Individual differences in visual comprehension of morphological complexity

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Abstract

This paper explores variability in individual strategies of processing morphologically complex words. We examined the eye-movement record that 71 readers showed during reading of suffixed words (*truck+er*): the readers also took part in a battery of 17 skill tests, which allowed for a fine-grained characterization of their verbal abilities. Statistical analyses revealed that an individual's ability to segment words as well as his or her level of reading comprehension shifted the balance between recognition of a complex word as a whole and its recognition via decomposed morphemes. Effects of whole-word frequency and base morpheme frequency were observed in both good and poor readers, yet their qualitative nature varied by skill. Good readers suffered from lexical competition between whole words (*trucker*) and base morphemes (*truck*), while poor readers received a recognition boost from base words. We discuss these interactive patterns in the context of computational models of morphological processing and argue that readers strategically adjust weights of different sources of morphological information, depending on the quality of the lexical representation for both the complex words and their morphemes.

Keywords: word recognition; morphological processing; individual differences; computational models; eye-movements

Introduction

There is a growing consensus in word recognition research that human comprehenders simultaneously access multiple sources of morphological information: lexical forms of whole complex words (*trucker*), their morphemes (*truck*, *-er*), and their morphological families (*trucking, truckload, firetruck*). Prior work has extensively explored the link between formal, semantic and contextual properties of words that affect the degree of engagement of the different sources of probabilistic information (distributional, semantic, syntactic, phonological and other) in lexical access of complex words (e.g., Bertram, Pollatsek, & Hyönä, 2004). Evidence points to a processing system in which higher-frequency, shorter or semantically opaque complex words tend to rely more on full-form representations, while words with higher-frequency, larger-family, or otherwise easily identifiable morphemes are preferentially recognized via decomposed morphemes (e.g., the dual-route model of Baayen, Dijkstra & Schreuder, 1997). Recognition via full-forms is suggested by effects of whole-word properties (such as frequency of occurrence or length) and morpheme-based processing is diagnosed by effects of morphemic properties (morpheme frequency, family size, affix productivity or length, etc.). The parallel engagement of processing routes shows up in the interactions of whole-word and morphemic properties, attested in behavioral measures throughout the entire time-course of word recognition. The interactions reported thus far in the literature indicate competition between information sources, such that whole-word frequency effects are weakened in words with higher-frequency or otherwise salient morphemes (see Kuperman, Bertram, & Baayen, 2010, and references therein). The parallel operation of multiple access routes, as well as trade-offs between the routes, are at the core of several computational models of morphological processing: for example, trade-offs were implemented as simultaneous activation and lexical competition of words that match the perceptual input (Baayen & Schreuder, 2000), or as the simultaneous adjustment of weight coefficients for the amounts of information associated with distributional properties of complex words, their morphemes and morphological families (Kuperman, Bertram, & Baayen, 2008).

Importantly, these models have developed for the most part independently of a large body of reading research that suggests that efficient word recognition is not simply about linguistic characteristics of words, but rather about linguistic characteristics of words *as learned by particular individuals* (but see Reichle & Perfetti, 2003). While some subjective aspects of lexical variables have been investigated earlier (e.g., Balota et al., 2004 and references therein), relatively little is known about how engagement of the information sources contributing to recognizing complex words is modulated by the skill-level of individual readers (see however Carlisle & Katz, 2006 for morphological processing in children). The present study aims at characterizing variability in processing strategies that readers of different skill levels employ when reading complex word structures. As a diagnostic, we use the interactions between individual scores in skill tests that tap into particular verbal abilities (e.g., word decoding, word segmentation, reading comprehension) on the one hand, and the distributional properties of the full-form of complex words and their component morphemes, on the other hand.

We take as a guiding assumption the idea advocated iby the Lexical Quality hypothesis (Perfetti, 2007) that individuals differ in the average quality of their word representations. High quality lexical representations are characterized by i) highly automatic associations of precise orthographic forms to the phonological representations learned during oral language acquisition; ii) automatic associations of these same phonological representations to semantic representations; and iii) a highly elaborated and redundantly specified semantics, encompassing the full variety of syntactic and semantic contexts for the word (cf. Seidenberg & McClelland, 1989; Harm & Seidenberg, 1999 for a connectionist implementation of some aspects of this idea). Concomitant with high quality lexical representations is a qualitative, experience-dependent shift from deliberate constituent-based decoding (e.g., letter-by-letter, or syllable-by-syllable reading) to a unitary, fully-specified representation of individual words (Perfetti, 1992; 2007; see also Andrews, 2008; Ehri, 1999 for similar proposals). This perspective leads to markedly different predictions about how morpheme-based sources of information may affect word recognition. Namely, individuals who possess a higher proportion of full-form lexical representations may suffer interference from similar lexical forms: in morphologically related forms this similarity is afforded by a substantial orthographic, phonological and, typically, semantic overlap (compare *truck* and *trucker*). On the other hand, these same sources of interference would not be present for individuals without full-form representations of most words. Rather, the constituent-based word recognition strategy employed by these readers may be facilitated by the ability to identify segments of words, be they affixes, base words or lexical constituents of compounds. To examine these hypotheses further, we focus on individual skill measures that provide an index of lexical quality, the subskills required to produce high-quality lexical representations, and general reading comprehension ability.

Methods

Stimuli: Our data source is the eye-movement record for 69 English suffixed words (*sing+er*) read silently within unrelated sentences by 71 participants, e.g., *The well-known singer thanked his fans during intermission.* All target words were semantically transparent, and ended in one of three productive suffixes: *-er/-or* (noun), *-ist* or *-ing* (adjective). The suffixed words offered natural variability in the frequencies of whole words and base morphemes. Our choice of suffixes restricted their distributional and orthographic characteristics, allowing us to focus on the interaction of derived words and their bases. The preceding contexts were semantically neutral.

Participants: Participants (43 females; 28 males) belonged to the age group of 16-24 (mean = 20.8; SD = 2.6). In order to maximize variation in reading ability, we recruited from the local community and only accepted non-college-bound individuals (formal level of education did not exceed the equivalent of high school). All were native English speakers, and none had a diagnosed reading or learning disability. In addition to the reading task, participants undertook a battery of 17 reading ability tests, chosen based on previous research outlining the component factors of reading ability (e.g., Scarborough, 1998; Vellutino et al., 1996). The observed range of scores in skill tests was considerable and their distributions were nearly uniform with a slight skew towards higher scores. In the word segmentation task (see below), scores ranged from the equivalent of the 2nd grade to the equivalent of the 10th grade (mean = 6.4, sd = 3.8); in the reading comprehension Peabody Individual Achievement Test-Revised the lowest score was the equivalent of the 4th grade, and the highest was the first year of college (mean = 9.8, sd = 4.3).

Battery of skill tests: The 17 tests of the battery targeted individual ability at the sub-word, word, and sentence-level. They included measures of phonological processing (e.g., phonological awareness, phonological memory, and rapid naming), grapheme-to-phoneme decoding, working memory, and both listening and reading comprehension ability. To foreshadow the results, the skill tests that proved to have the strongest impact on the choice of processing strategies were the word and non-word segmentation tests and two tests of reading comprehension, both described below. As other tests did not show consistent reliable interactions with the properties of full-forms and morphemes, we do not discuss them further.

1. *Word and nonword segmentation tasks*: Participants were instructed: "I'm going to say a word and I want you to repeat it. Then say the word one sound at a time. Say each sound that you hear in the order that your heard it. For example, if I say "me", you would say the word "me" and then you would say m-ee." Twenty trials were given with 2-8 phoneme-long words, and another twenty trials with 2-8 phoneme-long nonwords.

2. *Peabody Individual Achievement Test-Revised* (Dunn & Markwardt, 1970): In this reading comprehension test, participants read a list of increasingly difficult sentences and then choose a picture, from an array of four, that best matches the meaning of the sentence. Notably, difficulty is increased mainly with respect to vocabulary items in the sentences, and not complexity of the sentence structure. Odd-numbered items from the subtest were administered, with a stop condition of 5 errors in 7 consecutive items.

3. *Fast Reading subtest of the Stanford Diagnostic Reading Test* (Karlson & Gardner, 1995). This reading comprehension test consists of a short expository passage containing 30 choice points (similar to a cloze format) at which the participant is required to select the appropriate word from among three alternatives. For example, the test begins "San Francisco, California is known as the city with cable cars. These are essentially street..." (here the participant must choose between "cleaners", "cars", or "lights") "that are pulled up or down the steep hills of that city by means of a.." (again participants must choose, choices are "horse", "sail", or "cable"). In previous work with this population, we determined that the proportion of correct responses was a better indicator of their ability than their absolute score, thus all analyses reported here are based on the proportion correct measure.

Procedure: Participants were seated in front of a 17-in. display with a refresh rate of 85.03 Hz with their eyes approximately 64 cm from the display. They wore an EyeLink II head-mounted eye tracker (SR Research, Mississauga, Canada), sampling at a rate of 250 Hz from both eyes. Sentences were presented one at a time on a single line, with a maximum of 90 characters, using a monospace font. Type size was such that 3.5 characters occupied 1 degree of visual angle. The eye tracker was calibrated using a series of nine fixed targets distributed around the display, followed by a 9-point accuracy test. Data from the right eye only were analyzed, except for one participant for whom only the left eye calibration was valid. Comprehension questions occurred on 55% of trials. Participants indicated their answer by pressing the associated button on a button box.

Variables and statistical analyses: We fitted linear mixed-models to the temporal eye-movement measures associated with the target words: first fixation duration; single fixation duration (duration of the single fixation on the word before the gaze leaves the word for the first time); gaze duration (summed duration of fixations on the word before the gaze leaves the word for the first time), as well as total fixation time (summed duration of fixations on the word). Critical predictors were log frequency of the suffixed word and that of the base word (both estimated from the 410 million token Corpus of Contemporary American English by Davies (2008)), as well as individual scores in 17 tests of verbal skills. (The size of morphological family for the base word showed weaker predictivity of reading times than base word frequency and is not reported further.) To avoid the harmful impact of collinearity between measures of individual performance on the models' estimates, we fitted multiple models to each of the dependent variables with exactly one test score at a time. Controls included the length of the suffixed word and the base word; word position in the sentence; presence of skips prior to or after the target word; productivity of suffix; and others. The random effects structure was established using the log-likelihood ratio model comparison test and included participant, word, and suffix as intercepts as well as several random slopes.

Results and Discussion

We trimmed the eye-movement data by removing fixations that were shorter than 50 ms and longer than 1,000 ms, and we pooled adjacent fixations that landed within one character (about 12% data). The resulting data pool consisted of 4,738 data points for gaze duration and total fixation time (and 3,247 for single fixation duration). Our criterion for considering a test of verbal skill as relevant for complex word recognition was whether the test scores entered into statistically reliable interactions with both log frequency of the suffixed word (*trucker*), and log frequency of the base morpheme (*truck*) for the given dependent variable. Three-way interactions of skill by base frequency by whole-word frequency did not reach significance in any of our models, possibly due to insufficient statistical power. Since these frequencies separately diagnose access to either a full-form or a constituent (see Introduction), we took the presence of simultaneous interactions between each type of lexical frequency and skill as evidence that skill affected the efficiency of one of the morphological processing mechanisms. Several tests passed this criterion in the models fitted to single fixation and gaze duration (other eye-movement measures did not reveal consistent interactive patterns and are not reported further). Individual scores in the reading comprehension Stanford Diagnostic Reading test interacted with log suffixed word frequency and log base word frequency in models fitted to both single fixation and gaze durations, while the Peabody Individual Achievement Test and segmentation tasks showed similar interactions in respective models for gaze duration. We return to this finding in the General Discussion.

Qualitatively, interactions followed the same patterns across tests and dependent measures. All readers demonstrated negative effects of whole-word frequency, while the effect was much greater on readers with lower scores on the tests listed above. Moreover, the contrast in processing times between relatively poor and good readers was maximal in low-frequency words, see Figure 1. This interaction replicates the Word Frequency x Skill interaction documented in eye-tracking literature (Ashby et al., 2005; Hawelka et al., 2010; Kuperman & Van Dyke, 2011). The same interaction has been observed in naming and lexical decision tasks (e.g., Pugh et al., 2008; Shaywitz, 2003). We interpret this interaction as an indication that higher-frequency words have good quality representations in the mental lexicons of both good and poor-performing readers, with particularly strong associations between the word's meaning and its orthographic form, gained through repeated exposures to the word. These associations alleviate the disadvantage that arises from poor-readers' inferior grapheme-to-phoneme associations, which leads them to have greater difficulty when they must engage sublexical processing to read words for which they have not stored full-form orthographic representations (i.e., infrequent words), see Strain & Herdman (1999).

The unique contribution of this paper is the observed interaction of skill by log frequency of base morpheme (*truck*). Readers with the strongest performance in the comprehension and segmentation tasks showed a positive correlation of eye-movement latencies with base word frequency (the dashed light-grey bottom line in Figure 2). That higher-frequency base words slowed down the recognition time for the derived words suggests lexical competition between morphemes and full-forms in skilled readers. Competition appeared to increase when base morphemes were more entrenched in an individual's mental lexicon due to their high frequency of occurrence. Crucially, the positive correlation of base frequency with eye-movement durations weakened in readers who performed less well in the selected tasks, and finally the correlation became *negative* in readers with poor comprehension or segmentation skills (the solid top line in Figure 2). We interpret this change in polarity as suggestive of readers with the poorest skills receiving a recognition boost from identifying the base morpheme (*truck* in *trucker*), and that the boost is stronger, the more frequently this morpheme occurs in the language. Readers in the mid-range of test scores show

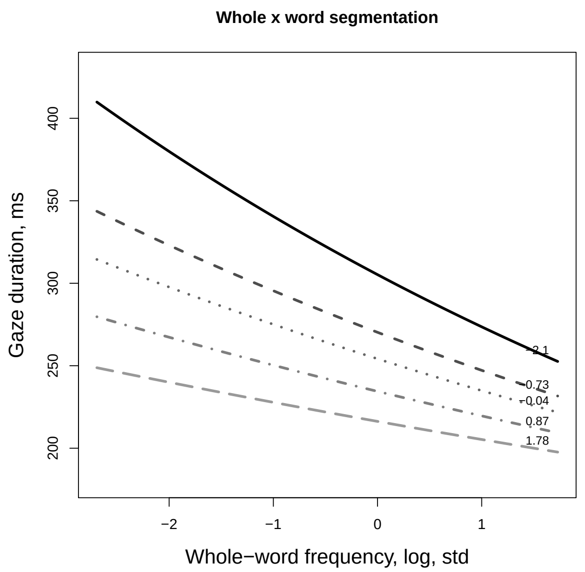

Figure 1: Interaction plot for gaze duration: log suffixed word frequency (standardized) by segmentation test score (standardized). The lines plot the effect of derived word frequency for the quartiles of segmentation test score (quantile values provided at the right margin). Word frequency comes with the strongest negative effect at the 1st quartile (solid line), the effect gradually levels off at the 2nd quartile (dashed line), the 3rd quartile (dotted line), and the 4th quartile (dotdash line), and is the weakest in the top performers in the test, the 5th quartile (longdash line). Same interaction was observed for comprehension tests.

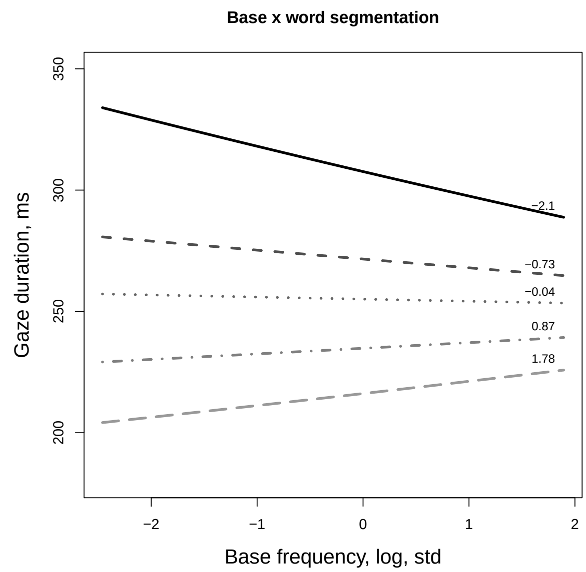

Figure 2: Interaction plot for gaze duration: log base morpheme frequency (standardized) by segmentation test score (standardized). The lines plot the effect of base frequency for the quartiles of segmentation test score (quantile values provided at the right margin). Base frequency comes with the negative effect at the 1st quartile (solid line), the effect reverses its direction and becomes increasingly positive through the 2nd quartile (dashed line) to the 5th quartile (longdash line). Same interaction was observed for comprehension tests.

only moderate reliance on morphological structure, as evidenced by weak correlations of their eye-movement latencies with base word frequency: in this subpopulation, the derived words are identified without noticeable competition with or boost from their morphemes.

General Discussion

Our eye-tracking study of English suffixed words revealed two novel patterns in morphological processing. First, we observed that the degree of engagement of whole-words and morphemes in the recognition of complex structures is affected by individual performance in a small subset of the 17-test battery that tapped into most major components described in the literature: namely, word and nonword segmentation tasks, and the two reading comprehension tests. Predictivity of segmentation tasks for morphological processing is not surprising, and is perhaps the most indicative of our skill measures, as segmentation is a direct index of the ability to parse out the embedded morphemes from a string of characters. This ability demonstrably depends on well-studied phonological, orthographic and distributional properties of morphemes (e.g., Laudanna & Burani, 1995). The present study additionally points to the import of individual aptitude at segmentation, and not just properties of the word, as a determiner of morphological decomposition.

The predictivity of the two reading comprehension tests, which produced an identical interaction, points to the link between the overall quality of an individual's lexical representations and comprehension. In particular, these tests are the only tests in our battery that specifically tap into *semantic* aspects of an individual's lexical representation, and hence may serve as an index of the amount of interference arising from similar-meaning morphological neighbors. It goes without saying that poor word knowledge, either at the decoding stage where the relationship between orthography and the phonological representations of known words is unlocked, or else at the meaning stage presents a significant barrier to text comprehension. A question for further research is the relationship between the deficit at the level of word (morpheme) segmentation and that at the level of comprehension; one could imagine that segmentation problems could play a significant causal role in producing poor comprehension, although admittedly there are a range of other contributing factors that may also play equally significant or greater causal roles.

Our results are consistent with the predictions of the Lexical Quality hypothesis (Perfetti, 2007). It follows straightforwardly that the increased quality of the lexical representation of base morpheme, measured by its higher frequency of occurrence, would lead to its automatic activation, increased interference and a larger effort necessary for inhibiting the meaning of the base morpheme and the correct identification of the meaning of the whole-word. Conversely, word decoding may not be an automatic process for readers with inferior verbal skills: poor readers are often engaged in sublexical word processing, due to weak orthography-phonology and phonology-semantics associations in their lexical representations (e.g., Coltheart et al., 2001). Poor readers are more likely to recruit information about the form and meaning of morphemes as a cue for the meaning of the whole complex word in order to compensate for absent or inferior full-forms. Hence, for these readers, sublexical components serve as an *aid* for word recognition, rather than a source of interference. With the left-to-right direction of reading and suffixation under study here, recognition of the base word (*truck*) as a meaningful initial fragment of the character string does not impede the identification of the word's full-form in poor readers, but rather facilitates it as it activates a word that is semantically, phonologically and/or orthographically similar to the longer word that the readers ultimately need to identify (*trucker*). Thus, in poor readers the task of complex word recognition is helped by the quality of lexical representation of both the whole word and the base morpheme, where the quality is indexed by lexical frequency.

The observation of both inhibitory and facilatory roles for morphemic information is an important contribution of the present paper. Our data point to a strong link between the way that morphemic information contributes to word recognition and individual reading ability; namely, good readers suffer from competition from morphologically related words more than less skilled readers do, while poor readers receive a recognition boost from base words. The notion of lexical competition – such as observed here in skilled readers – is not novel in morphology and has been proposed to account for well-documented interactions wherein effects of whole-word frequency are weaker in words with salient (high-frequency, large family-size or long) morphemes; for an overview of interactions in visual and auditory comprehension see Kuperman et al. (2010). Such competition has been implemented in most computational models of morphological processing in the form of trade-offs between a full-form and a morpheme-based processing route. For example, Baayen and Schreuder (2000) modeled competition via assigning increasing activation weights to access representations that either match the target word or are orthographically similar to (have a small edit distance from) the word. This architecture leads to the simultaneous activation of both complex words and the morphemes they embed, and gives rise to stronger competition if the resting activation level of the morpheme is higher, due to, for instance, the morpheme's higher-frequency of occurrence. A slightly different aproach was adopted by Kuperman et al. (2008), who accommodated trade-offs of lexical competition via weight coefficients assigned to amounts of information that correspond to whole-word and morphemic frequency, along with other sources of probabilistic information. Since a given weight coefficient may have different signs when occurring with differing amounts of information in Kuperman et al.'s model, a larger value for a given coefficient would simultaneously translate into a stronger effect of base morpheme frequency and a weaker effect of whole-word frequency on reading times, thus replicating the interactions observed here. The interactive nature of the processing routes was also implemented in the morphological extension of the E-Z Reader model of eye-movement control in reading by Pollatsek, Reichle and Rayner (2003). (Reichle and Perfetti's (2003) model is underspecified with respect to the effect of embedded morphemes on recognition of complex words). Thus, lexical competition, such as that observed here in skilled readers, is easily accommodated within the architectures of several popular computational models of morphological processing. Crucially, however, these models appear unable to accommodate the recognition boost seen in our low-skill readers especially when they were processing higher-frequency base words.

To conclude, we present evidence that individual skill-level plays a determining role in how morphological information is processed. This is a particularly noteworthy observation, in light of the fact that previous studies have focused on participant populations with a narrow range of reading abilities (undergraduate students). Our evidence points to the simultaneous activation of both morphemic and whole-word routes, as suggested by dual- and multiple-route models such as Baayen et al. (1997), Baayen and Schreuder (2000), and Kuperman et al. (2008), yet the engagement of these routes appears to vary qualitatively as a function of individual verbal skill. In terms of the weight-adjustment model of Kuperman et al., readers appear to shift the relative importance of different sources of morphological information depending on the quality of the representation of both whole words and morphemes, indicated here via lexical frequency, and on the ability of individuals to segment complex words into morphemes as well as the more general individual ability of reading comprehension. Further research is necessary to incorporate the regulating role of skill-driven individual strategies of word identification into computational models of morphological processing.

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