malenky A (2001) Awareness of linear and nonlinear morphology in Hebrew: a developmental study. First Lang 21 (61):25–56.
Ravid D, Schiff R (2006) Roots and patterns in Hebrew language development: evidence from written morphological analogies. Read Writ 19(8):789–818. https://doi.org/10.1007/s11145-006-9004-3.

Ravid D, Tolchinsky L (2002) Developing linguistic literacy: a comprehensive model. J Child Lang 29(2):417–447. https://doi.org/10.1017/S0305000902005111.
Ressel V, Wilke M, Lidzba K, Lutzenberger W, Krägeloh-Mann I (2008) Increases in language lateralization in normal children as observed using magnetoencephalography. Brain Lang 106 (3):167–176. https://doi.org/10.1016/j.bandl.2008.01.004.
Rispens JE, McBride-Chang C, Reitsma P (2008) Morphological awareness and early and advanced word recognition and spelling in Dutch. Read Writ 21(6):587–607. https://doi.org/10.1007/s11145-007-9077-7.
Rorden C, Karnath H-O, Bonilha L, et al. (2007) Improving Lesion-Symptom Mapping. J Cognitive Neurosci 19(7).
Sahin NT, Pinker S, Halgren E (2006) Abstract grammatical processing of nouns and verbs in Broca's area: evidence from FMRI. Cortex 42(4):540–562. https://doi.org/10.1016/S0010-9452(08)70394-0.
Shany M, Bar-On A, Katzir T (2012) Reading different orthographic structures in the shallow-pointed Hebrew script: a cross-grade study in elementary school. Read Writ 25(6):1217–1238. https://doi.org/10.1007/s11145-011-9314-y.
Shany M, Lachman D, Shalem Z, Bahat A, Zeiger T (2006) Alef-Taf, Evaluation system for the diagnosis of disability in the reading and writing process according to national norms. Holon: Yesod Publishing.(Hebrew).
Share DL, Bar-On A (2017) Learning to read a semitic abjad: the triplex model of Hebrew reading development. J Learn Disabil. https://doi.org/10.1177/0022219417718198.
Shechter A, Lipka O, Katzir T (2018) Predictive models of word reading fluency in Hebrew. Front Psychol 9. https://doi.org/10.3389/fpsyg.2018.01882.
Singson M, Mahony D, Mann V (2000) The relation between reading ability and morphological skills: evidence from derivational suffixes. Read Writ 12(3):219–252. https://doi.org/10.1023/A:1008196330239.
Smolka E, Gondan M, Rösler F (2015) Take a stand on understanding: electrophysiological evidence for stem access in German complex verbs. Front Hum Neurosc I:9. https://doi.org/10.3389/fnhum.2015.00062.
Solomyak O, Marantz A (2009) Evidence for early morphological decomposition in visual word recognition. J Cognitive Neurosci 22(9):2042–2057. https://doi.org/10.1162/jocn.2009.21296.
Solomyak O, Marantz A (2010) Evidence for early morphological decomposition in visual word recognition. J Cognitive Neurosci 22 (9):2042–2057. https://doi.org/10.1162/jocn.2009.21296.
Sparks E, Deacon SH (2015) Morphological awareness and vocabulary acquisition: a longitudinal examination of their relationship in English-speaking children. Appl Psycholinguist 36 (2):299–321. https://doi.org/10.1017/S0142716413000246.
Szaflarski JP, Holland SK, Schmithorst VJ, Byars AW (2006) FMRI study of language lateralization in children and adults. Hum Brain Mapp 27(3):202–212. https://doi.org/10.1002/hbm.20177.
Taft M (1979) Recognition of affixed words and the word frequency effect. Mem Cognition 7(4):263–272. https://doi.org/10.3758/BF03197599.
Taft M (2004) Morphological decomposition and the reverse base frequency effect. Q J Exp Psychol-A 57(4):745–765. https://doi.org/10.1080/02724980343000477.
Taft M, Forster KI (1975) Lexical storage and retrieval of prefixed words. J Verb Learn Verb Be 14(6):638–647. https://doi.org/10.1016/S0022-5371(75)80051-X.
Traficante D, Marelli M, Luzzatti C (2018) Effects of reading proficiency and of base and whole-word frequency on reading noun- and verb-derived words: an eye-tracking study in italian primary school children. Front Psychol 9:2335. https://doi.org/10.3389/fpsyg.2018.02335.
Traficante D, Marcolini S, Luci A, Zoccolotti P, Burani C (2011) How do roots and suffixes influence reading of pseudowords: a study of young Italian readers with and without dyslexia. Lang Cognitive Proc 26(4–6):777–793. https://doi.org/10.1080/01690965.2010.496553.
Turkeltaub PE, Gareau L, Flowers DL, Zeffiro TA, Eden GF (2003) Development of neural mechanisms for reading. Nat Neurosci 6 (7):767–773. https://doi.org/10.1038/nn1065.
Tyler A, Nagy W (1989) The acquisition of English derivational morphology. J Mem Lang 28(6):649–667. https://doi.org/10.1016/0749-596X(89)90002-8.
Tyler LK, Bright P, Fletcher P, Stamatakis EA (2004) Neural processing of nouns and verbs: the role of inflectional morphology. Neuropsychologia 42(4):512–523. https://doi.org/10.1016/j.neuropsychologia.2003.10.001.
Tyler LK, Stamatakis EA, Post B, Randall B, Marslen-Wilson W (2005) Temporal and frontal systems in speech comprehension: an fMRI study of past tense processing. Neuropsychologia 43 (13):1963–1974. https://doi.org/10.1016/j.neuropsychologia.2005.03.008.
Tzourio-Mazoyer N, Landeau B, Papathanassiou D, Crivello F, Etard O, Delcroix N, Mazoyer B, Joliot M (2002) Automated anatomical labeling of activations in SPM using a macroscopic anatomical parcellation of the MNI MRI single-subject brain. Neuroimage 15 (1):273–289. https://doi.org/10.1006/nimg.2001.0978.
Vaknin-Nusbaum V, Miller P (2011) The importance of vowel diacritics for the temporary retention of high and low frequency Hebrew words of varying syllabic length. Mem Cognition 39 (3):516–526. https://doi.org/10.3758/s13421-010-0026-3.
Vaknin-Nusbaum V, Sarid M, Raveh M, Nevo E (2016a) The contribution of morphological awareness to reading comprehension in early stages of reading. Read Writ 29 (9):1915–1934. https://doi.org/10.1007/s11145-016-9658-4.
Vaknin-Nusbaum V, Sarid M, Shimron J (2016b) Morphological awareness and reading in second and fifth grade: evidence from Hebrew. Read Writ 29(2):229–244. https://doi.org/10.1007/s11145-015-9587-7.
Vannest J, Newport EL, Newman AJ, Bavelier D (2011) Interplay between morphology and frequency in lexical access: the case of the base frequency effect. Brain Res 1373:144–159. https://doi.org/10.1016/j.brainres.2010.12.022.
Visser M, Jefferies E, Lambon Ralph MA (2009) Semantic processing in the anterior temporal lobes: a meta-analysis of the functional neuroimaging literature. J Cognitive Neurosci 22(6):1083–1094. https://doi.org/10.1162/jocn.2009.21309.
Whiting C, Shtyrov Y, Marslen-Wilson W (2014) Real-time functional architecture of visual word recognition. J Cognitive Neurosci 27 (2):246–265. https://doi.org/10.1162/jocn_a_00699.
Wood AG, Harvey AS, Wellard RM, Abbott DF, Anderson V, Kean M, Saling MM, Jackson GD (2004) Language cortex activation in normal children. Neurology 63(6):1035–1044.
Yablonski M, Polat U, Bonneh YS, Ben-Shachar M (2017) Microsaccades are sensitive to word structure: a novel approach to study language processing. Sci Rep 7(1):3999. https://doi.org/10.1038/s41598-017-04391-4.
Yablonski M, Rastle K, Taylor JSH, Ben-Shachar M (2019) Structural properties of the ventral reading pathways are associated with morphological processing in adult English readers. Cortex 116:268–285. https://doi.org/10.1016/j.cortex.2018.06.011.
Ziegler JC, Goswami U (2005) Reading acquisition, developmental dyslexia, and skilled reading across languages: a psycholinguistic grain size theory. Psychol Bull 131(1):3–29. https://doi.org/10.1037/0033-2909.131.1.3.

*(Received 24 July 2021, Accepted 18 December 2021)*
*(Available online 11 January 2022)*