Le-ma‘an Ziony

Le-ma‘an Ziony: Essays in Honor of Ziony Zevit

edited by

FREDERICK E. GREENSPAHN
& GARY A. RENDSBURG

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Visual Grammar: An Eye-Tracking Perspective on Cognitive Complexity in Biblical Hebrew Pronunciation[1]

Cynthia L. Miller-Naudé, Jacobus A. Naudé, Tanya Beelders, and Luna Bergh
University of the Free State
(Bloemfontein, South Africa)

1. Introduction

It is a pleasure for us to dedicate this chapter to Ziony Zevit, whose first book—*Matres Lectionis in Ancient Hebrew Epigraphs*—dealt with the question of spelling (and thus reading) of Hebrew at its earliest attestations in epigraphic sources. In this article we examine how contemporary students

1. An earlier version of this article was presented in the Applied Linguistics for Biblical Languages Section of the Society of Biblical Literature, 24 November 2014. We are grateful for the questions and comments of participants at the section. This work is based on research supported in part by the National Research Foundation of South Africa (Jacobus A. Naudé UID 85902 and Cynthia L. Miller-Naudé UID 95926). The grantholders acknowledge that opinions, findings and conclusions or recommendations expressed in any publication generated by the NRF supported research are those of the authors, and that the NRF accepts no liability whatsoever in this regard.

learn to read Biblical Hebrew, including the *matres lectionis*. We are interested in gaining insight into the processing of Biblical Hebrew in light of the cognitive complexity of the Hebrew writing system. In particular, we want to know how adult learners of Biblical Hebrew decode and interpret the orthography of Biblical Hebrew as compared to the orthography of their home language.

In order to understand precisely what students are focusing on when they read Biblical Hebrew, we have employed eye-tracking technology. Eye-tracking technology allows researchers to see exactly what students are focusing on when they read Biblical Hebrew—for example, how long they look at an orthographic feature or whether their eyes regress to a previous feature. It is therefore possible to ascertain the eye movements that fluent speakers of Biblical Hebrew use to interpret the orthography as opposed to the eye movements used by beginning students. It is also possible to compare the eye movements used by students in reading the orthography of their home language as opposed to the orthography of Biblical Hebrew.

Writing represents a form of visual communication[2] and is therefore suitable for an eye-tracking experiment. Ware describes verbal language, written language, and sign language as socially designed tools for communication, whose symbols and grammars are shared by the respective language users and which use the same specialized areas of the brain for processing information.[3] In contrast and complementary to this, visual representations of information are processed by the visual system–"an extremely powerful pattern finding system which is very good at finding structure in diagrams."[4] Its logic differs from that of verbal logic and consists mostly of structural relationships such as those revealed by voweled Biblical Hebrew, where vowel diacritics surround consonantal letters spatially and especially vertically and horizontally.[5] Biblical Hebrew thus presents a very strong form of visual communication. The word *grammar* is derived from the Greek *grammatike,* with the meanings "the art of reading and writing," "grammar," or "alphabet."[6] The first phrase of our title, Visual Grammar, emphasizes these focal points in our research.

Behavioral studies have shown that the visual characteristics of words, such as the direction in which they are written or read, word length, and their orthographic and morphological structure, affect the way in which

2. Kress and Van Leeuwen, *Reading Images*, 17.
3. Ware, *Visual Thinking for Design*, 133.
4. Ibid.
5. Ware, *Visual Thinking for Design*, 57, 133.
6. Kress and Van Leeuwen, *Reading Images*, 22.

words are perceived.[7] Research investigating the possible sources of slowness in both reading acquisition and skilled reading of another Semitic language, Arabic, compared to other languages has focused on the relationship between the specific characteristics of the Arabic orthographic system and cognitive processes that might be involved during word recognition and the acquisition of reading.[8] Abdelhadi et al. point out that there are two separate aspects of this relationship that might be related, namely orthographic depth (the "distance" between the graphic system and the lexical items it represents) and the visual complexity of the letters themselves.[9] With regard to Arabic for beginning readers, Abu-Rabia et al. emphasize the following points:

> Recognizing the nature of these letters and their diverse writing rules in different positions, and recognizing the different short vowels under, in, and above the letters is critical for readers' word pronunciation, which may demand considerable cognitive attention. Furthermore, short-vowel diacritics are located above, and/or in, and/or below the letters for letter-sound pronunciation. Thus, reading a fully voweled text is likely to be cognitively demanding for a beginning reader, who simultaneously must process many rules in order to extract meaning from print or read out loud accurately. A minor error can lead to a mistaken decoding through confusion of letters of the same shape.[10]

Linguistic complexity has been a research focus area in terms of fluency for some time, and it has been found that stuttering tends to occur in utterances that are linguistically more complex.[11] Packman explains that if a person uses a fluency enhancing technique, such as prolonged speech, "an increase in arousal may result in them paying more attention to it, hence increasing their control over their stuttering."[12] Our linguistics framework is that of Cognitive Linguistics. Andrews points out that one of the noteworthy contributions of Cognitive Linguistics to the study of language and brain is

7. Abdelhadi et al. "Perceptual Load in the Reading of Arabic: Effects of Orthographic Visual Complexity on Detection," 117.

8. See the summary of this research in Abdelhadi et al., "Perceptual Load in the Reading of Arabic."

9. Abdelhadi et al., "Perceptual Load in the Reading of Arabic," 118.

10. Abu-Rabia et al., "Word Recognition and Basic Cognitive Processes among Read-Disabled and Normal Readers in Arabic," 425.

11. See Packman, "Theory and Therapy in Stuttering: A Complex Relationship."

12. Ibid., 228.

> its emphasis on combining cognitive theory-based models with reliable data sets of linguistic forms; these data sets are both pragmatically and semantically viable within their corresponding languages, speech communities, and communities of practice. CL [Cognitive Linguistics] is interested in the study of not only *imagery*, but also *perception* (*visual and non-visual*).[13]

This view of Cognitive Linguistics relates to neuroscientific research on mental imagery, specifically viewer-oriented and object-oriented mental representations. Our notion of cognitive complexity invoked in this article involves cognitive attention and processing, and visuo-spatial, verbal, linguistic, and orthographic considerations.

The organization of the chapter is as follows: In section 2, we discuss notions of reading in Biblical Hebrew and difficulties in reading the Biblical Hebrew orthography, especially as compared to Modern Hebrew. Section 3 provides an overview of the theoretical aspects of the cognitive processes of reading, specifically cognitive neuroscience, active vision, cognitive linguistics, active memory, and eye movements. Section 4 describes the present eye-tracking experiment, Section 5 describes its results, and Section 6 discusses the significance of those results. Section 7 provides the conclusions.

2. Reading Biblical Hebrew

2.1 Notions of Reading Biblical Hebrew

Reading can be defined generally as "the process of decoding and comprehending written language."[14] However, because Biblical Hebrew is both a second language and a written language for students, the definition of Nassaji concerning learning to read a second language is more appropriate: "learning to read becomes less about comprehension or getting information from text than a tool for developing basic language skills."[15]

The various notions of "reading" with respect to Biblical Hebrew can be identified.[16] These notions can be summarized as follows: (1) reading involves the pronunciation of the Hebrew letters without understanding or

13. Andrews, "Language and Brain: Recasting Meaning in the Definition of Human Language," 22.

14. Perfetti, "Reading," 699.

15. Nassaji, "Issues in Second-Language Reading: Implications for Acquisition and Instruction," 175.

16. See Miller-Naudé and Naudé, "A Typological, Complex Systems Approach to the Teaching of Biblical Hebrew Reading."

with only limited understanding of what is being communicated; (2) reading involves the visual processing of letter-strings for word identification; in other words, reading involves "a match between the graphic input and the corresponding word representation";[17] (3) reading involves the identification of discourse-level features such as compound sentences, the embedding of direct and indirect speech, and genre specific features such as poetic lineation and poetic word pairs; (4) academic reading comprehension of Biblical Hebrew includes culturally relevant information for processing the pragmatic inferences of biblical texts. In this paper, we concentrate on the first level of reading—reading Hebrew orthography for pronunciation.

2.2 Biblical Hebrew Orthography

The orthography of Hebrew differs significantly from the orthography of the Latin alphabet. First, it is written from right to left, rather than from left to right. Second, the Latin alphabet is linear, with consonants and vowels having equivalent representational space on the line. The Hebrew alphabet differentiates consonants, which are large letters, from vowels which are superimposed as small marks below, above, or to the left of the consonants. These two features mean that the eye movements required to read Biblical Hebrew differ significantly from those used in reading a language written in the Latin alphabet.

Furthermore, the Hebrew alphabet requires the reader to interpret the orthography in a variety of ways in order to read correctly. First, the consonants that may function as *matres lectionis* must be interpreted within the context of the word as either consonants or composite vowel letters. Second, the *shewa* vowel point must be interpreted within the syllable structure of the word as either silent (ending a syllable boundary) or vocal. Third, the *qameṣ* must be interpreted within the syllable structure as either representing /o/ in closed, unaccented syllables or /ā/ elsewhere. Fourth, *dageš* may signal either a doubled consonant (*dageš forte*) or a plosive rather than a fricative consonant (*dageš lene*); readers must interpret its function within the context of the word in order to read correctly. Additional hurdles for reading the biblical text involve, first, the accentual system that is superimposed upon the text. Beginning readers must differentiate accents from vowels. Second, the *ketiv-qere* variants indicated in the biblical text require readers to consult the *masora parva* in the margin in order to properly pronounce the word. Reading Hebrew thus requires the reader to be able to

17. Perfetti, "Reading," 700.

interpret a dramatically different orthography in exceedingly sophisticated ways.

The process of learning to read Biblical Hebrew as a second language also differs in dramatic ways from immigrants to Israel learning to read (and speak) Israeli Hebrew. First, the orthography of Modern Hebrew is a "deep" alphabetic orthography in the sense that "the letters represent phonemes, but the mapping of graphemes-to-phonemes is not entirely transparent."[18] Because vowels are not usually indicated, Modern Hebrew orthography "cannot specify a unique phonological unit, and a printed consonant string is phonologically ambiguous, often representing more than one word."[19] As described by Frost, reading in Modern Hebrew involves two processes. First, the recognition of single letters as providing consonantal information; this process may be sufficient to read the word.[20] Second, a complete phonological representation must be provided by the reader drawing upon morphological information from the word pattern (the missing vowels).[21] Word recognition in Modern Hebrew requires that words be decomposed into their roots and then into their constituent morphemes.[22]

By contrast, the orthography of Biblical Hebrew is a shallow orthography in the sense that consonants and vowels are indicated. But this advantage is offset by the fact that Biblical Hebrew is *over*-differentiated. By this we mean that Biblical Hebrew does not offer a purely phonemic orthographic representation of the language, but rather also represents phonetic and prosodic features. As one example of phonetic representation, the *dageš lene* represents the difference between a stop and a fricative in approximately the same point of articulation (e.g. [t] vs. [θ]). The occurrence of the stop and the fricative, however, are in complementary distribution and completely predictable (i.e., the stop occurs in two positions—word initially and syllable initially after a closed syllable—whereas the fricative occurs elsewhere). There is therefore no need for these two phonetic sounds

18. Frost, "Reading in Hebrew vs. Reading in English: Is There a Qualitative Difference?" 236.

19. Ibid., 237.

20. Frost, "Prelexical and Postlexical Strategies in Reading: Evidence from a Deep and Shallow Orthography"; Frost, "Phonological Computation and Missing Vowels: Mapping Lexical Involvement in Reading."

21. Frost, "Becoming Literate in Hebrew: The Grain-Size Hypothesis and Semitic Orthographic Systems."

22. See Frost, "Reading in Hebrew"; Frost et al., "Decomposing Complex Words in a Nonlinear Morphology"; Frost et al., "Morphological Priming: Dissociation of Phonological, Semantic, and Morphological Factors"; Frost et al., "What Can We Learn from the Morphology of Hebrew: A Masked Priming Investigation of Morphological Representation."

to be indicated orthographically. If the *dageš* in a consonant was used purely to indicate a doubled consonant (the *dageš forte*) the task of learning to read Biblical Hebrew would be greatly simplified. The same is true of the use of one symbol—the *shewa*—to represent both the end of a syllable and an audible half-vowel. As an example of prosodic representation, we can mention the use of conjunctive *dageš* (across word boundaries).

Second, learning to read Modern Hebrew occurs concomitantly with learning to speak Hebrew. This means that learners have an oral component in their cognitive processes of learning as well a visual component. Efforts to include oral speaking in the learning of Biblical Hebrew are attempts to close this gap between the learning of Modern and Biblical Hebrew.[23]

3. Reading and Cognitive Processes

3.1 Cognitive Neuroscience of Reading

How do students actually learn to recognize the letters on the page and pronounce the words? In other words, how is the visual image on the page (letters configured as words) transformed into phonemes and words in the brain? Recent research concerning the science of reading sheds important light on the reading process. Especially significant in this regard is the work by Stanislas Dehaene and his colleagues in France.[24]

Recognising and processing the written image begins when a specialised portion of the retina, the fovea, receives photos reflected off of the written page.[25] Because the fovea occupies only 15 degrees of the visual field, a person's eyes must be in constant motion during reading in order to bring the fovea in contact with the written words. The eyes' movements are in small jerky steps called saccades. In a single fixation, the gaze can perceive about 7–9 letters.[26] There is an important asymmetry based on the direction of reading—persons who read an orthography that is arranged from left to right have a visual span greater towards the right side of the visual field, whereas persons who read a right-to-left orthography have a greater visual span towards the left.[27] This culturally determined difference in reading also

23. Buth, *Living Biblical Hebrew: Part One*; Buth, *Living Biblical Hebrew: Part Two*; and Overland, *Learning Biblical Hebrew Interactively*.

24. This research is summarized in Dehaene, *Reading in the Brain: The New Science of How We Read*. For a summary of the science of reading from the viewpoint of a reading specialist, see Smith, *Understanding Reading*, 65–103.

25. Dehaene, *Reading in the Brain*, 13.

26. Ibid., 14–15.

27. Ibid., 17.

relates to other writing systems; for example, readers of Chinese (which has greater character density in the visual field) will have shorter saccades and reduced visual span.

There are two major processing paths which coexist in the brain and which supplement one another during the process of reading.[28] One is the phonological path which converts a string of letters into sounds (pronunciation) and then attempts to access the meaning of the sound pattern. The second path is the lexical path, in which the brain attempts first to access the word in the mental lexicon in order to recover the identity and meaning of the word and then to recover its pronunciation.

These paths relate to the brain's neurophysical features. Magnetic imaging has demonstrated that the left occipito-temporal region is the visual word form area.[29] This area of the brain performs the visual analysis of letter and word shapes (letter strings) and transmits the information to two areas of the brain in the temporal and frontal lobes which encode sound pattern and meaning. It is important to note that the visual word form area is not identical to the area of the brain which recognizes faces, objects, etc.[30] Nor is the visual word form area identical to the area where hearing and speech perception is processed in the brain.[31] In all literate cultures, writing is processed by the same brain circuits in spite of differences of language and differences in surface forms; there are therefore neurological limits on cultural diversity in reading.[32]

Acquiring the ability to read as a child involves three major phases:[33] First, there is a brief "pictorial stage" in which children's brains "photograph" a few words. Second, there is the phonological stage in which children learn how to decode graphemes into phonemes. Third, there is the orthographic stage in which word recognition becomes fast and automatic. Brain imaging has shown that in the process of learning how to read, the brain is altered, especially in the left occipito-temporal lobe, so that the neural activity evoked by written words increases and becomes selective based upon the specific visual characteristics of the writing system. These changes in the brain occur even when illiterate adults learn how to read. For this reason, learning to read a second orthography has significant "carry-over" effects from the initial experience of the brain's learning to read.

28. Ibid., 38–39.
29. Ibid., 62, 68, 75.
30. Ibid., 74.
31. Ibid., 68.
32. Ibid., 97, 119.
33. Ibid., 195.

3.2 Active Vision

The notion of Active Vision provides an integrated account of seeing and looking, taking into consideration the role of eye-movements.[34] Active Vision emphasizes visual attention, which in turn ties in with other cognitive phenomena in our study, such as working memory (see section 3.4 below).

Active Vision is "all about understanding perception as a dynamic process" where, by means of directing the eyes, "the brain grabs just those fragments that are needed to execute the current mental activity."[35] The basis of visual thinking is "pattern perception," which is partly innate and partly learned through visual interaction with the world. Visual designs are almost always combinations in that they have aspects that support visual thinking through pattern finding and aspects that are conventional and processed through language systems. More broadly and in a unifying way, in cognitive neuroscience every piece of stored information can be thought of as a pattern, which entails that complex patterns are patterns of patterns.[36] This would be the case for the Modern Hebrew root and word patterns described by Frost et al.[37] as well as the metaphorical patterns surrounding Biblical Hebrew described below in section 3.3. It is in the inferotemporal cortex that neurons respond to particular meaningful patterns such as faces, hands, and letters of the alphabet, although in slightly different areas.[38]

Five points about Active Vision are relevant here. First of all, visual thinking is based on pattern perception, as was pointed out above. Secondly, Ware points out that almost all seeing involves "visual search," although we are not constantly aware of it.[39] Thirdly, efficient visual search can be achieved through the use of "pop-out properties."[40] The strongest pop-out effects occur when a single target object differs in some feature from all other objects. Pop-out contrast is defined in terms of the basic features that are processed in the primary visual cortex, namely color (including hue and lightness), orientation, size, motion, and stereoscopic depth as well as elongation, spatial layout, and form.[41] The features that pop out are hardwired

34. Findley and Gilchrist, *Active Vision: The Psychology of Looking and Seeing*. See also Bergh and Beelders, "An Eye-Tracking Account of Reference Points, Cognitive Affordance and Multimodal Metaphors."

35. Ware, *Visual Thinking for Design*, ix.

36. Ibid., 63.

37. Frost et al., "Decomposing Complex Words in Nonlinear Morphology."

38. Ware, *Visual Thinking for Design*, 168.

39. Ibid., 41.

40. Ibid., 42.

41. Ibid., 29, 42.

in the brain, not learned,[42] and can be seen in a single fixation—as opposed to elements that do not pop out and require several eye movements to find.[43]

Visual thinking is, fourthly, based on a "hierarchy of skills," which means that sophisticated cognitive skills build on simpler ones. Although human mental models of space perception are grounded in real-world interaction, the neural architecture and the most basic human capabilities (such as seeing closed shapes bound by contours as "objects") are innate.[44]

Lastly, Ware explains that when we see patterns in graphic designs, we are mostly relying on the same neural machinery that is used to interpret our everyday environment. There is, however, a "layer of meaning"—"a kind of natural semantics"[45]—that is built on top of this. For example, we use a big graphical shape to represent a large quantity in a bar chart.

3.3 *Cognitive Linguistics*

The exposition in the previous section ties in with two tenets of cognitive semantics; namely, that "cognitive models are mainly perceptually determined" and that "semantic elements are based on spatial or topological objects."[46] Gärdenfors proposes the notion of a conceptual space as a framework for geometric structure in cognitive semantics.[47] A conceptual space comprises a number of quality dimensions such as color, pitch, temperature, weight, and the three ordinary spatial dimensions, and corresponds closely with the domains of Langacker.[48] Also, within this framework a linguistic symbol is bipolar in that it consists of a semantic pole, a phonological pole, and the link between them.[49] Langacker defines a unit as "any cognitive or cognitively derived activity."[50] What should be kept in mind in this regard is that not only should linguistic units be seen on a continuum with non-linguistic units, but that the same applies to traditional divisions such as phonology, syntax, and morphology.

42. Ibid., 32.
43. Ibid., 29.
44. Ibid., 103.
45. Ibid., 62.
46. Gärdenfors, "Some Tenets of Cognitive Semantics," 22.
47. Ibid.
48. Langacker, *Foundations of Cognitive Grammar*, 147.
49. Ibid., 76.
50. Ibid., 60.

The natural semantics discussed above permeate our spoken language, as well as the language of design.[51] In this regard, Lakoff and Johnson argue that spatial metaphors are not just ways of making language more vivid, but that they are fundamental to the way language works in communication and reasoning.[52] Spatial metaphors occur even in an expression such as *vowels are superimposed as small marks below, above, or to the left of the consonants* that is so general in the Biblical Hebrew context that we do not necessarily even consider it to be metaphoric. To Lakoff and Johnson metaphors represent the way in which we make sense of the world, and follow the pattern-seeking of Active Vision. This aspect will be elaborated on in our forthcoming article dealing with the conceptual metaphorical patterns related to this experiment.

In a study on Arabic, researchers Ibrahim, Eviatar, and Aharon-Peretz established that specific features of Arabic orthography (such as vocalization marks) produce a visual load in respect of visual word recognition and that the effect is slower orthographic recognition as compared with other orthographies.[53] Taha postulates that the complexity of the visual information that each written Arabic word carries (such as different shapes of different letters, dots, and the vocalization marks) forces the reader to rely heavily on visual processing in addition to phonological processing.[54] In respect of the present study, it should be kept in mind, however, that phonology may have a reduced role in lexical decision tasks or silent reading compared to oral reading.[55] Oral reading may also involve more attention to phonological analysis than orthographic units or meaning relative to silent reading.[56]

Ibrahim indicates that, traditionally, oral reading accuracy and fluency are assessed by reading aloud a list of words (or pseudo-words) that are graded for length, "difficulty," and frequency of occurrence.[57] Furthermore, although measures of accuracy seem to be good predictors of variability in literary acquisition of less transparent scripts, measures of speed may be better predictors of variability in more transparent scripts. These observations

51. Ware, *Visual Thinking for Design*, 62.

52. Lakoff and Johnson, *Metaphors We Live By.*

53. Ibrahim et al., "The Characters of the Arabic Orthography Slow its Cognitive Processing."

54. Taha, "Reading and Spelling in Arabic: Linguistic and Orthographic Complexity."

55. See Share, "On the Anglocentrics of Current Reading Research and Practice: The Perils of Overreliance on an 'Outlier' Orthography."

56. Corcos and Willows, "The Processing of Orthographic Information."

57. Ibrahim, "Reading in Arabic: New Evidence for the Role of Vowel Signs," 249.

are also applicable to the voweled Biblical Hebrew passages in our study, which also provide morpho-syntactic information.

In the study by Ibrahim et al. as well as that of Eviatar et al., it was found that Arab-Israeli participants were slower in processing Arabic letters than Hebrew letters, despite Arabic being the participants' first language.[58] The researchers concluded that this difference was due to the greater degree of visual/graphic complexity of Arabic script compared to Hebrew. Other studies have shown, though, that decoding of both Arabic and Hebrew demands more visuo-spatial awareness or visual attention than decoding in English,[59] while Geva and Siegel established that English-Hebrew bilingual children made more visual letter recognition errors in Hebrew than in English.[60] In addition, Shimron and Sivan found that adult Hebrew-English bilinguals read text more quickly in English than in unvoweled Hebrew, but not more quickly than in Hebrew texts with vowel diacritics.[61] From this research it can be inferred that even though the addition of vowels results in a more complex visual form of the text, it still facilitated the speed of reading among that particular bilingual group.

3.4 Working Memory

A person can process limited information in working memory at a specific point in time.[62] At a cognitive level, "we allocate scarce working memory resources to briefly retain in focal attention only those pieces of information most likely to be useful."[63] As Lee, Lin, and Robertson point out, every task has a cognitive cost, and as a person becomes more used to performing a specific task, that activity requires less cognitive energy.[64] They provide the example of how a new bicycle rider must concentrate fully to learn the skills involved, which, with practice, become more automated, although a certain amount of attention is always necessary for this activity. Related to this, the

58. Ibrahim et al., "The Characteristics of the Arabic Orthography Slow its Cognitive Processing"; and Eviatar et al., "Orthography and the Hemispheres: Visual and Linguistics Aspects of Letter Processing."

59. Share and Levin, "Learning to Read and Write in Hebrew"; and Shatil and Share, "Cognitive Antecedents of Early Reading Ability."

60. Geva and Siegel, "Orthographic Factors in the concurrent Development of Basic Reading Skills in Two Languages."

61. Shimron and Sivan, "Reading Proficiency and Orthography: Evidence from Hebrew and English."

62. Archer, "Digital Distractions," 50.

63. Ware, *Visual Thinking for Design*, 3.

64. Lee et al., "The Impact of Media Multitasking on Learning."

concept of executive attention refers to "our ability, within the context of working memory, to prioritize information and to focus on accomplishing a specific goal without distraction from irrelevant stimuli."[65]

In this chapter, the term *language* refers to "a variety of neurological functions that serve as the basis for a wide range of actions and behaviors."[66] This implies that it is assumed that the various forms of language, such as speech, comprehension, reading and writing, are not represented in the same way neurologically. Given that the focus of this study is on pronunciation and not reading for comprehension as such, it is furthermore assumed that cognitive load was not increased in the experiment by way of language task-shifting or multitasking, which would increase demand on working memory.[67] The primary verbal-visual task for participants was pronunciation of the lines of Biblical Hebrew orthography in a right-to-left direction.

Visual working memory refers to "the temporary activation of visual objects" and has a capacity of between one and three objects, depending on their complexity.[68] A similar number of objects can be held in verbal working memory, and often the two kinds of objects are bound together. Furthermore, some objects are constructed and held only for the duration of a single fixation. A few objects are held from fixation to fixation, but retaining objects reduces what can be picked up in the next fixation.

Ware explains that "visual working memory capacity is something that critically influences how well a design works. When we are thinking with the aid of a graphic image we are constantly picking up a chunk of information, holding it in working memory, formulating queries, and then relating what is held to a new information chunk coming in from the display."[69] Ware adds that this implies that when a visual comparison is required between two graphic objects, it would be to the advantage of the viewer if the images are on the same page, for "in each case visual working memory capacity is the same, but we can pick up a chunk or two, then navigate to a new point of comparison at least ten times faster with eye movements than we can switch pages (either web pages or book pages), so side-by-side comparisons can be hugely more efficient."[70]

Visual chunks may trigger eye-movement plans and cognitive action plans needed to execute the next few mental operations.[71] Ware explains

65. Archer, "Digital Distractions," 50.

66. Andrews, "Language and Brain" Recasting Meaning in the Definition of Human Language," 26.

67. Archer, "Digital Distractions," 50.

68. Ware, *Visual Thinking for Design*, 126.

69. Ibid.

70. Ibid., 127.

71. Ibid.,115.

these temporary bindings as "acts of attention, the shifting focus of the mind."[72] As Ware points out, the prefrontal cortex has long been considered critical to the temporary bindings that occur as part of more complex plans.[73] The neuroscientists Miller and Cohen explain this as follows:

> [C]ognitive control stems from the active maintenance of patterns of activity in the prefrontal cortex that represent goals and the means to achieve them. They provide bias signals to other brain structures whose net effect is to guide the flow of activity along neural pathways that establish the proper mappings between inputs, internal states, and outputs needed to perform a given task.[74]

In Active Vision, attention is the essence of human perception and also of eye-movement control, "because looking is a prerequisite for attending."[75] The sequence of eye fixations is therefore linked to the thread of visual thinking. Ware explains that cognitive thread shifts back and forth between visual processing and language processing modalities and also that we cannot perform more than one visual or verbal task simultaneously, although we can perform a visual and a verbal task at the same time—if one of the two cognitive tasks represents a highly learned skill.[76] Thirdly, when visual and language modalities are combined, the brain is most effective. In terms of the last point, the task of pronouncing orthography is facilitated cognitively. Furthermore, in visual thinking, perception is a cognitive action sequence.[77] This also means that any images that we see and process to some extent prime the visual pathways involved in their processing and will be processed faster the next time.

3.5 Eye Movements and Cognitive Processing

The eye movements of interest in eye-tracking are saccades and fixations. As mentioned above in section 3.1, saccades are high-velocity ballistic movements which are used to reposition the eye over an area or object of interest.[78] Visual acuity is suppressed during saccades,[79] which means that

72. Ibid.
73. Ibid., 116.
74. Miller and Cohen, "An Integrative Theory of Prefrontal Cortex Function," 167.
75. Ware, *Visual Thinking for Design*, 179.
76. Ibid., 180.
77. Ibid., 118.
78. Gregory, *The Eye and the Brain: The Psychology of Seeing*.
79. Rayner, "Eye Movements in Reading and Information Processing: Twenty

while people are moving their eyes they are unable to "see." In order to "see" an object, the eye must be held still over the object. These periods of relative stability are called fixations.[80] Even during fixations, the eye is subject to small involuntary movements, referred to as fixational movements.[81] Fixational movements are not relevant to the current study and will therefore not be discussed further.

Fixations during scene perception typically last between 260 and 300 milliseconds,[82] but vary in length while reading from 100–500 milliseconds,[83] depending on whether the reading is silent or verbal.[84] Both the home language and the Hebrew passage were read aloud in this study, which may influence the fixation length. However, since both passages were read aloud, the effect would be present in both readings and is therefore implicitly controlled for.

Eye movements are good indicators of whether a person is experiencing any difficulty with reading material. The duration of a fixation, or the length of time the eye remains stable on a word, can give an indication of the cognitive processing that is occurring at that moment.[85] This can be indicative of the amount of resources required to assimilate and understand the word.

Furthermore, three types of saccades are generally present during reading.[86] The first of these are forward progressive saccades in the direction of the text. Secondly, line sweeps are saccades which move in the opposite direction and slightly downwards and serve to connect the end of a line with the start of the next line. Finally, regressive saccades are also saccades which move in a direction opposite to the direction of the text but are performed in order to re-examine a word or words which were not clearly understood.[87] Regressive saccades are dependent on the same characteristics as fixations[88]

Years of Research."

80. Ibid.

81. Martinez-Conde and Macknik, "Fixational Eye Movements across Vertebrates: Comparative Dynamics, Physiology, and Perception."

82. Rayner and Castelhano, "Eye Movements."

83. Hyrskykari, "Eye in Attentive Interfaces: Experiences from Creationg iDict, a Gaze-Aware Reading Aid."

84. Rayner and Castelhano, "Eye Movements."

85. Rayner and Pollastek, *The Psychology of Reading*.

86. Siegenthaler et al., "Comparing Reading Processes on e-ink Displays and Print."

87. Morrison and Inhoff, "Visual Factors and Eye Movements in Reading."

88. Siegenthaler et al., "Comparing Reading Processes on e-ink Displays and Print."

and give an indication of the difficulty experienced while reading.[89] The features of the reading material, such as the contrast and font characteristics, can also impact the fixation duration as well the number of fixations performed during reading. Since the font and contrast were consistent between texts in the current study, they should not unduly influence the results. Linguistic factors also influence the fixation duration while reading, amongst them the familiarity of the word, the semantic relationships between the word and the previous words, and how many meanings the fixated word has.[90]

4. The Present Study

4.1 Overview of the Experiment

Each participant was requested to read a passage aloud in English, Afrikaans, or Sesotho. These languages were chosen as they were the first languages for the sample.[91] Each participant could choose the language they were most comfortable reading for the first passage. Following this, the participant was requested to read a Hebrew passage aloud.

The text chosen for analysis was Deut 31:24–28. A text (rather than isolated words) was selected so that the analysis could better utilize the capabilities of the eye-tracking equipment to examine saccades and regressions. A biblical text was chosen which students had not read in class and which they would not be likely to recognize from their knowledge of the Bible. The text chosen also has a good selection of the phonological and orthographical features for analysis. In retrospect, it seems that the text was a bit too long for many of the students, especially those in the first year of study. This is indicated by the fact that they began to fatigue before they had completed reading the text and tended to make more errors in reading. In future research, a shorter text will be selected.

The Hebrew text was prepared for the eye-tracking experiment as follows: All verse numbers were removed from the passage so that the passage was presented as a continuous text. Since Biblical Hebrew does not use the

89. Rayner and Castelhano, "Eye Movements."

90. Ibid.

91. It is possible that there are significant differences in the rate of reading in Sesotho as opposed to English or Afrikaans, because Sesotho is an agglutinative language. In an eye-tracking study comparing reading in English and isiZulu (a related Bantu language), the rates of reading in isiZulu were considerably slower than those in English even though the isiZulu orthography is more transparent than that of English; see van Rooy and Pretorius, "Is Reading in an Agglutinative Language Different from an Analytic Language?"

punctuation marks of European languages (such as the period, comma, or colon), the *sof pasuq* (literally 'end of verse') mark was retained to assist students in segmenting the text into readable units. The other Masoretic accents were removed from the text, but a simple accent mark was placed over words in which the accent is not final to assist students in reading correctly. The *qere perpetuum* of the divine name (YHWH) as written by the Masoretes was retained, because this is how students learned to read the name in class.

Equivalent texts were prepared of the translation of Deut 31:24–28 into the three languages that are represented as "home languages" among the students—Afrikaans, English, Sesotho. The texts were prepared without verse numbers and in paragraph format, but all normal punctuation marks that are found in the translations were retained.

4.2 Participants

Participants were all students at the University of the Free State and were enrolled for a Biblical Hebrew class at the time the test was conducted. Participants were all undergraduate students, but varied in study year from first year to third year. Since the University of the Free State is a bilingual university, students must be fluent in at least one of the instructional languages (English and Afrikaans). Each session was therefore conducted in either English or Afrikaans based on the preference of the participant.

In total, 27 participants were tested. The data of four participants had to be discarded for the purposes of analysis as they all had a very low accuracy rate for the duration of the test. Additionally, since the analysis was conducted on only the first two lines of each passage, another four participants had to be excluded as there was no gaze data present for them for the first two lines. The analysis was therefore conducted with the participants as follows:

	English	Afrikaans	Sesotho	TOTAL
1st year	1	10		**11**
2nd year		6		**6**
3rd year		1	1	**2**
TOTAL	**1**	**17**	**1**	

Table 1. Participants in the eye-tracking study

Since the Sesotho and English groups only have one participant each, the analysis will be conducted by distinguishing between reading in a home language (the first passage in the language of choice of the participant) and Biblical Hebrew. Due to the small number of participants in each year, the analysis will not be conducted per year group.

4.3 Eye-tracking Methodology

Eye movements were recorded using an eye-tracker, which is a piece of hardware that is used to measure eye movements.[92] The texts (one in the participant's home language and one in Biblical Hebrew) were shown to each participant using a Tobii T120 eye-tracker. The frequency of this eye-tracker is 120Hz (a relatively low frequency), which means that the gaze position is sampled once every 8.3 milliseconds. For reading research, it is advisable to use a high frequency eye-tracker[93] in order to accurately measure fixation progress on words.[94] Unfortunately, a high resolution eye-tracker was not available for use in the study. As a result, the lower frequency eye-tracker was used, with the limitations thereof being recognized for the analysis of reading behavior. However, previous studies have analyzed gaze metrics during reading with low frequency eye-trackers,[95] some even as low as 60Hz.[96]

The resolution of the eye-tracking screen was set to 1280×1024. All texts used for the tests fit on a single screen so there was no need for paging or scrolling. Font size was consistent between texts, implying that the visual angle should be approximately the same for each text. Video recordings were captured of each participant reading aloud. Analysis of the eye-tracking data was primarily conducted using Tobii Studio 3.2.1. Where necessary, adjustments were uniformly made to the position of the fixations using a custom built software application. Adjustments were only made when the calibration was found to lack accuracy and was verified through the video of the participant reading aloud.

The Tobii Studio software allows various metrics to be extracted and analyzed. Applicable metrics for this study are as follows:

92. Duchowski, *Eye-Tracking Methodology: Theory and Practice*.

93. Biedert et al., "A Robust Realtime Reading-Skimming Classifier."

94. Hyrskykari, *Eye in Attentive Interfaces*.

95. Sharmin et al., "The Effect of Different Text Presentation Formats on Eye Movement Metrics in Reading."

96. Cf. Luegi et al., "Using Eye-Tracking to Detect Reading Difficulties."

- Number of fixations—this value indicates the total number of fixations for each participant while they were reading the passage.
- Fixation duration—this is the length, in milliseconds, of each fixation. This can then be interpreted as a total for all fixations, or the average fixation length can be analyzed.

Qualitatively, analysis can be performed using heat maps and gaze plots. A heat map indicates gaze intensity for a stimulus by superimposing a color overlay of the aggregated fixations on the stimulus. The warmer the color, the more participants looked at that location and the longer the period of the gaze. The cooler the color, the less participants looked at that location.[97] As previously mentioned in section 3.5, both fixations and saccades are of interest to eye-tracking. Because eye gaze alternates between saccades and fixations, a scan path can be constructed. Fixations are represented as circles, where the fixations of each participant is shown using a different color. The size of each individual circle is indicative of the fixation duration. The lines between the fixations are representative of saccades (drawn as straight lines even though saccades are not actually straight). Each circle has a number in it, illustrating the index of the fixation within the scan path from the start of the viewing time. Gaze plots show the scan paths of all participants while viewing the selected stimulus. Regressive saccades were detected for each participant by inspecting their respective gaze plot.

5. Results and Analysis

5.1 Average Fixation Length

The average fixation length for Afrikaans readers was 192.4 milliseconds when reading the first two lines of the Afrikaans passage; for English readers, it was 167.0 milliseconds when reading the first two lines of the English passage, and 110.0 milliseconds for Sesotho speakers while reading the first two lines of the Sesotho passage. In contrast, the mean fixation length, for all participants, when reading the first two lines of the Hebrew text was 418.3 milliseconds, markedly longer than while reading the first language text.

Suppose the following null hypothesis was tested:

> *Ho,1: There is no difference between the mean fixation length of a reader when reading in their home language and when reading in Hebrew.*

97. Tobii, "An Introduction to Eye Tracking and the Tobii Eye Trackers."

A paired t-test confirmed that the null hypothesis could be rejected since p < 0 (t=5.79, df=18). Therefore, there is a significant difference between the mean fixation length when reading in the home language and when reading in Hebrew—average fixation length is much higher when reading Hebrew than when reading in one's home language. Therefore, cognitive processing was higher when reading Hebrew than when reading a home language passage.

The images below show a gaze plot for an English, Afrikaans, and Sesotho participant reading in their home language. Directly next to each of these is the same participant's gaze plot when reading in Hebrew. In the case of the English and Sesotho images, these were the images of the only participant in those groups. The images for the Afrikaans speaking participant were chosen as being representative of the group.

Figure 1: Gaze plot for English reader reading (a) English and (b) Hebrew passages

Figure 2: Gaze plot for Afrikaans readers reading (a) Afrikaans and (b) Hebrew passages

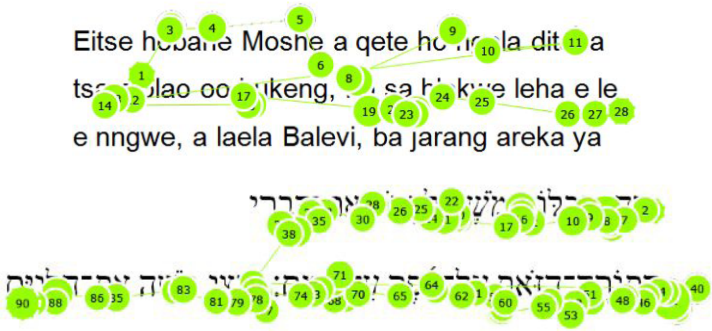

Figure 3: Gaze plot for Sesotho reader reading (a) Sesotho and (b) Hebrew passages

Inspection of the gaze plots clearly shows more and longer fixations for the Hebrew than for the home language, specifically in the case of the English and Afrikaans groups. However, since there was only one participant in the English group, this is not a conclusive observation. Similarly, the Sesotho speaking participant exhibited much the same gaze pattern in his home language and Hebrew. The study should then be extended to include larger groups of each home language in order to determine whether this behavior is representative or unique to the participant.

5.2 Number of Fixations

The number of fixations was calculated for the first two lines of each passage. The average number of fixations for the home language is 19.95, whilst for the Hebrew passage the average number of fixations is 125.79. The English and Sesotho passages both consisted of 18 words and 67 and 68 characters respectively. The Afrikaans passage consisted of 17 words and 69 characters, while the Hebrew passage consisted of 12 words and 98 characters. The table below summarises the number of words, number of characters and average fixations per word for home language, taking the various languages into account, and Hebrew:

	Average number of fixations	Average fixations per word	Average fixations per characters
Home language	19.95	1.16	0.29
Hebrew	125.79	10.48	1.28
	$t(18) = 5.79$, $p < 0.05$	$t(18) = 6.16$, $p < 0.05$	$t(18) = 6.45$, $p < 0.05$

Table 2. Fixations in home language and in Biblical Hebrew

Paired t-tests for each of these metrics show that there is a significant difference between the average number of fixations, the average number of fixations per word, and the average number of fixations per character. Therefore, the participants struggled significantly more to read the Hebrew passage than the passage in their home language.

Regressive saccades

The mean number of regressive saccades when reading the home language passage ($\bar{x}$ = 1.6) is slightly less than the mean number of regressive saccades when reading a Hebrew passage ($\bar{x}$ = 2.5). A paired-test was used to test the following null hypothesis:

> $H_{0,1}$: *There is no difference between the mean number of regressive saccades of a reader when reading in their home language and when reading in Hebrew.*

Since $p < 0.05$ ($t=2.66$, $df=18$), the null hypothesis could be rejected, indicating that the number of regressive saccades is significantly more for Hebrew reading than for home language reading. Since readers fixate on each word and for longer periods, they concentrate on each separate word and read it before moving on. Because of this, one might expect that there may be less need for regressive saccades than when reading more fluently, as with the home language. However, this was not found to be the case as the Hebrew reading had significantly more regressive saccades.

6. Discussion

6.1 Eye-Tracking Metrics

With all the eye-tracking metrics analyzed, it was shown that the participants struggled significantly more whilst reading the Hebrew passage than while reading the passage in their home language. Fixation lengths were significantly longer, indicating that the participants expended more cognitive resources while reading in Hebrew. Furthermore, participants required more fixations per word and per character in order to read the Hebrew. This directly relates to the perceptual span of the reader, as readers can generally see more characters than those they are fixating on.[98] However, the perceptual span is dependent on the orientation of the text,[99] and since

98. Hyrskykari, *Eye in Attentive Interfaces*.

99. Ibid.

participants were all accustomed to reading left-to-right, their perceptual span would have been attuned to extend towards the right of their fixation. Therefore, they required more fixations in order to perceive the entire word when reading right-to-left. Increased regressive saccades also indicate that participants had to return to prior words or characters in order to successfully read the passage. In conclusion, there was increased difficulty when reading Hebrew, which is not entirely unexpected as the majority of the participants had very little experience in reading Hebrew.

6.2 Reading ability

Although our focus is on speed rather than accuracy (as discussed in sections 5.1 and 5.2), the following brief points are worth mentioning regarding pronunciation accuracy, especially in interpreting ambiguities in vowel orthography.

One question that we were particularly interested in is that of the interpretation of vocal versus silent *shewa*. Since fixation time relates to cognitive processing time, we were interested to know whether all *shewa*s are, on average, equally difficult to process or whether *shewa*s in some positions in the word are more difficult. Our findings can be summarised as follows:

First, when students encountered a known word and an unknown word with the same morphological structure and approximately the same phonological shape, they found it more difficult to process the *shewa* in the unknown word. In our text, the word דִּבְרֵי has a *shewa* in the middle of the word which must be interpreted by students as a silent *shewa*. The word was known by students and had relatively shorter fixations. By contrast, in pronouncing the word שִׁבְטֵיכֶם, which was not known to students, students required long fixations to cognitively process the silent *shewa* in the middle of the word, although the length (and thus greater phonological complexity) of the word may have also been a factor. The unknown word זִקְנֵי, which is precisely identical to דִּבְרֵי in shape, would have made an excellent word for comparison, except that it appeared too late in the text and the fatigue of the students may have contributed to the long fixation times. A similar example with almost identical words involved the word וַיְהִי, which has been learned by students and which most students were able to pronounce without excessive fixation, and the word וַיְצַו, which was not known by students at the time they read the text and which resulted in very long fixations. We therefore conclude as a first working hypothesis that words which students have encountered previously require less cognitive processing to pronounce.

Second, we examined instances of vocal *shewa* appearing in the initial syllable of a word. We found that students had relatively shorter fixation times for the initial syllable of the words וְהָיָה, וְאֵת, וְשַׂמְתֶּם, all of which involve a morphologically distinct first syllable—the conjunction *waw*. We also found relatively short response times which were comparable to those with conjunctive *waw* for the *shewa* in the initial syllable of the words כְּכַלֹּות, בְּךָ, בְּעוֹדֶ֫נִּי. We hypothesise that in these environments the fact that the individual syllable is a separate morpheme (an inseparable preposition) assists with the phonological processing of the word. Evidence from Modern Hebrew has demonstrated that readers process the orthographic structure of the word and the morphological structure of the word separately. The congruence of these two types of structure appears to aid in pronunciation. Less clear results were obtained concerning the word בְּרִית. The fact that the processing time for the initial syllable was roughly comparable even though the word is only one morpheme might be used as counter-evidence against our hypothesis that morphological information is significant for cognitive processing. However, because students knew this word, this fact could also result in decreased processing time. In future research, we wish to test this hypothesis further.

6.3 General overview

The perspective presented in this exposition is not a causal model, but rather a framework for understanding cognitive complexity related to the lack of fluency in Biblical Hebrew pronunciation among participants who were still inexperienced in this skill. Similarly, by viewing the findings regarding pronunciation through the lens of complexity (non-linear dynamics) one opens up the potential for a holistic view of the results,[100] which then includes neural occurrences, which could lead to changes in the mind and body, and in turn influence and be influenced by the communication context, situation, purpose of the task, attitudes, anxiety, and fear of negative evaluation.

In accordance with the exposition in 3.5 and the cognitive action sequences described and discussed above, the Biblical Hebrew letters and morphemes that were seen and processed prime the visual pathways involved in their processing and should be processed faster subsequently.

Our research adds to the body of literature affirming the cognitive complexity of Biblical Hebrew. It strengthens the findings in the literature mentioned that especially the visuo-spatial and orthographic complexity

100. See Packman and Kuhn, "Looking at Stuttering through the Lens of Complexity"; and Packman, *Theory and Therapy in Stuttering*, 228, 230.

of written Semitic languages slows down reading. The novel contribution of our findings lies especially in the eye-tracking results that show a high level of regressive saccades in the Biblical Hebrew texts, which reveal that in addition to being slowed down by complex orthography, even for pronunciation, some participants were slowed down because of their reliance on sentence context and morpho-syntactic information for problem-solving.

7. Conclusions

The initial explorations in an analysis of Biblical Hebrew reading using eye-tracking technology as reported here have a number of implications for the teaching of Biblical Hebrew:

First, it seems that the overall direction of Hebrew script from right-to-left presents some difficulty for students whose home language is written in a left-to-right script. This fact probably accounts for the increased regressive saccades in reading Hebrew as compared with reading in the home language.

Second, in interpreting the orthographically ambiguous *shewa*, students found a *shewa* in the initial syllable of a word easier to process than a *shewa* in the middle of the word. There are three possible explanations: (a) word initial position is an unambiguously vocal *shewa* and therefore easier to process; (b) word initial *shewa* often has a morphologically distinct item, such as the conjunction *waw* or the clitic preposition *beth*. The morphological boundary assisted students in identifying and correctly pronouncing the morpheme. (c) The word in the sample that does not involve a morpheme boundary was known to the students and thus required less orthographic processing to pronounce. We hope to explore the issue of orthographic ambiguities and their cognitive processing in future research.

Third, recall that acquiring the ability to read as a child involves three major phases: First, there is a brief "pictorial stage" in which children's brains "photograph" a few words. Second, there is the phonological stage in which children learn how to decode graphemes into phonemes. Third, there is the orthographic stage in which word recognition becomes fast and automatic. The reading skills of the Hebrew students are mostly in the phonological stage in which they learn how to decode graphemes into phonemes. Before they can reach the third phase in which recognition becomes fast and automatic, they have to internalize at least enough vocabulary. This gives support to teaching methods where the teaching of the alphabet and reading is postponed or where at least the focus is initially on spoken communication rather than reading.[101]

Finally, we wish to return to an observation made in Zevit concerning the study of Biblical Hebrew:

> The grammatical study of biblical Hebrew, which has continued more or less unabated since the eighth century of the common era, has traditionally been broadly focused, responding not only to "How and why does a text mean?" but also to "What does it mean?" In other words, it has never severed the nexus between exegesis and eisegesis, between text hermeneutics and the grammatical triad of phonology, morphology and syntax. This situation prevails, on the one hand, owing to the unique position of the Bible in Western civilization and its compartmentalization as an object of study primarily in university departments of religion and in denominational seminaries; on the other, it prevails because, apart from the Bible, we possess no significant, extended text in Judahite or Israelite Hebrew from the tenth through the fourth centuries B.C.E. on which we can perform our analysis uninfluenced by a 2000-year tradition of reading. Because the study of grammar, narrowly defined, has presupposed an understanding of the text, grammar has been pressed into the service of semantics. It is a rare and, I believe, a relatively modern phenomenon when an insight into grammar has led to a new appreciation of "meaning" on the semantic level.[102]

It may just be that a visual grammar based on an eye-tracking perspective of cognitive complexity in Biblical Hebrew pronunciation provides such a novel, yet anticipated, appreciation of meaning.

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101. See, e.g. Buth, *Living Biblical Hebrew*; Overland, *Learning Biblical Hebrew Interactively*.

102. Zevit, "Talking Funny in Biblical Henglish," 25.

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