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ORIGINAL ARTICLE

Linear and nonlinear processing of Hebrew templatic words: the role of metalinguistic awareness

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Abstract
While universal linguistic theories advocate linear processing of words across languages, psycholinguistic research of Semitic templatic words supports the nonlinear processing into the root and template, mainly due to semantic specifications related to the root and the morphological awareness needed in the tasks. The present study examined whether the root and template affect the word processing of Hebrew native speakers due to metalinguistic awareness regardless of semantics. We designed an auditory rhyme judgment task, a phonological awareness test that requires linear processing and reduces semantics. The task included Hebrew CVCVC templatic word pairs comprising varying root and template phonemes, transposed-phoneme roots emphasizing phonological cooccurrence restrictions, and identical phoneme roots accentuating lexical-syntactic information pronounced in the vocalic melody templates. Findings revealed low accuracy rates in rhyming pairs, particularly those with accentuated linguistic information, indicating distraction from linear processing. However, the accuracy distributions among participants and between and within the stimulus types showed that linear processing also occurred. These results suggest that both linear and nonlinear processing modes are accessible to native Hebrew speakers. The study aligns with models of the mental lexicon proposing dynamic language processing influenced by both linguistic and non-linguistic factors, highlighting the idiosyncratic nature of word processing strategies.

Keywords: Hebrew templatic words; linear processing; mental lexicon; metalinguistic awareness; nonlinear processing; rhyme judgment task

Introduction

Semitic languages feature templatic words that are a combination of a consonantal root and a vocalic template (sometimes with additional consonants); both are discontinuous morphemes and cannot be pronounced independently of each other (Schwarzwald, 2019). The root conveys the semantic core meaning(s) while the template contributes a general grammatical meaning, like lexical (e.g., parts of speech, verbal patterns) and semantical categories (e.g., instruments, diseases, professions). For instance, the words *xazar* "returned," *xizur* "courting," *mixzur* "recycling," *hexzer* "refund/return," and *xazara* "rehearsal/returning" result from combining the root *xzr* (semantic core: redo) with the templates *-a-a-*, *-i-u-*, *mi–u-*, *he–e-*, *-a-a-a*, respectively, yielding different degrees of semantic transparency.

Traditional Semitic grammar posits a nonlinear process (aka root-template mechanism), where the root and template are interwoven (Arad, 2005; Ephratt, 1997; Shimron, 2003), forming stem words—the core part of a word to which affixes can be added (e.g., in English, "like" is the stem word of dislike, unlike, likely, likelihood, among others), premising the root autonomous status in the mental lexicon. Psycholinguistic experimental studies support the representation of the root in the mental lexicon and, therefore, nonlinear processing (Bentin & Frost,2013; Deutsch et al., 1998; Feldman & Bentin, 1994; Feldman et al., 1995; Frost et al., 1997; Gafni et al., 2019; Yablonski & Ben-Shachar, 2016). Semantics played a crucial role in these studies due to the focus on the degrees of semantic transparency of the root and the tasks' requirements. Conversely, linguistic-universal theories (Bat-El, 1994, 2003; Benmamoun, 2003; Bolozky, 2003; Laks, 2007, 2013; Heath, 2003) view the root merely as phonological elements within stem words that follow universal grammatical mechanisms of word formation. Hence, the linguistic-universal approach denies the root independent representation, advocating for a stem-word-based lexicon (Bat-El, 2017; Aronoff, 1976, 1994), where word formation across languages results from grammatical rules based on words or stem words. Also, computational models like Optimality Theory (Ussishkin, 2000) and Bayesian decision frameworks (Norris & McQueen, 2008) propose unified processing mechanisms across languages.

The ensuing controversy around the autonomy of the root in the mental lexicon is due to a modular view of language processing. In this view, the lexicon is a repository for raw material (stem words), postulating the principle of economy, i.e., the assumption that each piece of information is represented only once, while grammar rules apply in other linguistic components like syntax, phonology, etc. (for review, see Lehmann, 2019). This renders the processing of templatic words binary: nonlinear if the root has an independent morphemic representation or linear if not. However, alternative models reject the principle of economy, embracing instead flexibility and adaptability to account for the dynamic nature of language processing and storage in the human mind. The Heteromorphic Distributed Lexicon model (Wray, 2002) emphasizes the nature of linguistic cognition and the interaction of various lexicons that serve different linguistic functions. It allows for a more flexible representation of linguistic units, which gain entry to the lexicon not based on structural principles but expediency—individuals store things they have a use for. Additionally, MacWhinney's (2005, 2013) Unified model considers language processing as a result of neural circuits entrenched by usage. These models may render linear and nonlinear processing modes a strategy.

Berman (2012) proposes that both root-based and word-based approaches play a crucial role in the mental lexicon, and their impact on processing is also influenced by non-linguistic factors like processing type (word formation or perception), modality (written or spoken), setting (in context or in isolation), and literacy, which impacts linguistic knowledge. Thus, different processing modes, i.e., linear and nonlinear, may result not only from the linguistic properties of the root or the template but also from the cognitive skills associated with non-linguistic factors, used in real-life use of the language and translated into methodology in experimental studies. Reviewing the linguistic information concerning the root and template and the non-linguistic parameters used in the psycholinguistics experimental studies, in the present study, we designed an experiment in which nonlinear and linear processing compete. Specifically, this research examines whether nonlinear processing occurs in templatic words based on grammatical information of the root and template in a context-less setting using an auditory phonological awareness task that requires word decomposition through linear processing.

Templatic morphology in Hebrew

Most Hebrew vocabulary is characterized by templatic words, which spread across the nominal and verbal systems, encompassing all parts of speech (Shimron, 2003). The templatic words are composed of intertwined roots providing the core meaning(s) and templates providing grammatical information. A templatic word is the ensemble of both sources of information. Due to possible, however not obligatory, multiple meanings of the root or the template, both auditory and written words may have more than a single meaning, usually resolved in context. For example, *xaʃav* חשב "he thought"/ "accountant" is composed of the root *xʃv* חשב (semantic core: think/ calculate) and the template *-a-a-* (Verb in the Past tense of binyan Pa'al, 3rd pr.sg.ms., and Noun denoting profession sg.ms.; historically, different templates).

The semantic core conveyed by the root applied in the different templates creates a spectrum of semantic relations and transparency degrees: from transparent (*hizmin* הזמין "he invited," *hazmana* הזמנה "invitation") to opaque (*zarak* זרק "he threw," *mazrek* מזרק "syringe") to even opposite (*ʃereʃ* שירש "he uprooted," *hiʃriʃ* השריש "he implanted," both from the root *ʃrʃ* שרש "root"), and no relation when the root has more than one semantic core (e.g., *xalat* חלט "he brewed (tea/herbs)," *xilet* חילט "he impounded," *hixlit* החליט "he decided," *muxlat* מוחלט "completely"). Interestingly, not all roots intertwine across all templates, leaving many "gaps" that may either serve as reserves to be filled in once the need arises or be blocked for various linguistic reasons. These potential roots are used in experiments as a basis for nonwords with real roots, where the focus is on the language's grammatical rules or, in other words, metalinguistic awareness.

Root and phonological cooccurrence restrictions

Hebrew roots predominantly feature three consonantal phonemes (displayed as $C_1C_2C_3$), while the less common four consonantal phoneme roots exhibit a higher rate of new word generation. A few roots have five (e.g., *ʃmrtf*, *snxrn*, *tlgrf*) or six (e.g., *trnsfr*, *strptz*, *kmplks*)) consonantal phonemes (Shimron, 2003)). Roots are divided into two sets: full (aka complete or strong), in which all the consonants

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(phonemes or letters) are transparent, and weak (aka ill or defective), in which one consonant (sound or letter) is omitted in part of the root realization scope.

Greenberg (1950), who investigated the phonological cooccurrence restrictions of the Semitic roots, reported that in 3-consonantal roots ($C_1C_2C_3$), C_1C_2 and C_2C_3 could not be homorganic, i.e., sharing the same place of articulation, mainly related to phonemes that differ only by the phonological feature voice (vibration of the vocal cords) (e.g., /p,b/, /d,t/, /k,g/, /f,v/, /s,z/). He also reported that Semitic roots obey the obligatory counter principle (OCP), i.e., identical phonemes cannot appear in a row, although he mentioned one exception (*ddh*) in Hebrew.

Template and lexical-syntactic information

The templates, richer in the nominal system, are vocalic patterns, without (e.g., vocalic melody *-a-a-*) or with consonants (e.g., ma–e- $maC_1C_2eC_3$), denoting a general meaning relating to grammatical information. In the nominal system, the templates (*mishkalim*) denote lexical information (parts of speech) and semantic information, such as places (*mi–a-a, mispara* מספרה "barbershop"*; mi–a-, mitbax* מטבח "kitchen"), instruments (*ma–e-, mazleg מזלג* "fork"), diseases *(-a-e-et*, *kalevet* כלבת "rabies"), characteristics, and professions *(-a-a-, zamar* זמר "singer"*; -a–an*, *paxdan* פחדן "coward"), etc. In the verbal system, the templates are patterns of *binyanim* (singular binyan) denoting syntactic tense, voice, mood, and linguistic constructions that describe different ways in which actions and relationships are expressed in a language, such as reflexive, reciprocal, causative (Cohen-Weidenfeld, 2000). Thus, the binyanim convey information related to the predicate's (verb) argument structure (how many arguments are involved in the event the verb conveys), thematic grid (what kind of arguments, e.g., doer, receiver, cause, location, goal, source, experiencer, instrument), and subcategorization (arguments of the verb's compliments).

Modern Hebrew comprises seven binyanim: Pa'al, Pi'el, Hif'il, Hitpa'el, Huf'al, Pu'al, and Nif'al. Generally, each binyan hosts verbs associated with a dominant construction: one reflexive/reciprocal/inchoative structure (Hitpa'el), three active structures (Hif'il (causative), Pi'el (intensive), Pa'al (simple), and three mirror passive structures (Huf'al, Pu'al, and Nif'al (also active, reflexive), respectively) (Appendix, Figure A1). Nevertheless, the distribution of constructions per binyan is not a one-to-one relationship (Cohen-Weidenfeld, 2000). For instance, Pi'el is intensive (*hilex* הילך "he walked back and forth") but also simple (*bikeʃ* ביקש "he asked") and causative (*limed* לימד "he taught") (for examples of all the binyanim, see Appendix, Table A1). Moreover, having three binyanim for active voice may lead to duplications (Cohen-Weidenfeld, 2000): a verb in Pa'al (*ragaz* רגז) and Hitpa'el (*hitrarez* התרגז) bearing the same meaning "got angry" (for examples of all the binyanim, see Appendix, Table A2). Remarkably, the syntactic relationships of the active-passive derivation between Pi'el-Pu'al (e.g., *limed-lumad* "he taught-it was taught") and Hif'il-Hufa'l (e.g., *hizmin-huzman* "he invited-he was invited") are stringent and predictable, and therefore transparent, with the *-u-a-* template recognized with the passive voice. Other relations are less systematic. Evidence from non-healthy populations associates this syntactic information of binyanim with the lexicon. Damage to the binyanim relations was shown among Semitic language

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speakers suffering from aphasia (Biran & Friedmann, 2012; Friedmann et al., 2013; Prunet et al., 2000), providing evidence for a lexical-syntactic component, separated from the semantic component and from the phonological component that appears in the lexical retrieval model (Biran & Friedmann, 2012; Friedmann et al., 2013).

Moreover, an active lexicon approach that views the lexicon as a factory instead of a repository claims for a lexicon-syntax parameter that allows operations to apply either in the lexicon or the syntax, or one after the other, respectively (Horvath & Siloni, 2005; Siloni, 2003). Specifically, in Semitic languages, derivations in the binyanim may transpire in two loci: the syntax and the lexicon, where morpho-phonological operations can apply (Laks, 2007). The difference between the loci amounts to the number of outputs involved: lexical operations, which involve several operations with more than one possible output (bi-directionality) accessible to further operations, and syntactical operations acting in a one-to-one relationship (unidirectionality), which involve thematic relations, such as active-passive in the verbal system in Modern Hebrew and Modern Standard Arabic, and require only one operation in which the vocalic pattern changes (Laks, 2013).

Psycholinguistic studies supporting nonlinear processing

Psycholinguistic studies investigating the role of the root and template in Semitic languages provide evidence of the psychological reality of the root and templates required for lexical access in the mental lexicon and consequently argue for language-specific nonlinear processing. Preschool children aged 3–5 have demonstrated the ability to coin novel nouns from their related verbs (Clark & Berman, 1984), including active-passive relations (Berman, 1994). Experimental studies performed by both Hebrew speakers (Berman, 2003) and Palestinian Arabic speakers (Ravid, 2003) showed that children as young as preschool relate actively and passively to both the structural and semantic basis for new word formation performing morphological awareness tasks. While word roots are recognized at an early age, patterns develop across school-age cohorts (Ravid & Malenky, 2001).

Among adults, morphological priming effects were reported in visual experiments in the Hebrew verbal system (Deutsch et al., 1998) but not in the nominal one (Frost et al., 1997). However, effects were later reported in both verbal and nominal domains (Yablonski & Ben-Shachar, 2016), with real roots in nonwords resulting in lower accuracy and longer response time than nonwords with non-real roots or real words. Priming effects were also found in cross-modality experiments (visual and auditory), showing semantic-dependent priming effects in Arabic (Marslen-Wilson, 1994) or semantic-increasing effects in Hebrew (Gafni et al., 2019; Frost et al., 2000a). Priming effects were also shown in the transposed consonants of the root condition (letters in a different order) in visual experiments showing deteriorated performance in Hebrew compared to English (Velan & Frost, 2007) and in Hebrew words of Semitic vs. non-Semitic origin (Velan & Frost, 2011) and inhibition in recognizing real roots, but not non-real roots, after being exposed to a transposed version of these roots (Velan & Frost, 2009). Priming effects were also shown in auditory repetition tasks (Oganyan et al., 2019).

Further studies have espoused the role of the consonantal structure of the root (Berman, 2003; Frost et al., 2000b) or the CV-skeleton of the template

(Boodela & Marslen-Willson, 2004), which may moderate, but not neutralize, the semantic parameter of these morphemes (Frost et al., 2000a), still endorsing the nonlinear processing and the psychological reality of the root in the mental lexicon. Notably, the CV-skeleton is considered an essential component in prosodic morphology, also supporting the language-specific nonlinear processing of templatic words (McCarthy, 1981).

Methodological caveats

The psycholinguistic experimental studies include varied methods, modalities, tasks, conditions, and templatic word types, flanking morphological processing from diverse angles, reinforcing the psychological reality of the root and template morphemes and nonlinear processing. However, these studies' findings may be influenced by methodological factors. First, the root phonological cooccurrence restrictions are overlooked in many of these studies. The nonword condition, which is a manifestation of "gaps" in templatic words, is problematic since no attention was given to the difference between gaps blocked for phonological/phonotactic reasons and gaps that are potential reserves. Facilitating effects of the root and template in the naming or lexical decision tasks based on nonword conditions may be affected by phonological rules and phonotactic restrictions in addition to or instead of semantics and internal nonlinear morphological structure. The importance of the phonological cooccurrence restrictions is also related to the transposed root condition (Velan & Frost, 2007; 2009), making it unclear if the deteriorated performance was due to the semantic status of the root in the lexicon or awareness of phonological restrictions, as it was wrongly assumed that each root consonant could appear in every position. In Arabic, which shares similar root phonological cooccurrence restrictions (Greenberg, 1950), a priming effect was shown when transposed letters were of the root and the template but not within the root letters, suggesting limited tolerance to noise in the order of the root consonants (Perea & Carreiras, 2010). By contrast, in French, a concatenative language, letter transposition showed a priming effect in seven-letter words irrespective of letter position and in inner letter transposition in five-letter words (Schoonbaert & Grainger, 2004). The difference between Semitic and non-Semitic language concerning the impact of phoneme order within words or roots emphasizes the need to consider the root phonological cooccurrence restrictions when investigating the root morpheme.

Furthermore, the visual modality coupled with the often-used nonword condition poses two methodological issues. The first relates to the Hebrew grapheme-phoneme discrepancy, considering that the written or printed lexical representations are coded and accessed phonologically (Lukatela & Turvey, 1991). Due to the evolution of the Hebrew language, in Modern Hebrew, grapheme-phoneme correspondence does not have a one-to-one relation; one phoneme may be written by two different letters irrespectively of the other phonemes (vowels or consonants) next to it. Six of the phonemes are represented each by two graphemes (/x/ by כ, ח; /k/ by ק, כ ; /t/ by ת, ט ; /v/ by ב, ו ; /s/ by ס, ש ; and /ʔ/ by א, ע and for some speakers also by ה), and the /f/ and /p/ phonemes both correspond to the same grapheme פ (for a full list of the grapheme-phoneme correspondence, see Appendix B,

Table B). Hence, if the root has an independent representation in the lexicon, the 3-consonantal root may pertain to three different representations: graphemic, phonemic, or meaning. This yields an ununiformed quantity of entries. Due to the grapheme-phoneme discrepancy, the number of phonemic root representations is not equal to those of the graphemic roots, and since one root may have more than one meaning, the number of roots by meaning entries is not equal to the phonemic or the graphemic root representations. Thus, the discrepancy between the phonemic and graphemic root representations in visual experiments might encumber the organization of and access to the roots in the mental lexicon and also pave more than one accessible path. Moreover, visual experiments of printed nonwords cannot be detached from the lack of written vowels in the Hebrew orthography (abjad), leaving the vowels to be inferred by the reader with the aid of four auxiliary letters that reduce vowel possibilities and context. Thus, the desired deciphering is obtained by the interaction of phonology, orthography, and semantics (Ravid, 1996). Therefore, nonwords without context may go through different decomposition ways.

Lastly, the experiments in the studies encompass varied templates without precision between and within templates (e.g., maCCeCa, maCCaCa, miCCaCa, miCCaCat, taCCuCa, taCCeCa, taCCiC, miCCoC, maCCeC, aCCaCa, CaCCan, CaCCut, CaCCanut, CCiCut, CCaCa, CoCeCet, CoCeC, CCuCa, CCiCa, CuCCa (from Frost et al., 1997, Appendix B)), some of which are argued to involve linear affixation (e.g., CaCCan, CaCCut, CaCCanut (Schwarzwald, 2019)), so results might have been balanced out. The importance of discerning templates does not amount to differences between nominal and verbal templates or templates with or without affixation but also for templates within each of these groups. For example, a study distinguishing Pa'al from Pi'el (Farhy et al., 2018) within the verbal patterns found that the root priming effect appeared selectively in Pi'el but not in Pa'al. That is, Pi'el was processed nonlinearly and Pa'al linearly, suggesting that both linear and nonlinear processing modes transpire in the verbal system regardless of semantics, with the binyanim perceived as abstract morphological categories.

The present study

Evidence for nonlinear processing is linked to linguistic factors associated with semantic specifications related to transparent roots (full) when decomposing words and the derivational function of templates when forming words. The non-linguistic factors that might affect the nonlinear processing are associated with the tasks addressing morphological awareness using the visual modality in context. This leads to the question as to whether nonlinear processing of templatic words may occur without meeting those linguistic and non-linguistic parameters.

The present study explores if nonlinear processing of Hebrew templatic words may occur under the following conditions: (i) employing a word decomposition task devoid of morphological awareness, (ii) the root is not associated with semantics but rather with phonological grammatical regularities, and (iii) the template conveys lexical-syntactical information. To this end, we used a phonological awareness task, the rhyme judgment task (say if two words in a pair rhyme), that requires linear processing to be successfully fulfilled. Phonological awareness is the ability to understand that words are a series of sounds (phonemes) apart from their meanings (Lewkowicz, 1980). This ability requires linear processing measured by the grain size: whole word, syllable, sub-syllabic units (body-coda/onset-rime), and phonemes (Goswami, 2002). Phonological awareness battery tests (PhAB, QPAS, PALS; PALPA, PAT-2:NU) are used across languages to assess language development or impairment (Armon-Lotem & Chiat, 2012; Claessen et al., 2013; Ramus et al., 2013; Zourou et al., 2010). Notably, phonological awareness is a universal construct (Branum-Martin et al., 2015) and a primary predictor of reading (Bentin & Leshem, 1993; Perfetti et al., 1987; Verhoeven et al., 2016).

The rhyme judgment task is a validated tool for phonological awareness tests, showing ceiling effects at an age as early as six (Lewkowicz, 1980; Peters, 1985), with errors shown in non-rhyming pairs (Lenel & Cantor, 1981). Recognizing rhymes requires identifying identical final words' vowel and consonant phonemes, which is successfully performed when breaking the words down linearly into syllables, sub-syllabic units, and, in certain cases, also phonemes (Lewkowicz, 1980), for example, CVCVC > CV. CVC > CV. C. VC (or CV.C) > C. V. C. V. C. The final VC phonemes in the coda are next to each other. In contrast, nonlinear processing means disentangling the intertwined root and template to CCC and VV morphemes and then discriminating and comparing phonemes while the final V and C are in two separate units. Thus, nonlinear processing is not beneficial in this task, as it is cumbersome, costlier, and, therefore, prone to errors. Moreover, linear processing is easier than nonlinear processing (Nathaniel et al., 2023).

To avoid visual biased results, we used audial stimuli. The audial modality also compels linear processing as all phonemes, consonants, and vowels are provided and forcibly heard sequentially. For transparency, we used only full roots and one type of templatic word, the CVCVC, except for controls. All stimuli were real words. We handled the root and template with linguistic precision, focusing on grammatical regularities irrespective of semantics. The linguistic information of the root without semantics amounted to the phonological cooccurrence restrictions. Examining the distribution of transposed full 3-consonantal phoneme roots shows that due to the phonological cooccurrence restrictions, transposed root pairs do not have final phonemes (word's coda) contrasted only in voice or strident features. Therefore, it is hypothesized that the limited realization of transposed roots accentuates the application of root phonological restrictions. The linguistic information of the template relates to the lexical-syntactic information pronounced in the relations between binyanim in the verbal system. Hence, providing this task with auditory Hebrew templatic words, especially with emphasized linguistic features of the root and template, creates a ground where the linear and nonlinear processing modes can compete. Importantly, it enables a minimal context environment, excludes grapheme-phoneme discrepancy, and addresses metalinguistic awareness.

Success in the rhyme judgment task is an indicator of linear processing. In non-rhyming pairs, errors may occur when the codas are distinct by one phonological feature only, such as voice, sonorant, or strident, due to rhyme perception, i.e., they are close enough in sound to be considered a rhyme although they are not identical. Therefore, errors in non-rhyming pairs cannot indicate whether linear or nonlinear processing occurs. However, in rhyming pairs, which share both the vowel and the final consonant(s), errors are not expected. Testing Hebrew native speakers, we anticipated that in such a task, if nonlinear processing is activated because of the root and template morphemes, errors in rhyming pairs would emerge.

Methods

Participants

86 Hebrew native speakers without hearing problems volunteered to participate in the online experiment, 28 of whom were excluded from the sample for not completing the experiment. 58 participants remained (20–82 years, 39 females). Since the experiment was online, to ensure the participants were Hebrew native speakers, they were asked to self-rate their Hebrew level on a 0–10 scale in speech (mean 9.8), reading (mean 9.8), and writing (mean 9.7). The study was approved by the ethics committee of the Faculty of Humanities, Bar-Ilan University, Israel.

Participant information, stimulus lists, data, and analysis scripts for this study can be retrieved from https://osf.io/my9bt/.

Stimuli

The experiment included 198 stimulus pairs consisting of 138 non-rhyming (NR) and 60 rhyming (R) iambic (final stressed syllable) pairs. All words were real words (a few archaic) with valid roots in valid templates, confirmed by the Even Shoshan dictionary (1984) and The Academy of the Hebrew Language site (2022).

The templatic word type investigated was the bi-syllabic CVCVC. The CVCVC CV-skeleton comprises full 3-consonantal roots and vocalic melody templates, allowing many combinations. The CVCVC is pervasive in Hebrew, displayed in all parts of speech, namely, nouns (*sapak* "supplier"), adjectives (*xazak* "strong"), adverbs (*levad* "alone"), and verbs (*lomed* "he learns"; *lamad* "he learned"; *limed* "he taught"; *lumad* " it was taught").

The roots were taken from a 3-consonantal phonemic root pool we created based on the dictionary and site mentioned above. To keep all words auditorily syllable-structure-matched, we excluded the weak roots (including geminate roots, e.g., tss, cll, etc.), and the phonemes /ʔ/ (א), /ʕ/ (ע), /h/ (ה) (e.g., VCVC אבד (*avad*), CVCV גבה (*gava*), CV.VC שאג (*ʃa'ag*), or CVCVVC פותח (*pote'ax*) instead of CVCVC) from the full root pool. To prevent confusion with suffixes, we excluded words with final /*-im*/ and /*-ot*/ (plural morphemes), /*-an*/ (personal characteristics), and /*-on*/ and /*-it*/ (diminutive). Thus, the templatic word pairs were combinations of 0-3 similar phonemes of the consonantal root (CR) and 0-2 similar vowel phonemes of the vocalic melody (VM).

Graphemic representations were not taken into consideration due to the non-univalent relationship between graphemes and phonemes in Hebrew, which may tap into varied graphemic representations as well as varied meanings. For example, two-fifths of the Hebrew roots are homonymous, i.e., the same spelling or pronunciation but different meanings (Schwarzwald, 1976, cited by Berman, 2012), and 20% of the verbs have more than one meaning (Berman, 2012). For the current experiment, 77% of the CVCVC pairs comprise words whose phonemic representation is ambiguous vis-à-vis the graphemic representations, regardless of whether the additional graphemic representations of a word yield nonwords like in *ratan* (רטן "grumbled" or רתן nonword) or real words like in *cavar* (צבר "accumulated" or צוואר "neck"). When the additional graphemic representations are real words, there is no way to tell which graphemic representation is available to the hearer or which meaning. Moreover, in the absence of standardized frequency lists covering spoken and written Israeli Hebrew roots and words (Berman, 2012), which also provide the frequency of polysemous words by all the possible meanings, there was no way to control for frequency. Nonetheless, for the current task, an impact of frequency was not predicted for word decomposition as the target is technical parsing, to isolate and compare the rime (-VC) and phonemes of the words in a pair, all the more so with the experiment focusing on non-semantically linguistic aspects.

The focus was on two stimulus types of CVCVC pairs accentuated by grammatical rules: the transposed consonantal root (TCR) concerning the root and the highlighted vocalic melody (HVM) concerning the template. However, to verify that the results in these two stimulus types are unique in their grammatical information, we used contrast: CVCVC pairs with varying phonemes in the root (Baseline) were used as a baseline with respect to the accentuated pairs TCR and HVM. We also used two stimulus types as control. To show that the Baseline did not differ from other bi-syllabic templatic words that were not accentuated, we used mVCCVC pairs, another bi-syllabic templatic word type that does not possess lexical-syntactic information nor accentuate the phonological cooccurrence restrictions. To show that nonlinear processing is linked to the root and template in bi-syllabic templatic words, we used mono-syllabic CVC pairs, which are linearly processed, as they are not templatic words nor transparent patterns of templatic words.

Importantly, it is the judgments in rhyming versus non-rhyming pairs that confirm the participant's ability to perform the task well and know the difference between rhyme and non-rhyme. It is mainly the judgments within non-rhyming pairs that confirm the ability to discern phonemes. Notably, the number of pairs with contrasting phoneme possibilities (non-rhyming pairs) is greater than the number of pairs with identical phoneme possibilities (rhyming pairs). This creates an imbalanced number of stimuli, with non-rhyming pairs comprising two-thirds of the stimuli pool and rhyming pairs only one-third. This imbalance might create a bias towards a "no" response. To reduce this potential bias, all stimuli were tested in the same experiment session, with stimulus types mixed and presented randomly. 115 CVCVC pairs (38R, 77NR) were divided into three types.

Baseline

A total of 30 pairs (12R, 18NR) are representative of the phonemic variety of the roots and vocalic patterns in CVCVC words. The Baseline pairs include roots ranging from 0 to 2 similar consonantal phonemes (out of 3) and similar vowels (out of 2) between words (see Table 1 for examples). We used this stimulus type as a baseline and reference point for comparison with the bi-syllabic stimuli.

Transposed consonantal root (TCR)

Examining the inventory of transposed roots in the 3-consonantal phonemic root pool showed that transposed root pairs do not have codas contrasted only in voice or strident features. Therefore, we hypothesize that this transposed root stimulus

Table 1. Examples of stimulus types

		R		NR	
		Example	Translation	Example	Translation
1	**Baseline**	*mazal-kaval*	luck-complained/ or bound with a rope	*pagaz-rigeʃ*	shell (munitions)-moved (emotional)
		xomek-xilek	evades-divided	*gamad-ʃamat*	dwarf-dropped
		karaʃ-xaraʃ	coagulated-plowed	*romes-romez*	tramples-implies
2	**Transposed-CR (TCR)**				
	C123–C213	*giʃer-ʃiger*	bridged-launched	–	–
	C123–C132	–	–	*xivet-xitev*	wired-toned a body
	C123–C321	–	–	*xalam-malax*	dreamed-ruled (king)/sailor
	C123–C231	–	–	*zaram-ramaz*	flowed-hinted
	C123–C312	–	–	*ʃamar-raʃam*	kept-registered/register(noun)
	C123–C231-Control			*raxak-xakar*	shunned-explored
	C123–C312-Control			*xakar-raxak*	explored-shunned
3	**Highlighted-VM (HVM)**	*kaʃer-koʃer*	kosher-ties(verb)	*natav-nituv*	router-routing
	Binyanim relations				
	MIX	*dabur-dibur*	hornet-talk(noun)	–	–
	Pa'al-Pi'el	*lomed-limed*	learns-taught	–	–
	Pa'al-Pu'al	*saxak-suxak*	laughed-was played	–	–
	Semantic relatedness				
	non-related	*bocer-bicer*	picked grapes-fortified	–	–
	Related	*ʃamen-ʃimen*	fat(adj)-greased	–	–
4	**CVC**	*gen-ʃen*	gene-tooth	*gil-gir*	age/joy-chalk
5	**mVCCVC**	*mavreg-mazleg*	screwdriver-fork	*mivcar-migdal*	fortress-tower

CR = consonantal root, HVM = Highlighted Vocalic Melody, NR = non-rhyming pairs, R = rhyming pairs, TCR = Transposed Consonantal Root, VM = vocalic melody.

type highlights the cooccurrence restrictions in the roots, pointing at phonological impact. The TCR comprises 56 (8R, 48NR) pairs of words that have identical vocalic melody templates and the same consonantal roots in a different order. It is noteworthy that pairs comprising TCRs have five 3-consonant swaps, which are alternations of the consonantal phonemes in the second word in the pair vis-à-vis the order of the consonantal phonemes in the first word in the pair C123). Table 1 presents examples of the five swaps named after the second word's alternations. Notably, only one swap consists of rhyming pairs, while the others consist of non-rhyming pairs. Since these alternations relate to the syllable and sub-syllabic units, they may affect the linear processing. Hence, the rhyming pair was examined against each non-rhyming pair swap to pinpoint the impact of the phonological cooccurrence restrictions in this research setting. Alternations of phonemes are within syllable (C132; *xivet-xitev* (wired-toned a body)), cross-syllable (C213; *giʃer-ʃiger* (bridged-launched)), cross-word boundaries (C321; *xalam-malax* (dreamed-ruled(king)/sailor)), and both cross-syllable and word boundaries (C231 and C312; *zaram-ramaz* (flowed-hinted) and *ʃamar-raʃam* (kept-registered), respectively). The C231 and C312 swaps are mirror swaps, i.e., the same words in a pair in a different order. To check if having different words (*zaram-ramaz* (flowed/hinted), *ʃamar-raʃam* (kept/registered)) or the same words (*xakar-raxak* (explored-shunned), *raxak-xakar* (shunned-explored)) in mirror swaps makes a difference, we added pairs of the same words for control: C213control and C312control. Collectively, this stimulus type comprises 6 comparisons of the 8R with each 8NR swap.

Highlighted vocalic melody (HVM)

In the verbal system, the CVCVC is realized in the binyan Pa'al in the Present and Past tenses, and in binyanim Pi'el and Pu'al in the Past tense, all in the 3rd pr.sg form (e.g., *lomed* "he learns"; *lamad* "he learned"; *limed* "he taught"; *lumad* " it was taught." respectively). To allow assessment of the influence of the vocalic melody templates only, we kept the roots identical in a pair. Pi'el and Pu'al have predictable active-passive relations (e.g., *niser-nusar* "he sawed-it was sawed"). However, Pa'al and Pi'el do not hold active-passive relations when the same root is applied, whether there is no semantic relatedness (e.g., *saxak -suxak* "laughed-was played") or there is an opaque relatedness (e.g., *gadal-gudal* "grew up/older-was brought up"). Thus, we hypothesized that violating this relation by having pairs of Pi'el or Pu'al with Pa'al (Pi'el-Pa'al; Pu'al-Pa'al) with identical roots would highlight the lexical-syntactic information pronounced in the vocalic melody template. Moreover, combining verbs of Pa'al and Pi'el with identical roots in a pair also accentuates the difference in tense pronounced in the vocalic melody: Present tense (Pa'al) vs. Past tense (Pi'el). These pairs may show no semantic relatedness (e.g., *posel-pisel* "he cancels-he sculptured") or an opaque relatedness (e.g., *ʃomer-ʃimer* "he keeps-he preserved"). Taken together, the lexical-syntactic (linguistic) information pronounced in the vocalic melody templates is accentuated in these mentioned combinations of rhyming pairs when the roots are identical in a pair, reflecting distortions of binyanim relations concerning active-passive and tense. Moreover, comparing these combinations, i.e., semantically vs. non-semantically related, enabled testing the impact of the semantics.

The HVM comprises 29 pairs (18R, 11NR) in which the words have identical consonantal roots (CRs) and different vocalic melody templates (VMs). The non-rhyming pairs consist of pairs denoting tense distinction (present-past) in Pa'al-Pa'al (e.g., *xolem-xalam* "he dreams-he dreamed") and active-passive in Pi'el-Pu'al (*dileg-dulag* "he skipped-it was skipped"), and for control, pairs without binyanim relations, not necessarily verbs, with the same semantic core (e.g., *kitor-katar* "steam-locomative") or without (e.g., *ʃabat-ʃibut* "Sabbath-clone"). Importantly, combinations of non-rhyming pairs of Pa'al and Pi'el that differ in tense and in semantic transparency and of Pi'el-Pu'al that differ in active-passive voice and in semantic transparency do not exist. Due to these limits of the Hebrew language, there are fewer non-rhyming pairs than rhyming pairs in this stimulus type.

The rhyming pairs emphasize the lexical-syntactic information reflected in the relationships between Pa'al and Pi'el/Pu'al. The HVM rhyming pairs include Pa'al-Pi'el (6) pairs that differ by the Present and Past tense, respectively; Pa'al-Pu'al (6) pairs differ by active-passive voice, respectively, and for control, MIX (6) pairs that do not denote relations between the binyanim (see Table 1 for examples). The same rhyming pairs were also divided into semantically related and non-related pairs to examine if the lexical-syntactic information is semantic-dependent by the root (see Table 1 for examples).

Control stimulus types

Mono-syllabic CVC

The CVC type includes 62 pairs (15R, 47NR) comprising all identical and contrasting coda possibilities (see Table 1 for examples). The CVC pairs allow comparing results based on syllable length (mono-syllabic vs. bi-syllabic) and processing mode (linear vs. nonlinear).

Bi-syllabic mVCCVC

The mVCCVC (maCCeC/miCCaC) stimulus type contains 21 noun pairs, 7R and 14NR, denoting tools/instruments and places (see Table 1 for examples). This allows comparing results of non-accentuated pairs (Baseline(CVCVC) vs. mVCCVC) to ascertain the specification of the linguistically accentuated stimuli of the TCR and HVM types.

We recorded the stimuli (in a feminine voice) in a professional studio or a quiet room using the Audacity software. In each pair, the first word starts after 55 ms and the second word after another 300 ms. The pairs slightly varied in volume to aid in keeping the participants' attention. Response time was limited to up to 2 seconds to avoid a nonintuitive decision, as required according to a pre-trial pilot. We randomly divided the stimuli into five blocks, each containing all types, then fully randomized within blocks. The randomized order was similar for all participants.

Procedure

The experiment was performed on a specially designed online testing platform we built at the onset of COVID-19. Participants were asked to perform the task in a quiet room wearing headphones. Participants were instructed to use their computers to

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increase uniformity in testing conditions. After reading the research aim and requirements, the participants passed a hearing test to verify that the computer's speakers worked. They filled in a demographic questionnaire and then were instructed to follow their intuition when judging if a pair rhymes. Before experimenting, they got familiar with the procedure through a practice trial, which could be repeated as much as needed, whose stimuli were not part of the experiment's stimulus list and, therefore, not recorded. No feedback was given to the participants to avoid impacting or interfering with their rhyme judgment. The real experiment began once the participant clicked the start button. A pair was played immediately after a response was issued or after 2 seconds (displayed on a diminishing bar). The question "Does it rhyme?" and Yes and No buttons constantly appeared on the screen in each block. To avoid the practice effect, participants watched a silent 15-sec nature video between blocks, different videos from block to block, however, in a fixed order. To move to the next block, the participant had to press "continue" and "start"; thus, the pause could be longer than 15 sec.

The participants' answers were recorded in the database in their raw values: Yes, No. Then, the answers were converted to Correct (1) or Error (0) according to the following criterion: if both words of a pair have stress-matched identical final syllable's vowel and coda (-VC), the pair is a rhyming pair; otherwise, it is non-rhyming.

Statistical analysis

Since it was an online experiment of binary answers, to rule out malicious participants (pressing Yes/No blindly), we calculated the probability of each participant randomly/blindly answering the experiment question "Does it rhyme?" using the binomial distribution formula $\binom{m}{k} p^k (1-p)^{m-k}$ (for an explanation of the formula, see Appendix C). Results indicate that each participant had a probability of less than 0.05 (ranging from 0.02611312 to 2.7312E-48; for all the reuslts, see Appendix C, Table C) of achieving their accuracy. Hence, none of the results around 50% indicate by chance accuracy.

We used Student's *t*-tests and multilevel modeling (MLM) for repeated measures designs as it allowed us flexibility in modeling a more appropriate variance-covariance matrix and handling missing data using the Full Information Maximum Likelihood. The analyses were performed using SPSS IBM V.27. In case of significant main effects or interaction effects, a further set of post hoc comparisons were performed. To avoid alpha inflation, a Bonferroni adjustment was applied. Correlations between the experiment's five blocks (*r*-range .534–.921) indicate high stability and consistency; therefore, we analyzed the results without separating blocks. No correlation was shown between age and accuracy ($r = -.083$); therefore, no analysis included age as a covariate or control variable.

Results

Rhyming and non-rhyming pairs between and within stimulus types

To find whether the accuracy rate varies between non-rhyming and rhyming pairs between and within the stimulus types, we compared rhyme value (R/NR) × stimulus

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type (CVC/mVCCVC/Baseline/TCR/HVM). The analysis revealed significant effects of stimulus type [F (4,156) = 21.47, $p < .001$] and rhyme value [F (1,363) = 231.65, $p < .001$] and an interaction effect [F (4,156) = 35.70, $p < .001$].

Post hoc analysis indicated that differences between R and NR were shown within all the bi-syllabic pairs: (mVCCVC ($p = .004$), Baseline ($p < .001$), TCR ($p < .001$), and HVM ($p < .001$)), but not in the mono-syllabic CVC ($p = .352$) (Figure 1a; Table 2, marked with asterisks). In NR pairs, CVC was significantly lower than all the CVCVC types: Baseline ($p = .003$), TCR ($p = .029$), and HVM ($p = .013$), but not than mVCCVC ($p = .376$), which was also significantly lower than all the non-rhyming pairs of CVCVC: Baseline ($p < .001$), TCR ($p < .001$), and HVM ($p = .001$). Among the CVCVC pairs, no significance was found between Baseline and TCR ($p = .450$) and HVM ($p = .543$) nor between TCR and HVM ($p = .306$) (Table 2 marked with letters). By contrast, in rhyming pairs, CVC was significantly higher ($p < .001$) than all the other stimulus types (mVCCVC ($p < .001$), Baseline ($p < .001$), TCR ($p < .001$), and HVM ($p < .001$)). mVCCVC was significantly higher than TCR ($p < .001$) and HVM ($p < .001$) but not than Baseline ($p = .330$), which was also significantly higher than TCR ($p < .001$) and HVM ($p < .001$). Significance was also shown between TCR and HVM ($p = .045$) (Figure 1b; Table 2, marked with letters).

Table 2. Mean and (SD) of accuracy rates of all stimulus types

	Non-rhyming pairs	Rhyming pairs
Rhyme value by types		
CVC	.87 (0.23)$_a$	.91 (0.18)$_a$
mVCCVC	.86 (0.21)$_a$ *	.72 (0.29)$_b$
Baseline	.94 (0.09)$_b$ ***	.69 (0.21)$_b$
Transposed-CR (TCR)	.93 (0.14)$_b$ ***	.44 (0.33)$_c$
Highlighted-VM (HVM)	.95 (0.10)$_b$ ***	.33 (0.37)$_d$
Phonology restrictions		
TCR (-*a*-*a*-)	–	.43 (0.33)$_a$
Baseline (-*a*-*a*-)	–	.76 (0.23)$_b$
Swaps by position TCR		
C213	–	.44 (0.33) ***
C132	.91 (0.15)	–
C321	.91 (0.18)	–
C231	.95 (0.15)	–
C312	.92 (0.14)	–
C231-control	.95 (0.15)	
C312-control	.95 (0.16)	
Highlighted-VM		
Binyanim relations		
MIX	–	.38 (0.39)

(*Continued*)

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Table 2. (*Continued*)

	Non-rhyming pairs	Rhyming pairs
Pa'al-Pi'el	–	.33 (0.41)
Pa'al-Pu'al	–	.30 (0.36)
Semantics relatedness		
non-related	–	.33 (0.36)
Related	–	.33 (0.39)

Significant results are marked according to conventional critical *p* values: $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$ in comparison of rhyming pairs (R) with non-rhyming pairs (NR) in the same stimulus types.
Means in the same column that do not share the alphabetic sub-script are significantly different.

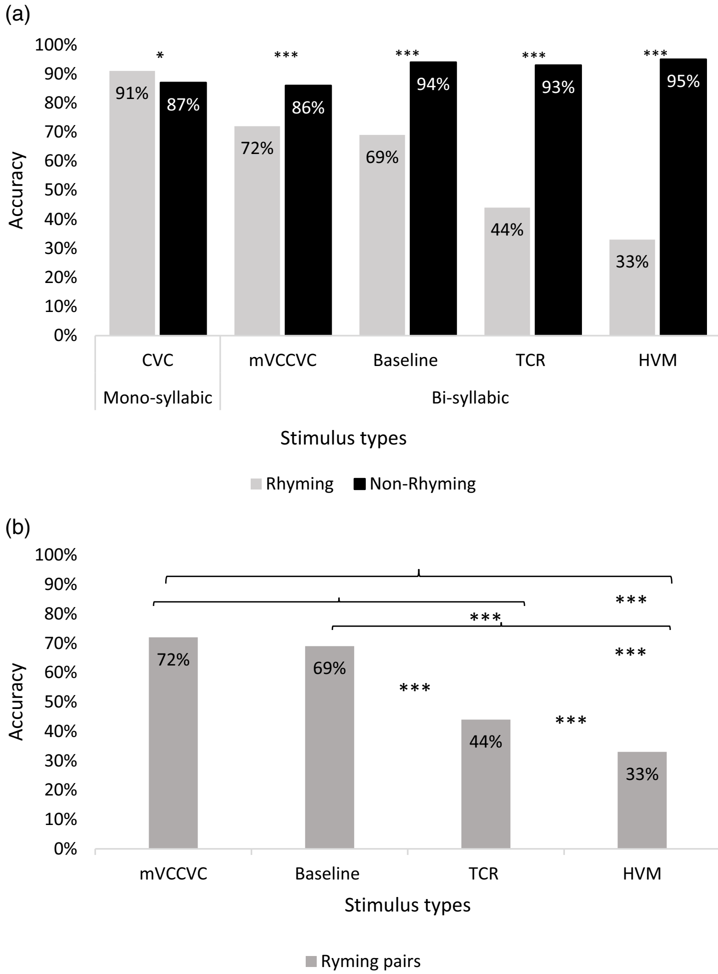

Figure 1. Rhyming and non-rhyming pairs between and within stimulus types. (a) Accuracy of rhyming (blue) vs. non-rhyming (gray) pairs in each stimulus type. (b) A comparison of accuracy in rhyming pairs in the bi-syllabic pairs. P values: $^*p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

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Phonological restrictions: transposed vs. varying CRs

To examine if the transposed roots impact accuracy, we compared rhyming pairs with identical structure (CVCVC) and *-a-a-* vocalic melody that differ in the roots: half with transposed (TCR) and half with varying consonantal roots (Baseline). A paired sample *t*-test showed that the accuracy rate in the Baseline pairs (M = .7554, SD = .2313) was significantly higher than in TCR pairs (M = .4273, SD = .3268); $t(57) = -8.286$, $p < .001$ (Figure 2; Table 2, marked with letters).

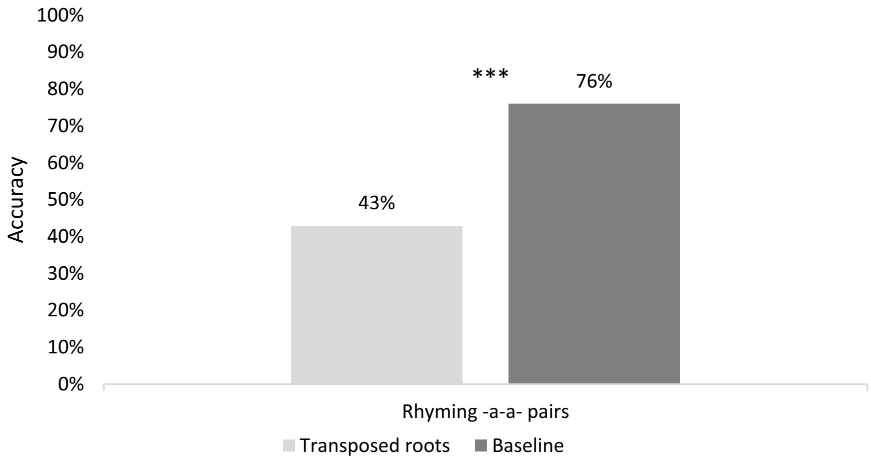

Figure 2. Transposed vs. varying roots. A comparison of rhyming pairs that have identical vocalic melody (-a-a-) but differ in roots: transposed (TCR) vs. varying phonemes (Baseline). ***$p < 0.001$.

Transposed position

To examine if the position of the swapped consonantal phoneme within the word in TCR impacts accuracy, we compared the seven swaps (C132, C321, C231, C312, C231control, C312control, C213). The analysis revealed a significant effect [$F(6,90) = 21.32$, $p < .001$]. Post hoc analysis showed that the scores in the rhyming pairs were significantly lower than all other swaps ($p < .001$). No other significance was found (C132-C321 ($p = .914$), C132-C231 ($p = .139$), C132-C312 ($p = .619$), C132-C231control ($p = .173$), C132-C312control ($p = .216$), C321-C231 ($p = .145$), C321-312 ($p = .574$), C321-C231control ($p = .178$), C321-C312control ($p = .215$), C231-C312 ($p = .287$), C231-C231control ($p = .886$), C231-C312control ($p = .838$), C312-C231control ($p = .351$), C312-C312control ($p = .413$), C231control-C312control ($p = .946$) (Figure 3; Table 2, marked with letters).

Highlighted-VM: Binyanim relations and semantic relatedness

To examine if the lexical-syntactic information encoded in the vocalic patterns impacts accuracy, we compared the three rhyming pair subclasses in HVM stimuli: Pa'al-Pi'el, Pa'al-Pu'al, and the MIX pairs without binyanim relations. No significant difference was found between the subclasses [$F(2,119) = .647$, $p = .525$]. Post hoc analysis confirmed the absence of significance (Pa'al-Pi'el – Pa'al-Pu'al ($p = .687$), Pa'al-Pi'el – MIX ($p = .501$), Pa'al-Pu'al – MIX ($p = .260$)).

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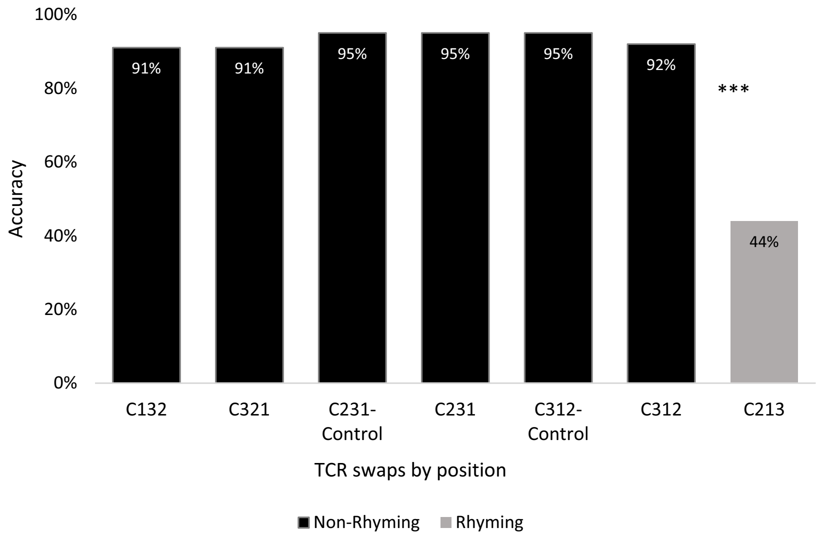

Figure 3. Transposed five-way swaps. A comparison of pairs with identical vocalic melody and transposed roots exhibiting five-way swaps (plus two controls) of non-rhyming (gray) and rhyming (blue) pairs. ***$p < 0.001$.

Next, we examined if semantics plays a role in the HVM stimuli, where all pairs are identical in roots but not necessarily in meaning and binyanim relations are involved. A paired sample t-test was performed to compare the accuracy in semantically related with non-related rhyming pairs with identical roots. Accuracy in semantically related pairs (M = .3348, SD = .3866) was not significantly different than in semantically non-related (M = .3315, SD = .3609) pairs; $t(57) = 0.201$, $p = .841$. (Figure 4; Table 2, marked with letters).

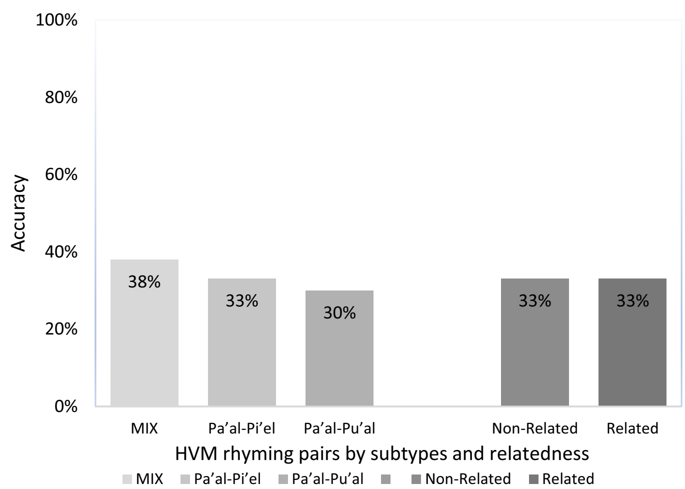

Figure 4. Rhyming pairs in HVM stimuli by subclass and semantics-relatedness. The same pairs are divided once according to binyanim relations (left) and once according to semantically related vs. non-related (right).

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Discussion

The present study examined Hebrew native speakers' word processing mechanisms of templatic words, focusing on metalinguistic awareness associated with the phonological cooccurrence restrictions concerning the root and lexical-syntactic information concerning the template. Specifically, we asked whether nonlinear processing would occur in templatic word decomposition regardless of semantics. We used the phonological awareness rhyme judgment task as a trigger for linear processing. Thus, errors in rhyming pairs suggest a distraction from the linear processing. The task was provided with auditory structure-matched CVCVC stimuli comprising varying root and or template phonemes (Baseline), transposed roots (TCR) assumed to accentuate the root phonological cooccurrence restrictions, and pairs accentuating the lexical-syntactic information reflected in the verbal binyanim relations through the vocalic melody (HVM). In addition, we used the CVC stimuli to compare mono-syllabic vs. bi-syllabic pairs and mVCCVC to compare with Baseline to affirm the impact of the accentuated linguistic information.

The findings show that rhyming and non-rhyming pairs are equally dealt with in mono-syllabic CVC pairs but not in bi-syllabic pairs, where rhyming pairs exhibited low accuracy. The high accuracy in CVC pairs rules out the difficulty in discriminating phonemes or misunderstanding the task. Low accuracy in the bi-syllabic pairs could stem from the phonological interplay involved due to the additional syllable, which applies to both rhyming and non-rhyming pairs, or due to alternation in phoneme position. However, these parameters did not play a role, as the findings demonstrate a clear cut between non-rhyming pairs, which show ceiling effects, and rhyming pairs showing varying degrees of low accuracy rates when the roots are transposed or identical with varying vocalic melody templates, regardless of semantics. Hence, the results suggest that nonlinear processing occurs in templatic words regardless of semantics, likely due to metalinguistic awareness and not meaning. The comparison of the two bi-syllabic pair types, Baseline and mVCCVC, which show similar accuracy rates in rhyming pairs, affirms that distraction from the linear processing resulted from the linguistic information accentuated when a pair consists of transposed roots or identical roots that highlight the vocalic melody.

Moreover, position in transposed roots did not play a role either, as all positions, as long as the pairs were non-rhyming, reached a high accuracy rate without differences among them. As results were not affected when phoneme alternation was within or cross-syllables, these findings rule out an impact of alliteration, i.e., the distraction of identical initial syllables, and sensitivity to the syllable boundaries. The low accuracy rate was shown only in the final position, the target position, which included only rhyming pairs, indicating that participants were attentive to the task, corroborating the impact of grammatical knowledge. This is not in line with concatenative languages like French, where an impact on the inner word was shown in five phonemes/letters words (Schoubaert & Grainberg, 2010). Furthermore, identical structure and template pairs with varying root consonants, as opposed to transposed, showed a higher accuracy rate. Thus, the low accuracy rate in the transposed roots is attributed to the root phoneme alternation. As semantics is not triggered by this task, phonological cooccurrence restrictions are considered to be the reason for the low accuracy in transposed pairs. Noteworthily, in Hebrew, the cooccurrence restrictions are valid with all roots, so the impact of linguistic awareness of phonological rules should also be found with the varying roots. However, we have demonstrated that transposed root phonemes have limited realization, which augments the saliency of phonological cooccurrence restrictions. Therefore, we conclude that the distraction from the linear processing in transposed root pairs amounts to the speaker's awareness of phonological and phonotactic rules in the language. The discrepancy between our conclusion and other studies of transposed roots (Velan & Frost, 2007, 2009) could be attributed to their focus on reading and assumed letter flexibility (i.e., each root consonant can appear in every position), associating their findings with the salience of the root morpheme due to meaning (Oganyan et al., 2019; Perea & Carreiras, 2010; Velan & Frost, 2007, 2009).

The results also show a low accuracy rate in pairs where the vocalic pattern stands out (HVM), including pairs exhibiting mismatched binyanim relations (Pa'al-Pi'el/Pu'al) concerning active-passive voice regardless of meaning. The low accuracy indicates distraction from linear processing. The fact that the accentuated lexical-syntactic information stood out without context suggests that the derivational function associated with the vocalic template leads to nonlinear processing. It also supports the general idea of the lexical-syntactic component in the mental lexicon (Biran & Friedmann, 2012; Friedmann et al., 2013), suggesting that the lexicon is an active component where syntactic knowledge is involved. However, support for the lexicon being an active component does not necessarily confirm the active lexicon (Siloni, 2003) that discerns operations applying to the lexicon or syntax (Laks, 2007, 2013). First, if the HVM pairs have already undergone syntactic operations in the syntax, i.e., out of the lexicon, low accuracy would not be expected, as words that have undergone syntactic operations are processed linearly, as is the case of inflected words (Vaknin-Nussbaum & Shimron,2011). Second, the idea of the active lexicon is that operations in the lexicon apply to verbs of passive, reflexive, and reciprocal constructions (Siloni, 2003). The data in this study show no such exclusiveness. The syntactic information examined included grammatical irregularities of binyanim relations regarding tense and active-passive voice, as well as control pairs without binyanim relations. The lack of difference between these three sub-types in this experiment does not support two loci of operations. It is possible that the words with the *-u-a-* vocalic melody that do not express syntactic passive voice in the control pairs (e.g., *bitul-batul* "cancelation-virgin") were perceived as passive because of the absence of context and the markedness of the *-u-a-* template. Further research is needed to explore the impact of marked templates in the absence of context.

Nonetheless, the lack of difference between the tested pairs that show a violation of binyanim relations and those that do not involve binyanim relations in this study may suggest that the vocalic melody template is associated with abstract representation. This aligns with Farhy et al.'s (2018) suggestion that the binyanim are perceived as abstract morphological categories. Notably, the binyanim templates were part of the Baseline type, where the root comprised varying consonantal phonemes. The impact of the binyan was not equal to that of the highlighted vocalic melody pairs. This raises the question of whether a degree of grammatical regularity affects processing. This cannot be dealt with within the scope of the data collected in this experiment. Further research is needed, with a greater stimulus corpus designated for the research question and precision given to each vocalic melody template apart.

Altogether, the results provide evidence for the nonlinear processing of templatic words due to the impact of grammatical information associated with the root and template, irrespective of meaning. This evidence differs from other studies where nonlinear processing was evidenced by the semantics associated with the root and by tasks tapping into morphological awareness. Here, we used non-linguistic parameters that favor linear processing, oriented to the awareness of phonemes, having semantics, the primer influence of the root, reduced to the possible minimum. Yet, linear processing was distracted by metalinguistic awareness. Nonetheless, an examination of all the results, breaking them down into all templatic word stimulus types, reveals that linear processing also occurred. Linear processing is evidenced by the accuracy rate in bi-syllabic pairs where the root and template were not accentuated, namely, the mVCCVC (72%) and Baseline (69%). Linear processing is also evidenced by the fact that low accuracy was seen in the accentuated stimulus types only to a certain degree. Explicitly, accuracy rates were 33% in the HVM pairs and 44% in the transposed root pairs (67% and 56% errors, respectively). This distribution of accuracy rates indicates that both linear and nonlinear processing modes were applied. At least a third of the participants inhibited either the nonlinear processing due to the task or the linear processing regardless of the task.

The variations within native Hebrew speakers suggest that linear and nonlinear processing modes compete, and both processing modes are accessible, tangible, and applied to templatic words. This renders the root and template mechanism helpful or dominant but not unescapably necessary. These results are not in line with linguistic theories that propose a modular view of language processing, according to which the mental lexicon and grammatical rules operate independently, with the lexicon providing the raw material (words), hence a repository, and grammar rules applying in other components to generate and interpret complex linguistic structures. Our findings agree with Berman's (2012) view, which states that nonlinear processing is a strategy affected by linguistic and non-linguistic parameters. Given that in Modern Hebrew, some templatic words are also formed linearly (Schwarzwald, 2019), there is a place for both linear and nonlinear to transpire, making it idiosyncratic for each speaker. Having multiple processing modes, both strategic and idiosyncratic, aligns with lexicon models such as MacWhinney's (2005, 2013) Unified model, in which language processing results from neural circuits entrenched by usage, and Wray's (2012) Heteromorphic Distributed Lexicon model, which accounts for the dynamic nature of language processing and storage in the human mind. In conclusion, our study suggests that both linear and nonlinear strategies are present and may be complementary.

Replication package. Participant information, stimulus lists, data, and analysis scripts for this study can be retrieved from https://osf.io/my9bt/.

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Appendix A

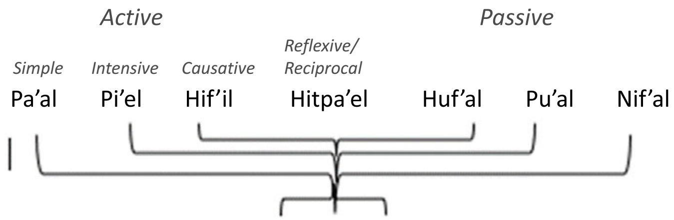

Figure A1. Binyanim Menora, used as a scaffolding in teaching the Hebrew verbal system to help students remember the grammatical information of each binyan: (a). which binyanim are active voice (left side) vs. passive voice (right side), and (b). which binyanim are Simple—indicating someone performed an action (outermost menorah branches), Intensive—repetitive or durative action or more than one receiver (second outermost), Causative—causing someone else to perform an action (third outermost), and Reflexive—the subject is both the doer and receiver of the action, or Reciprocal—the subject performs an action on others and receives the same action in return (center).

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Table A1. General grammatical information (linguistic concept) of each binyan, with examples

	Active	Active	Active		Passive of Hif'il	Passive of Pi'el	Passive of Pa'al Active
	Pa'al	Pi'el	Hif'il	Hitpa'el	Huf'al	Pu'al	Nif'al
Simple	*halax* הלך "he went"	*bikeʃ* ביקש "he asked"	*hizmin* הזמין "he invited"				
Intensive (repetitive)		*hilex* הילך "he walked back and forth" (vs. *halax* הלך "he walked"; Pa'al).					
Intensive (Durative(		*ʃimer* שימר "he preserved" (vs. *ʃamar* שמר "he kept"; Pa'al)					
Causative		*Limed* לימד "he taught" (vs. *lamad* למד "he learned"; Pa'al)	*higdil* הגדיל "he enlarged" (vs. *gadal* גדל "he became bigger"; Pa'al)				
Inchoative	*gadal* גדל "he grew up/ became bigger"	*gidel* גידל "he brought up so/sb" (it was small, and he made it bigger) only to Pa'al inchoative verbs (vs. *gadal* גדל "he grew up" in Pa'al)	*higdil* השמין "he got fat" (vs. *ʃaman* "he gained weight(fat)"; Pa'al)	*hitbaher* התבהר "it became clear, brightened"			*nirdam* נרדם "he fell asleep.".
Reflexive				*hitraxec* התרחץ "he washed himself"			*nixnas* נכנס "he entered" *nizhar* נזהר "he was careful"

(*Continued*)

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Table A1. (*Continued*)

	Active	Active	Active		Passive of Hif'il	Passive of Pi'el	Passive of Pa'al Active
	Pa'al	Pi'el	Hif'il	Hitpa'el	Huf'al	Pu'al	Nif'al
Reciprocal				*hitnašek* התנשק "he kissed (and was kissed)"			*nilxam* נלחם "he fought with or against so/ st"
					huzman הוזמן —*hizmin* הזמין "he was invited—he invited".		
						lumad לומד —*limed* לימד "it was taught—he taught"	
							nirmaz נרמז — *ramaz* רמז "it was hinted"—"he hinted"

Table A2. Examples of verbs with the same meaning in different binyanim, sharing the same concept

	Meaning (for both words in the raw)	Pa'al	Pi'el	Hif'il	Hitpa'el	Huf'al	Pu'al	Nif'al
Simple	hide/conceal (something inside something)	*taman* טמן		*hitmin* הטמין				
Reflexive	be destroyed (in Hebrew it is Active)	*xarav* חרב						*nexrav* נחרב
	assembled (Active)				*hitkahel* התקהל			*nikhal* נקהל
	hid oneself				*hitxabeʔ* התחבא			*nexbaʔ* נחבא
Causative	sank		*tibeʕa* טיבע	*hitbiʕa* הטביע				
Inchoative	got angry	*ragaz* רגז			*hitragez* התרגז			
Reciprocal/ inchoative	approached/came near	*karav* קרב			*hitkarev* התקרב			

Appendix B

Table B. Hebrew phonemes and graphemes

	Phonemes	Graphemes
1.	m	מ (ם)
2.	n	נ (ן)
3.	p	פ
4.	b	ב
5.	t	ת, ט
6.	d	ד
7.	k	ק, כ
8.	g	ג
9.	ʔ	א, ע, ה
10.	c	צ (ץ)
11.	f	פ (ף)
12.	v	ב, ו
13.	s	ס, ש
14.	z	ז
15.	ʃ	ש
16.	x	כ (ך), ח
17.	r	ר

(*Continued*)

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Table B. (*Continued*)

	Phonemes	Graphemes
18.	h	ה
19.	l	ל
20.	j	י

*Graphemes in brackets are the realization of the letter to their right in word final position.

Appendix C

We extract a participant's probability of Yes and No by simply counting the number of Yes answered and the number of No answered throughout the test (which is presented in random order), as we assume that a participant does not discriminate on which groups (e.g., CVC, mVCCVC, etc.) to choose blindly. A participant that blindly chooses Yes or No has an empirical probability p_y and p_n respectively. Similarly, the probability of a pair in question being a rhyme is q_y and q_n. This means that the probability of a said participant answering correctly is $p_n \cdot q_n + p_y \cdot q_y = p$. We have m questions, and let the number of answers the participant answered correctly be k. With all these parameters, we would like to calculate the probability (or likelihood) of a said participant to answer k correct "random guesses" out of m experiments, where each question has a probability p of being answered correctly. We notice that this is a Binomial distribution and is calculated by $\binom{m}{k} p^k (1-p)^{m-k}$. Results indicate that each participant has a probability of less than 0.05 (range from 0.02611312 to 2.7312E-48) of achieving their accuracy (meaning it is much more likely that they did not pick at random/ by chance) (Table C).

Table C. Participants' probability of achieving their accuracy by chance

P#	Probability	P#	Probability	P#	Probability	P#	Probability	P#	Probability
1	0.000182308	30	0.02611312	76	6.0831E-16	132	2.1827E-05	196	1.0604E-14
4	9.75326E-10	31	3.838E-09	85	0.00033073	135	4.3354E-06	197	8.6099E-37
5	7.57643E-10	34	6.7853E-34	104	7.8132E-05	144	1.1935E-21	200	0.00297771
6	1.85121E-09	39	1.0961E-27	106	7.7459E-16	151	3.9945E-14	208	0.00010982
7	5.26025E-06	42	1.2017E-06	110	0.00233291	154	7.6485E-10	213	1.2065E-18
9	7.51127E-06	43	2.7312E-48	112	4.1152E-14	164	2.891E-07	235	4.3854E-11
10	1.28457E-21	44	7.743E-27	115	6.1173E-07	167	7.4477E-17	236	2.352E-11
14	2.34738E-08	50	8.3543E-18	118	1.1198E-11	183	8.9265E-14	237	6.8635E-13
17	6.05573E-06	54	2.9296E-10	120	3.0286E-23	187	9.1145E-13	238	0.00081181
19	0.001691383	56	8.1694E-10	121	5.5549E-19	188	2.4217E-12	241	4.0983E-11
22	4.92789E-39	61	9.0222E-13	123	3.8973E-19	191	1.2171E-10		
29	8.15607E-05	64	2.6099E-05	124	1.3565E-17	195	0.00376875		

P = participant.

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