Rules vs. lexical statistics in Greek nonword reading

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Abstract

Graphophonemic conversion rules are posited by models of word reading in order to handle reading of unknown letter strings such as nonwords. Graphophonemic conversion is thought to be relied upon by readers especially in more transparent orthographies such as Greek. Here we test the hypothesis that Greek nonwords are read using rules, by exploiting a case of orthographic ambiguity found in Greek orthography. Participants read nonwords, some of which resembled their source words while others did not. Rule-based performance predicts uniform treatment of the stimuli. Results showed that readings were heavily influenced both by individual lexical items (when similar) and by distributional properties of the lexicon (majority readings of the ambiguous sequences), interpreted as neighborhood effects, as well as by additional factors. The findings are not consistent with exclusive reliance on graphophonemic conversion rules and point instead to emphasizing the role of the lexicon in providing the substrate for both regular and irregular reading performance.

Keywords: Single word reading; nonwords; graphophonemic conversion rules; neighborhood effects; orthographic lexicon.

Rules and statistics in word reading

The notion of rules has long attracted the interest of theoretical argument and empirical research in psycholinguistics. Closely relevant to cognitive modeling, rules have been the focus of lively debate for decades. Rules are conceptually most useful when distinguished sharply from statistical regularity, because then they lend themselves more fruitfully to alternative predictions and modeling efforts. The most highly researched domain of language performance with respect to rules concerns formation of the English past tense. Proponents of rules interpret the observed regularity to the operation of an underlying rule that computes the past tense by adding a suffix to the stem. This presumed syntactic operation preserves both the stem and the suffix and is therefore unaffected by verb pronunciation or meaning. Irregular verbs are considered exceptions to the rule, a closed set of items belonging to a special list, membership in which blocks application of the rule (Prasada & Pinker, 1993).

A telling test for the operation of rules employs pseudowords, that is, words that do not exist in the participants' vocabulary and are treated as verbs in the experimental context. To be able to provide a past tense for the imaginary verb "wug" as "wugged" indicates, according to this view, that an abstract rule is in operation which is not based on lexical knowledge but treats stems as variables (Prasada & Pinker, 1993). This theoretical notion of rules is entirely independent of distributional concerns, in that the regular (default) operation need not be the most frequent one. Indeed, in the well-known case of German plural inflection, only a minority of nouns conforms to the rule, according to this view, while most nouns belong to different classes of special cases (Marcus, Brinkmann, Clahsen, Wiese, & Pinker, 1995).

In reading research, rules are important in cognitive models of word recognition that are based on graphophonemic conversion, that is, the mapping of fixed orthographic units, termed graphemes, to the set of phonological segments of the language, called phonemes. In alphabetic orthographies with high transparency, that is, relatively consistent mappings between letters or letter sequences and individual phonemes, graphophonemic conversion rules are thought to dominate reading performance, especially in early phases of learning to read, and quite substantially thereafter (Ziegler & Goswami, 2006). Learning to read largely consists in mastering the alphabetic principle, that is, the notion that letters correspond to phonemes, and then learning the particular grapheme-phoneme mappings employed in the language-specific orthography. This notion allows estimation of the regularity of an orthographic system by considering a set of rules and calculating the proportion of words (or sublexical units) that are pronounced correctly using these rules. Words that cannot be pronounced correctly are listed as exceptions.

The most influential and comprehensive approach to graphophonemic decoding is seen in the Dual Route Cascaded (DRC; Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) model of word recognition and reading aloud. In this model, a set of graphophonemic conversion (GPC) rules are defined that process stimuli sublexically, while an interactive activation lexical network produces word pronunciations for known letter strings. In this approach, rules are defined by a pragmatic, distributional criterion: in cases of inconsistent mappings, the most frequent mapping is considered regular and others are considered exceptions, thus accounting maximally for correct reading performance. In DRC, the pronunciation of unknown letter strings is not determined exclusively by the GPC rules but is also influenced by the lexicon, due to phoneme activation by known words that share letters with the current input. DRC is currently the most thoroughly tested and probably the most successful modeling approach to word reading (and failures thereof, such as acquired and developmental dyslexia), even though there are certain findings it cannot fully account for (Coltheart, 2005; Reynolds & Besner, 2004).

In opposition to DRC, the triangle connectionist models (Plaut, McClelland, Seidenberg, & Patterson, 1996; Harm & Seidenberg, 1999) posit no particular sublexical units and no discrete graphophonemic conversion rules. Letter strings are mapped to phoneme sequences as distributed activation spreads through a network. The network is first trained on a large set of mappings between spellings of entire words and the corresponding correct pronunciations. It can then exhibit not only correct word reading performance but also largely correct generalization to nonwords, that is, to letters strings it was not trained on. Such networks have successfully accounted for interesting phenomena pertaining to reading and reading failure (Plaut, 2005). Consistent with similar approaches to connectionist modeling of morphological inflection (Plunkett & Juola, 1999), these networks show that it is possible to produce systematic behavior without the need to posit symbolic internal operations based on discrete categorical rules, because the distributional characteristics of the input suffice to constrain network behavior to achieve both generality (and generalization to novel cases) and specificity (correctly handling inconsistent cases).

Greek orthography and the CiV ambiguity

The Greek orthography is relatively transparent: grapheme to phoneme consistency has been estimated to exceed 95% in the feedforward (reading) direction (Protopapas & Vlahou, 2009). Although there are several complexities in the mappings between orthography and phonology, including digraphs and context-dependent graphemes, graphophonemic decoding remains largely predictable and poses little difficulty for children learning to read Greek, compared to other European orthographies (Seymour, Aro, & Erskine, 2003). The predictability is sufficiently high that a set of 80 rules suffices to read aloud correctly most Greek words (Protopapas & Vlahou, 2009, based on Petrounias, 2002). Thus one might conjecture that a rule-based strategy can in principle be used by Greek readers. An emphasis on graphophonemic decoding for Greek is also consistent with the current psycholinguistic grain size theory, because of the relatively high transparency of the orthography (Ziegler & Goswami, 2006).

The only significant departure from predictability arises in CiV sequences, that is, when a grapheme normally mapping to /i/ follows a consonant and precedes a vowel. In each such case there are two possible readings: one that includes the pronunciation of /i/ and one with a palatal consonant (depending on the specific C) and no /i/. In the vast majority of cases, only one of the two readings constitutes a word, therefore the correct parsing of the CiV is lexically determined. For example, μικρόβια ("germs") is pronounced /miˈkrovia/ whereas καράβια ("ships") is pronounced /kaˈravʝa/ (note βια→/via/ vs. βια→/vʝa/). Greek readers apparently have no trouble reading these sequences, as this ambiguity passes relatively unnoticed. However, lexical information is needed to decide, for each letter string containing a CiV sequence, whether an /i/ or a palatal reading is appropriate.

Protopapas and Vlahou (2009) examined the distribution of CiV words and were unable to discern any statistical regularities in favor of a general rule towards either /i/ or palatal readings. In the present study we approach the question experimentally and seek evidence for rule-based reading, using pseudowords, following the rationale previously applied for inflectional morphology. We hypothesize that, if Greek readers employ categorical rules for graphophonemic decoding, then they should be following rules to read the CiV sequences as well. By examining readings of nonwords with CiV sequences we should be able to identify what is "regular" behavior and therefore what the CiV rules are.

In this experiment we test two options. The first is that there is a general CiV rule that applies across all CiV instances and dictates either a universal /i/ reading or a universal palatal reading for all letter strings not known to be "exceptions." If this is the case then all CiV sequences in nonwords should be read in the same way, either as /i/ or as a palatal consonant. The second option is that there are particular graphophonemic conversion rules specific to each CiV sequence, that is, to each combination of consonant, /i/ grapheme, and vowel. If this is the case then each CiV sequence in a nonword should be read according to its corresponding rule, so that the same CiV will be read in the same way regardless of the nonword it is found in. Following the DRC conceptualization of regularity, we assume that for each CiV the "regular" reading is the one evidenced in the majority of words containing the specific letter sequence.

Method

In this experiment we examined nonword reading in search for evidence suggesting that Greek readers employ specific graphophonemic conversion rules. We identified CiV sequences with a clear tendency towards one reading, either /i/ or palatal, using both type and token counts from a large printed text corpus. Then we constructed nonwords containing these sequences by modifying real words in two ways. Some nonwords strongly resembled the words they were derived from and others did not resemble any particular words. If readers rely exclusively on GPC rules to read nonwords and use one general rule for CiV sequences, then all nonwords should be read in the same way, either with /i/ or with a palatal consonant. If readers use rules specific to each CiV, then each nonword should be read according to the majority of the words bearing the corresponding CiV sequence. These effects should be clearest for nonwords not resembling any words. If, however, readers do not use rules but apply their statistical knowledge of the entire orthographic lexicon, then particular CiV sequences will be read consistently to the extent there is lexical support for one of the two readings.

Participants

18 men and 22 women (23–41 years old) participated in the experiment. Most held university degrees, and many were graduate students at the time. All were proficient readers.

Stimuli

We analyzed a large corpus of journalistic texts including 439,029 word forms (types) accounting for a total of 267,605,342 occurrences (tokens), in which we identified 79,825 items (18.2% of types) totaling 23,880,083 occurrences (8.9% of tokens) containing a CiV letter sequence. These items were individually checked to verify their correct pronunciation as containing either an /i/ or a palatal consonant. We then identified CiV sequences for which a clear majority (at least 2:1 both by type and token count) was pronounced consistently with /i/ or with a palatal consonant. For each of these selected CiV sequences, we identified one low-frequency and one high-frequency word containing the CiV sequence and pronounced with an /i/, and another high/low-frequency pair of words containing the CiV sequence and pronounced with a palatal consonant. All four words contained the CiV sequence in the same place (word-initial, word-final, or internally). In this way, word groups were formed, fully crossed by frequency (high/low), word pronunciation of the CiV (i/pal), and CiV group majority pronunciation (i/pal). For example, the high-frequency words καράβια (/kaˈravʝa/) and σωσίβια (/soˈsivia/) and the low-frequency words μακρόβια (/maˈkrovia/) and κουτάβια (/kuˈtavʝa/) all contained the word-final CiV sequence βια, which is pronounced with an /i/ 81.6% of the time by types and 81.1% by tokens in the corpus counts. Due to lack of space, frequency will not be mentioned further in this presentation.

The four words in each CiV group were transformed to produce nonwords. From each word, we created one pseudoword closely resembling the word, by modifying a single letter, and one pseudoword not resembling the word, by modifying several graphemes while retaining the syllabic structure as much as possible. For example, from the word καράβια we constructed χαράβια and ξεζάβια. The resulting nonwords were submitted to a pretest in which volunteers indicated, next to each item, which word they thought it resembled. Wordlike nonwords were rejected if they failed to evoke consistently the source word, whereas unrecognizable nonwords were rejected if any word at all was consistently produced. This procedure resulted in 8 groups of 20 nonwords each, matched in CiV (letters, stress, and word position), mean bigram frequency, and length, and differing in word similarity, source word pronunciation, and group majority pronunciation.

In addition, we created a group of 40 unrecognizable nonwords with CiV sequences for which the majority pronunciation differed when computed by types vs. tokens. That is, if we split the words in the corpus that contain each of these CiV sequences into a subset pronounced with /i/ and a subset pronounced with a palatal consonant, we find that one of the two subsets (N group) contains more words whereas the other subset (F group) contains words with a higher cumulative frequency of occurrence.

These 200 items were mixed in a single experimental list with 100 nonwords not containing a CiV sequence, to divert participants' attention away from CiV to the extent possible.

Procedure

The procedure was controlled by DMDX (Forster & Forster, 2003). In each trial, a single nonword was displayed on a laptop screen in a white large sans serif font on black background. Participants were asked to read aloud each item as quickly as possible without making mistakes. Responses were recorded via head-mounted microphone.

Analyses

Responses were individually examined using CheckVocal (Protopapas, 2007) to check (and manually corret, if necessary) the response times (measured from the frame of stimulus display to the onset of the spoken response) and to classify each response as either (i) pronounced with an /i/ corresponding to the stimulus CiV sequence; (ii) pronounced with a palatal consonant; or (iii) missing or incorrect.

In analyses of variance we compared the proportion of items pronounced with an /i/ in the different conditions, as well as the latency to produce those responses. Analyses were performed both with participants as a random factor, averaging across nonwords (subjects analysis; F_1), and with nonwords as a random factor, averaging across participants (items analysis, F_2). Differences were considered significant when both F_1 and F_2 met the customary criterion $\alpha = .05$.

Results

First we analyzed responses to nonwords in the 8 CiV groups with a clear majority pronunciation that was the same by type and token counts. Figure 1 shows the proportion of readings with /i/ (as opposed to palatal) for each stimulus group, separately for nonwords resembling their source words and for nonwords not resembling any words. In a three-way ANOVA of /i/ reading proportions with word resemblance, source word pronunciation, and group majority pronunciation as factors, the main effect of word resemblance was not significant ($F_1(1, 39) = 2.12$, $p = .154$; $F_2 < 1$) but word resemblance interacted significantly with both source word ($F_1(1, 39) = 134.33$, $p < .0005$, $\eta^2 = .775$; $F_2(1, 152) = 33.36$, $p < .0005$, $\eta^2 = .180$) and group majority ($F_1(1, 39) = 26.12$, $p < .0005$, $\eta^2 = .401$; $F_2(1, 152) = 4.79$, $p = .030$, $\eta^2 = .031$) pronunciation. Therefore responses to the two kinds of pseudowords are further analyzed separately.

In a two-way ANOVA (2 source word pronunciations $\times$ 2 group majority pronunciations), both factors affected reading proportions. Specifically, for nonwords resembling words, there was a significant main effect of source word pronunciation ($F_1(1, 39) = 241.04$, $p < .0005$, $\eta^2 = .861$; $F_2(1, 76) = 167.88$, $p < .0005$, $\eta^2 = .688$) and of group majority pronunciation ($F_1(1, 39) = 11.65$, $p = .002$, $\eta^2 = .230$; $F_2(1, 76) = 14.27$, $p < .0005$, $\eta^2 = .158$), and no interaction ($F_1 < 1$; $F_2(1, 76) = 2.09$, $p = .152$). For nonwords not resembling any words, there were significant main effects of source word pronunciation ($F_1(1, 39) = 146.27$, $p < .0005$, $\eta^2 = .789$; $F_2(1, 76) = 8.07$, $p = .006$, $\eta^2 = .096$) and of group majority pronunciation ($F_1(1, 39) = 283.88$, $p < .0005$, $\eta^2 = .879$; F_2(1,

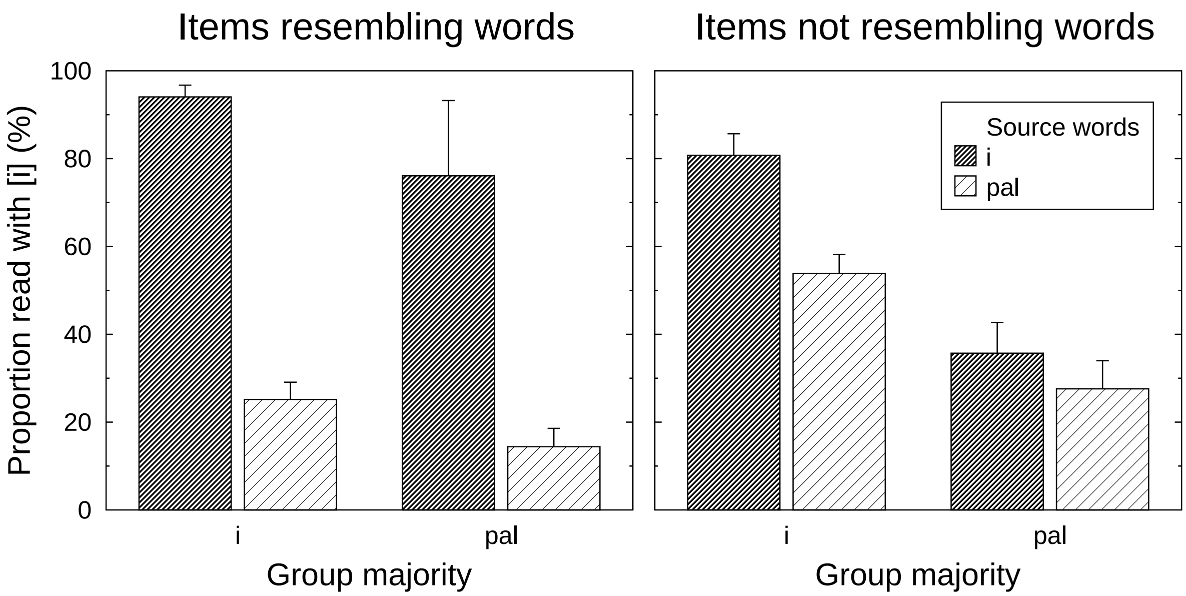

Figure 1: Proportion of nonword readings with an /i/, as opposed to a palatal consonant, by group: items based on source words pronounced with an /i/ or with a palatal consonant; and items with CiV sequences (groups) pronounced with an /i/ or with a palatal consonant in the majority of words they appear in. *Left:* Nonwords closely resembling their source words. *Right:* Nonwords not resembling any words. Values are estimated marginal means, by participants; error bars show corresponding 95% confidence intervals.

76) = 33.503, $p < .0005$, $\eta^2 = .306$), while the interaction between the two was significant by participants only ($F_1(1, 39) = 85.60$, $p < .0005$, $\eta^2 = .687$; $F_2(1, 76) = 2.02$, $p = .159$).

Nonwords resembling their source words were responded to faster than nonwords not resembling any words, whether they were read with an /i/ ($F_1(1, 15) = 28.84$, $p < .0005$, $\eta^2 = .658$; $F_2(1, 143) = 42.02$, $p < .0005$, $\eta^2 = .227$) or with a palatal consonant ($F_1(1, 8) = 12.24$, $p = .008$, $\eta^2 = .605$; $F_2(1, 139) = 20.49$, $p < .0005$, $\eta^2 = .128$).

Considering readings with /i/ only, to correspond with the reading proportion analyses above, response times were analyzed separately for each stimulus condition. The mean response times were necessarily calculated on a reduced dataset, due to excluded palatal readings, resulting in missing data for some participants and items, especially for nonwords resembling words pronounced with a palatal consonant. In a two-way ANOVA (2 source-word pronunciations $\times$ 2 group majority pronunciations), there were no significant differences. Specifically, for nonwords resembling words, there was no significant main effect of source word pronunciation ($F_1 < 1$; $F_2(1, 69) = 1.27$, $p = .263$) or of group majority pronunciation ($F_1(1, 15) = 5.12$, $p = .039$, $\eta^2 = .255$; $F_2 < 1$), and no interaction ($F_1(1, 15) = 2.16$, $p = .162$; $F_2 < 1$). Likewise, for nonwords not resembling any words, there were no significant main effects of source word pronunciation ($F_1(1, 29) = 26.93$, $p < .0005$, $\eta^2 = .481$; $F_2(1, 74) = 1.13$, $p = .292$) or of group majority pronunciation ($F_1(1, 29) = 1.66$, $p = .209$; $F_2(1, 74) = 1.23$, $p = .270$), and no interaction between the two ($F_1(1, 29) = 3.11$, $p = .088$; $F_2 < 1$).

Next we analyzed responses to nonwords from CiV groups with a majority pronunciation that was different by type and token counts. Figure 2 (bottom) shows the proportion of /i/ readings for each subgroup. In a one-way ANOVA there was a significant effect of stimulus group ($F_1(1, 39) = 41.83$, $p < .0005$, $\eta^2 = .518$; $F_2(1, 38) = 4.43$, $p = .042$, $\eta^2 = .104$), indicating that there were more readings with /i/ when the /i/ reading was consistent with the majority of words containing the same CiV (type count, N group) than when the /i/ reading was consistent with the more frequent words containing the same CiV (token count, F group). Analysis of the corresponding response times (Figure 2, top) did not show a significant difference between the two stimulus groups ($F_1, F_2 < 1$).

Discussion

In this experiment we tested Greek readers with nonwords containing the only kind of ambiguous letter sequence in the otherwise transparent Greek orthography. We found that pronunciation of the stimuli was significantly affected by word resemblance and by group majority with respect to the ambiguous letter sequence. The effect of group majority was evidently due to the sheer number of word forms (type count) rather than a cumulative effect of reading experience as indexed by frequency of occurrence of the words (token count). There were no significant differences in response times that might indicate speed-accuracy tradeoffs obscuring our interpretation, therefore we concentrate on reading proportions.

These findings are inconsistent with an exclusive reliance on graphophonemic decoding rules to read nonwords in

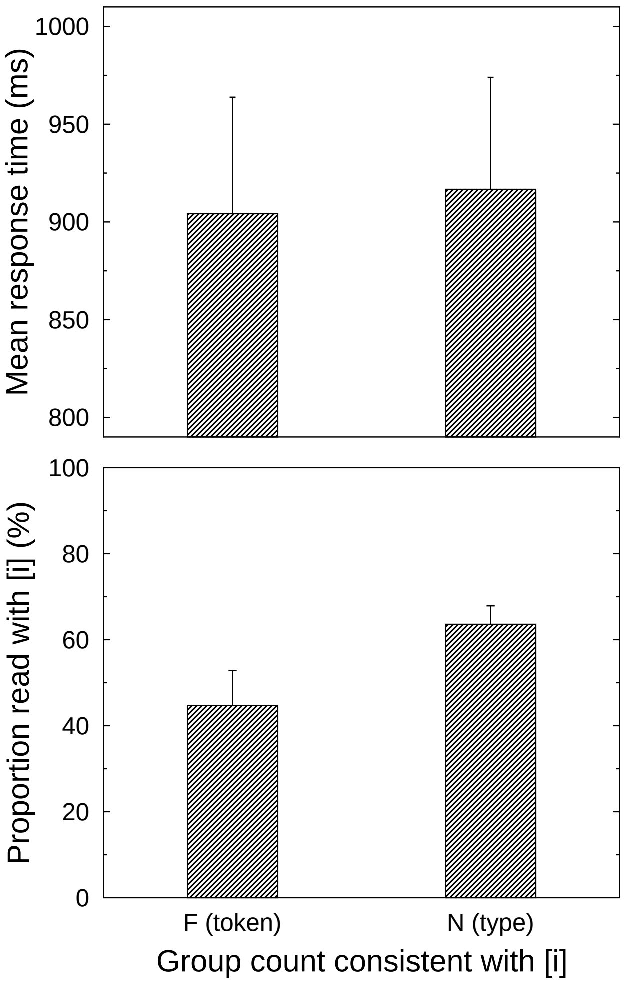

Figure 2: Results for items not resembling any words, with CiV sequences pronounced with an /i/ in the majority of word forms (types) or in the majority of word occurrences (tokens) they appear in. *Top:* Mean response times (latency from word display to speech onset) to responses with an /i/ (excluding palatal responses). *Bottom:* Proportion of nonword readings with an /i/, as opposed to a palatal consonant. Values are estimated marginal means, by participants; error bars show corresponding 95% confidence intervals.

Greek, at least in the usual understanding of the notion of rules as abstract, content-independent operators that apply indiscriminately to any syntactically appropriate representation. Our results are consistent with nonword reading being governed by orthographic patterns in the lexicon, sensitive to distributions of mappings between phonological and orthographic representations at lexical and sublexical levels. The results are also consistent with hybrid or dual-route approaches, as long as lexical effects are allowed to modulate nonwords readings without leading to lexicalization errors.

If the palatal pronunciation were an exception to regular reading of the CiV components, then we should expect all nonwords to be read with an /i/. In contrast, if the palatal pronunciation were the regular reading for modern Greek, and the /i/ were a literary relic of older times, then we should expect no /i/ in any nonword readings. It seems clear that neither option is consistent with the data and that there is no general reading behavior associated with the CiV phenomenon. However, it may be the case that there is no general CiV phenomenon. Rather, each CiV sequence may be a special case and subject to a special corresponding graphophonemic rule. If this were the case then all nonwords should be read consistent with the majority of the corresponding CiV group. Again, this prediction fails to fit the observed data. Group majority does exert a substantial and statistically significant effect on CiV reading; however, it is far from dominant. Allowing reading-by-analogy for the items resembling specific words, and focusing on the items not resembling any particular words, the effect of the group majority is substantial ($\eta^2 = .88$ by participants) but the proportions read consistent with the majority are far below 100%. The effect size is substantially smaller in the analysis by items ($\eta^2 = .31$), indicating that there is much greater variability among items, hence among CiV groups, than among participants.

The observed variability among CiV groups should be interpreted in light of the significant effect of source word pronunciation on CiV reading for items that did *not* resemble their source words at all. This finding was unexpected because we assumed that all there would be to CiV reading can be broken down into a lexical effect, specific to the particular word, and a group effect, specific to the particular letter sequence. Apparently, there are other uncontrolled properties of our items (beyond the matched properties of word frequency, bigram frequency, length, and syllabic structure) that affect reading of the ambiguous letter sequence. A possibility worth considering is that distributional properties of the lexicon at various grain sizes are simultaneously affecting processing of any orthographic stimulus, as would be predicted by an associative network of orthographic patterns mapping onto phonological patterns without explicit segmentation into graphemes and without rules converting graphemes into individual phonemes regardless of their context.

This finding is particularly important because of the relatively high transparency of the Greek orthography, which theoretically could afford successful reading performance with a minimum of processing and storage effort, based on a set of discrete rules or grapheme-phoneme mappings. Theoretical analysis has led some researchers to the conclusion that languages with transparent orthographies would rely more strongly on small "grain sizes," i.e., units of orthographic-phonological mapping, than opaque orthographies (Frost, Katz, & Bentin, 1987; Ziegler & Goswami, 2006). However, recent empirical evidence from Italian, a highly transparent orthography, indicates that the presumed reliance on graphophonemic conversion may be premature, as strong lexical influence has been found in the form of neighborhood effects on nonword reading (Arduino & Burani, 2004; Marcolini, Burani, & Colombo, in press) and strong frequency effects on word reading (Pagliuca, Arduino, Barca, & Burani, 2008). Along these lines, it may be interesting to consider whether the greater effect we found on CiV reading from the number rather than the frequency of words with the same CiV sequence may be a form of neighborhood size effect, if we loosely allow extension of the neighborhood concept to partial or sublexical matches. This needs to be fleshed out in more detail and investigated in future research, as at the moment there are no data regarding neighborhood size effects on nonword naming (reading) rather than lexical decision.

The extent to which a model incorporating GPC rules, such as the DRC, can account for these data, remains to be investigated. Our findings are certainly not inconsistent with the existence of GPC rules in general or with the DRC in particular. This study was designed in order to identify which CiV reading should be considered regular, that is, to determine what should be coded as a rule in future computational models of reading Greek. However, our failure to obtain an answer to this question raises questions regarding the psychological reality of GPC rules, whether or not models employing rules can account for the observed patterns. The CiV phenomenon of the Greek orthography has failed "the wug test" of regularity, which has been used in the past to argue in principle for the existence of abstract categorical rules in language processing. If regular behavior is not evident even when stimuli are specifically designed to minimize lexical effects, then what is the theoretical advantage of positing GPC rules in addition to an orthographic lexicon and to any finer-graing representations that may naturally arise due to statistical regularities in that lexicon? Future work across languages should provide a convincing answer to this important question.

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