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The prosodic property of lexical stress affects eye movements during silent reading

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Abstract

The present study examined lexical stress in the context of silent reading by measuring eye movements. We asked whether lexical stress registers in the eye movement record and, if so, why. The study also tested the implicit prosody hypothesis, or the idea that readers construct a prosodic contour during silent reading. Participants read high and low frequency target words with one or two stressed syllables embedded in sentences. Lexical stress affected eye movements, such that words with two stressed syllables took longer to read and received more fixations than words with one stressed syllable. Findings offer empirical support for the implicit prosody hypothesis and suggest that stress assignment may be the completing phase of lexical access, at least in terms of eye movement control.

Keywords

Prosody; Lexical stress; Reading; Implicit prosody; Eye movements

Since Huey (1908/1968), researchers have claimed that readers impose stress and intonation patterns during silent reading and, thus, experience inner speech (Brown, 1958; Rayner & Pollatsek, 1989). The presence of prosody during silent reading is intuitively apparent, as inner speech seems to mirror the intonation patterns of external speech. Paradoxically, inner speech is generated while reading text that does not explicitly encode most prosodic information. The present study investigated whether prosodic processing occurs during silent reading. Finding evidence of prosody would suggest that readers supply prosodic information that is not provided by the orthography. Fodor (1998) stated this idea in the implicit prosody hypothesis, which claims that readers impose a prosodic contour on text as they read it silently.

As yet, little experimental evidence exists for prosody during silent reading in English (but see Bader, 1998; Slowiczek & Clifton, 1980). This may reflect the difficulty of manipulating sentence prosody in written text, since the prosody of full utterances (e.g. the placement of pitch accents and prosodic boundaries) shows substantial optional variation and is not uniquely determined by the content of a sentence (Schafer, Speer, Warren, & White, 2000).

Lexical stress has far less variation than sentence prosody. Each word carries specific stress information that is part of its underlying identity (e.g. CONvict and conVICT are distinct words). Although the surface expression of stress can be modified (e.g. in fast speech or in conditions of stress shift), lexical stress plays an important role in spoken language production and perception (Greenberg, Carvey, Hitchcock, & Chang, 2003). Adults are more likely to omit unstressed syllables than stressed syllables when speaking (Carter & Clopper, 2002). Mattys and Samuel (1997) demonstrated that mispronunciations of stressed syllables impaired lexical access more than mispronunciations of unstressed syllables. Colombo (1992) reported

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faster naming times for visual Italian word with regular than with irregular stress patterns (but only for low frequency words). Cooper, Cutler, and Wales (2002) reported faster naming times for visually presented words when they were preceded by stress-matching, rather than stress-different, spoken primes.

Although lexical stress is a salient phonological property of spoken language, it is not encoded in the writing system of English. The present research explores whether the prosodic property of lexical stress affects eye movements during silent reading. Eye movements were used to examine lexical stress effects, as fixation durations are sensitive to word recognition processes (Rayner, 1998). Specifically, we asked whether it took longer to read words that contained more stressed syllables than words that contained fewer stressed syllables. We focus on the effect of number of stressed syllables because Sternberg, Monsell, Knoll, and Wright (1978) reported that this variable affected the time to retrieve words from memory. In Section 3, we consider our results with respect to Sternberg et al. raising the question of whether our effects in silent reading reflect differences in time to recognize words or to prepare or execute implicit speech. We also discuss the implications of our results for the E-Z Reader model of eye movement control in reading (Reichle, Rayner, & Pollatsek, 2003; Reichle, Pollatsek, Fisher, & Rayner, 1998).

1. Methods

1.1. Participants

Thirty-two native English speakers with normal vision from the University of Massachusetts participated in the experiment for \$5 or course credit.

1.2. Apparatus and procedure

Stimuli were presented by a Pentium PC. An A to D converter interfaced the computer with a Fourward Technologies Generation V Dual Purkinje eyetracker. The eyetracker monitored the right eye, and viewing was binocular. Letters were formed from a 7×8 array of pixels, using the fixed-pitch Borland C font. Participants sat 61 cm from a computer screen and silently read single line sentences while their head position was stabilized by a bite bar. At this distance, 3.8 letters subtended 1° of visual angle. At the beginning of the experiment, the eye-tracking system was calibrated for the participant and practice items were presented. At the start of each trial, a check calibration screen appeared, and participants were re-calibrated before the next trial if necessary.

A trial consisted of the following events. The check calibration screen appeared, the participant looked at the far left calibration square, and the sentence appeared. The participant read silently at his or her own pace while eye movements were monitored. When the participant finished reading the sentence, he or she clicked a response key to blank the screen. Following a quarter of the sentences, a yes/no comprehension question appeared that was answered by pressing a response key. The experiment was completed in one 30-min session.

1.3. Materials

Participants read 42 target sentences randomly interspersed with 70 fillers (examples are shown in Table 1). Each sentence contained one of two possible target words, and the counterbalanced design yielded data for 84 words. Presentation order was randomized for each participant. Words were selected from the CELEX database such that one word in each pair had one stressed syllable and the other had two stressed syllables (see Appendix)¹. Each stress pair was matched for number of letters and syllables, part of speech, and frequency category (i.e. high or low). Obtaining enough items made it necessary to sample from a wide range of occurrence frequencies. Because word frequency is known to have large effects on eye movements

(Rayner, 1998), frequency was added as a factor in the design. The addition of frequency also provided a test of one possible locus of the effect of lexical stress (see Section 3). Twenty-two pairs of high frequency words and 20 pairs of low frequency words had a mean of 108 and 3.9 occurrences per million, respectively (Francis & Kučera, 1982). On average, the one-stress targets occurred in text 63.3 times per million words, and the two-stress targets appeared 53.0 times per million words ($t(41) = 1.17$, ns).

Various measures confirmed that American English speakers pronounced the one stress and two stress words differently, including spoken word durations and syllable amplitudes. First, we measured durations of the words spoken in a list and in the sentence contexts in which they were read during the experiment. The list-recitation measure provided information about the time to prepare and name the words in citation form. Twelve participants recited 12 six-word lists. These 72 words were randomly chosen from the 84 in the primary experiment. Each list contained words with one stressed syllable or words with two stressed syllables, separated by the word *and* in order to minimize slurring between words, and each list was spoken twice. Using a waveform editor (Cool Edit Pro, 1999), the mean durations for the high frequency lists containing one and two stressed syllable words were 3.854 and 4.028 s, respectively. The corresponding means for low frequency words were 4.155 and 4.344 s. On average, each additional stressed syllable added 30.5 ms to the duration of each word ($F(1,11) = 10.68$, $P < 0.01$, and $F(1,12) = 6.65$, $P < 0.05$). Next, we measured the duration of each pair of words spoken in the context of the experimental sentences. Four participants each read one quarter of the experimental materials aloud. Target words were excised from the recordings in order to measure total word duration and the peak amplitude (dB) of the four syllables using Speech Analyzer software (1996). Beckman (1986; see also citations therein) suggests that duration and amplitude are indices of syllabic stress, but notes that these indicators are strongly influenced by the identity of segments composing the syllable. Since it was impractical to match four syllable words in terms of segmental makeup, any comparison of the one and two stress words on these measures is imprecise and confounded by differences in phonemic segments. Nonetheless, the total-word measures indicated that speakers distinguished between one and two stressed-syllable words. The mean durations for one and two stress words were 567 and 623 ms, respectively, $F(1,40) = 16.80$, $P < 0.001$. The mean peak amplitude of each syllable also confirmed the presence of one additional stressed syllable in half the target words (see Table 2). The majority of two stress words had relatively higher amplitudes in the first and third syllables as compared to the one-stress words, which had second syllable stress in all, but two cases. The stress by syllable position interaction was significant, $F(2,38) = 14.15$, $P < 0.001$ (Wilks' Lambda correction).

Norming studies were conducted to assess the overall familiarity of the targets and their goodness of fit in the sentence contexts. In the first study (see Table 3), 28 participants rated the familiarity of each isolated target word on a scale from 1 (unknown) to 7 (very familiar). On average, participants rated one-stress targets as being about as familiar as two-stress targets (5.9 and 5.7, respectively), $t(41) = 1.66$, ns. In the second study (see Table 3), 45 participants rated how well the targets fit into their sentence contexts on a scale from 1 (poor fit) to 7 (good fit). On average, one-stress targets appeared to fit into their sentences about as well as two-stress targets (5.2 and 5.4, respectively), $t(41) = 1.67$, ns.

It is also possible that the morpho-phonological structure of the targets could confound our eye movement data. In particular, we were concerned that competition effects during lexical access

¹After the fact, we confirmed the CELEX stress assignments against the assignments in *Merriam-Webster's New Collegiate Dictionary* (1995). All stress assignments agreed, except for one pair of words (*referendum-legislator*). The dictionary indicated that *referendum* contained a secondary as well as a primary stress, and that *legislator* had an optional pronunciation with two secondary stresses as well as a primary stress. This pair was included in all measures and analyses except for mean peak amplitude (Table 2), but excluding it changed mean reading times by no more than 5 ms in any condition of the experiment, affecting no conclusions.

of derived words (e.g. animation) might yield longer reading times, relative to non-derived words (e.g. penicillin). To avoid this, the number of derived vs. non-derived words was balanced across conditions (see Table 3). Also, some of the derived targets underwent a stress shift compared to the source word (e.g. monotone/*monotonous*). Table 3 shows that the number of stress-shift words was comparable in each stressed syllable condition.

2. Results

The purpose of the experiment was to investigate whether the number of stressed syllables in a word affects fixation durations. Because participants read the two length-matched words in a pair presented in the same sentence context, the number of stressed syllables was treated as a within factor in both the by-participants and by-items ANOVAS.² Target frequency (e.g. high or low) was treated as a within participants factor and a between items factor.³ First fixation duration, gaze duration, and number of fixations are reported here. *First fixation* measures the mean time spent reading the first time the eye lands on the target word. *Gaze duration* measures the summed duration of all the fixations a target receives before the eyes leave it. *Number of fixations* measures how many first-pass fixations the target received.

Predetermined cutoffs were used to trim the data (Rayner, 1998). Fixations under 120 ms or over 600 ms were eliminated from the analysis since they do not seem to reflect normal cognitive processing of the target word (Rayner & Pollatsek, 1989). Approximately 5% of the data were lost due to these cutoffs and to track losses. Readers regressed from the target on 7% of the trials, which were excluded from the analyses as regressions could indicate extraneous disruptions of word recognition. Participants who answered comprehension questions at below 90% accuracy were excluded, resulting in the elimination of two subjects from the original pool of 34.

2.1. First fixation

Table 4 shows the mean first fixation times for high and low frequency target words with either one or two stressed syllables. The number of stressed syllables in the target word did not affect the duration of the first fixation on the target (all $F_s < 1$). However, first fixations on high frequency targets were 21.5 ms shorter on average than first fixations on low frequency targets, $F_1(1, 31) = 22.99, P < 0.001$, and $F_2(1, 40) = 6.76, P < 0.01$. The interaction between frequency and number of stressed syllables was not significant (both $F_s < 1$).

2.2. Gaze duration

Table 4 shows the mean gaze durations for high and low frequency target words with either one or two stressed syllables. Gaze durations on words with two stressed syllables were 36 ms longer on average than the gaze durations on words with one stressed syllable, $F_1(1, 31) = 16.45, P < 0.001$, and $F_2(1, 40) = 7.15, P < 0.01$. A robust main effect of frequency appeared, with high frequency words being read 98 ms faster than low frequency words on average, $F_1(1, 31) = 61.15, P < 0.001$, and $F_2(1, 40) = 34.44, P < 0.001$. The interaction between frequency and number of stressed syllables was not significant, $F_1(1, 31) = 1.25$ and $F_2(1, 40) < 1$.

²Some readers might prefer treating the number of stressed syllables as a between factor in the items analyses. When the data were analyzed in this way, all effects reported in the text as significant remained significant at the $P < 0.02$ level or beyond.

³Frequency effects appeared in all the eye movement data, and are reported in the tables. Frequency affected spoken durations only in the list-recitation task, and were not reported for the other duration measures.

2.3. Number of fixations

Table 5 shows the mean number of fixations for high and low frequency targets with one or two stressed syllables. On average, readers fixated more often on words with two stressed syllables than words with one stressed syllable, $F_1(1, 31) = 9.52$, $P < 0.005$, and $F_2(1,40) = 8.23$, $P < 0.01$. Low frequency targets received more first-pass fixations on average than did high frequency targets, $F_1(1, 31) = 28.16$, $P < 0.001$, and $F_2(1,40) = 14.37$, $P < 0.001$. The interaction between frequency and number of stressed syllables was not significant, $F_1(1, 31) = 1.75$ and $F_2(1,40) = 1.245$.

3. Discussion

The current experiment tested whether eye movements are sensitive to the prosodic properties of lexical stress. Words with two stressed syllables took longer to read (and were more likely to be refixated) than words with one stressed syllable, indicating that readers processed stress during silent reading. As stress information is not encoded in written English, the lexical stress effect suggests that participants supplied that phonological information during silent reading. Thus, it appears that readers did construct complex phonological representations that included prosodic information, as suggested by the implicit prosody hypothesis (Fodor, 1998).

Finding an effect of lexical stress raises several questions, including the locus of the effect and why it registers in the eye movement record. Factors that arguably affect the speed of word recognition, such as frequency, homophony, ambiguity, and predictability, generally affect the first fixation measure (Rayner, 1998). In the current study, lexical stress affected only mean gaze duration, suggesting that it affects only some later stage of lexical access. Further, effects that are arguably pre-lexical (e.g. phonological effects) are often limited to low frequency words (Jared & Seidenberg, 1990; Lee, Binder, Kim, Pollatsek, & Rayner, 1999). However, lexical stress did not interact significantly with word frequency, and significantly affected gaze duration for both high and low frequency words (although it was numerically over twice as large for low frequency words as it was for high frequency words). The effect of lexical stress on high as well as low frequency words suggests that the effect is post-lexical. The current data are compatible with Frost's (1998) claim that lexical access makes a word's full phonological form (including its stress pattern) available to the reader, since gaze duration is often considered to indicate the time needed to complete lexical access.

If the observed lexical stress effects are not pre-lexical in nature, then by what mechanism does lexical stress affect eye movements? It may be that eye movement measures are simply sensitive to factors that increase the duration of implicit speech. There is reason to doubt this, however. We measured naming durations and fixation times during reading for pairs of single-stressed one and two-syllable words that were matched for number of letters, number of phonemes, and frequency. Naming durations were significantly longer (25 ms) for two-syllable than one-syllable words. Yet, this difference was not reflected in fixation durations when the same words were embedded in sentence contexts. Forty-two participants read 48 targets in one of two sentence contexts while their eye movements were monitored. Mean first fixation durations were 279 and 277 ms for one and two-syllable words, respectively. Mean gaze durations were identical (298 ms). This dissociation of naming and fixation durations makes it unlikely that naming duration differences alone would account for the lexical stress effect.

In the current experiment, lexical stress effects did appear in both naming duration and silent reading. This suggests some relationship between speech production processes and phonological processing during reading. We do not want to claim that the actual execution of articulatory programs is involved in reading. However, inner speech processes may involve the assembly and unpacking of phonological information. Sternberg et al. (1978) observed that the latency to begin reciting a memorized list was increased by the number of stressed syllables

(not the total number of syllables). They suggested that this latency reflected the time to prepare production units, and they proposed that a lexical stress group, or phonological foot, defines a production unit. If reading involves a similar assembly of linguistic units, then foot structure may be a relevant unit in processing written as well as spoken English (Pitt & Samuel, 1990; Selkirk, 1982).

Given the ample evidence that eye movement control is tightly linked to lexical access (Reichle et al., 2003), finding lexical stress effects probably indicates that stress assignment is a customary part of word recognition for skilled readers. If stress effects arise from the additional time needed to assemble more units for phonological recoding, then those assembly processes might be the completion phase of lexical access, at least in terms of triggering an eye movement to the next word. In this scenario, stress information accompanies lexical access, including how many stress units will be assembled for phonological recoding. The eyes remain on a word until the phonological units are assembled. Words with two stressed syllables involve assembling two units for one lexical item, rather than a single unit. This additional work could demand an additional fixation on the word. Once the assembly of units completes, the eyes move to the next word.

In summary, our data indicate that lexical stress affects when the eyes leave a word, influencing both the number and duration of first-pass fixations during silent reading. Words with two stressed syllables took longer to read and received more refixations than words with one stressed syllable. If the primary influence on probability of refixation is incomplete lexical access, then the assembly of stress units may be an integral part of word recognition. Finding that the prosodic property of lexical stress affects eye movements suggests that skilled readers construct fully formed phonological representations during silent reading.

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Appendix

One stressed syllable

High frequency

intensity
 authority
 community
 development
 significant
 appropriate
 professional
 relationship
 experiment
 dictionary
 efficiency
 particular
 executive
 impossible
 philosophy
 machinery
 available
 intelligence
 traditional
 historical
 responsible
 establishment

Low frequency

geography
 geometry
 medicinal
 atypical
 predicament
 provocative
 regrettable
 preposterous

photographer
incompetence
affirmative
enjoyable
insanity
adaptable
hysterical
rhinoceros
monotonous
repetitive
despondency
referendum

Two stressed syllables

High frequency

radiation
education
situation
competition
fundamental
independent
intellectual
independence
publication
application
preparation
democratic
individual
scientific
resolution
television
operation
conversation
residential
population
legislative
circumstances

Low frequency

emigration
animation
penicillin
honorary
persecution
maladjusted
detrimental
ostentatious
entrepreneur
exploitation
catastrophic
patriotic
ultimatum
acrobatic
amateurish
hemoglobin
incoherent
asymmetric
deprivation
legislator

Table 1

Example materials

<i>High frequency, one stressed syllable</i> Poverty is the most <i>significant</i> problem in our society today. Tom's recent <i>experiment</i> was regarded highly by his colleagues. Many nations admire the <i>particular</i> style of government in the United States. The students loved the <i>traditional</i> college atmosphere. The voters approved of the <i>responsible</i> actions taken by the new governor.
<i>High frequency, two stressed syllables</i> Poverty is the <i>most fundamental</i> problem in our society today. Tom's recent <i>publication</i> was regarded highly by his colleagues. Many nations admire the <i>democratic</i> style of government in the United States. The students loved the <i>residential</i> college atmosphere. The voters approved of the <i>legislative</i> actions taken by the new governor.
<i>Low frequency, one stressed syllable</i> Ken dressed for Halloween in his <i>preposterous</i> bird costume. The newspapers publicized the <i>incompetence</i> of the auto-workers. Susan will take a course in <i>geometry</i> next semester. Bob said that his girlfriend's <i>insanity</i> really frightened him. The mother of the <i>provocative</i> teenager wondered what she had done wrong.
<i>Low frequency, two stressed syllables</i> Ken dressed for Halloween in his <i>ostentatious</i> bird costume. The newspapers publicized the <i>exploitation</i> of the auto-workers. Susan will take a course in <i>animation</i> next semester. Bob said that his girlfriend's <i>ultimatum</i> really frightened him. The mother of the <i>maladjusted</i> teenager wondered what she had done wrong.

Table 2

Means of the peak amplitude per syllable for words spoken in sentence contexts

	Syllable 1	Syllable 2	Syllable 3	Syllable 4
<i>One stressed syllable</i>				
Stress pattern	Weak	Strong	Weak	Weak
Peak amplitude	-16.34	-14.12	-18.62	-18.13
<i>Two stressed syllables</i>				
Stress pattern	Strong	Weak	Strong	Weak
Peak amplitude	-13.87	-17.68	-15.38	-17.89
Difference (stressed – unstressed)	2.47*	3.56*	3.24*	NA

Decibels (dB) relative to full 16-bit amplitude (* $P < 0.005$).

Table 3

Characteristics of one stressed syllable targets and two stressed syllable targets

	High frequency		Low frequency	
	One stress	Two stress	One stress	Two stress
Frequency (per million)	117	98	4.5	3.2
Number of letters	10.9	10.6	10.1	10.3
Familiarity of target	6.4	6.3	5.5	5.0
Target fit into sentence	5.3	5.5	5.0	5.4
Derived words (<i>n</i>)	18	18	15	16
Stress-shift words (<i>n</i>)	4	4	5	5

Table 4

Measures of processing time on the target word (ms)

	Stress	
	One stressed syllable	Two stressed syllables
<i>First fixation</i>		
High frequency	282	282
Low frequency	300	307
<i>Gaze duration</i>		
High frequency	360	382
Low frequency	444	494

Table 5

Number of first-pass fixations

	Stress	
	One stressed syllable	Two stressed syllables
High frequency	1.31	1.37
Low frequency	1.48	1.64