The dual-route cascaded (DRC) model of word recognition and reading aloud was implemented in German. In this paper, we describe crosslinguistic differences and similarities between the German and the English DRC. The German DRC was evaluated with respect to its ability to correctly pronounce all German monosyllabic words and to simulate the loan word (regularity) effect. Furthermore, we obtained DRC predictions concerning a number of benchmark effects previously investigated in English, namely effects of word frequency, word length, and neighbourhood size.

A person who has not studied German can form no idea of what a perplexing language it is. Surely there is not another language that is so slip-shod and systemless, and so slippery and elusive to the grasp.
—Mark Twain, 1880/1979
More than a decade ago, Eckart Scheerer (1987) concluded his review on visual word recognition in German by stating that “if certain amendments are made to it, dual route theory (Coltheart, 1978) is a viable candidate for an orthography-invariant model of visual word processing” (p. 242). Since this time, computational modelling has become a major tool for developing and testing theories in word recognition (e.g., Grainger & Jacobs, 1993, 1994, 1996; Jacobs & Grainger, 1992, 1994; Jacobs, Rey, Ziegler, & Grainger, 1998; Norris, 1994; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989; Ziegler, Rey, & Jacobs, 1998; Zorzi, Houghton, & Butterworth, 1998). In the spirit of this movement towards computational models of reading, the previously mentioned dual-route theory was implemented in English in the form of a localist connectionist model, the dual route cascaded model (DRC; Coltheart, Curtis, Atkins, & Haller, 1993). Since then, the DRC stood its test against a variety of empirical data (Coltheart & Rastle, 1994; Rastle & Coltheart, 1998, 1999a, 1999b). After recent strong inference testing against a number of competitive models, the DRC seems to provide a better quantitative account of reading performance than its competitors (Coltheart, Rastle, Perry, Langdon, & Ziegler, submitted).

However, up to now, the DRC has not been implemented in any other language than English. Thus, Scheerer’s intuition that the DRC (as an implementation of dual-route theory) would be suitable as an orthography-invariant model of word recognition has never been explicitly tested. Extending the DRC to German was therefore the main focus of the present research. To anticipate some of the conclusions, the DRC could be easily extended to German using the same parameter values as its English counterpart. Differences in linguistic structure between German and English were reflected in the nonlexical rule system. Orthography-to-phonology relations in German could be captured by a fairly general rule system. The implemented version of the model makes quantitative predictions that should motivate future research in psycholinguistics and neuropsychology in German.

The present article is organised as follows. First, we briefly describe some relevant features of German orthography and phonology. Second, we summarise the architecture and basic mechanisms of the English DRC. Third, we describe the implementation of the German DRC and some structural differences between the German and the English DRC. Fourth, we test the model’s ability to correctly translate all German monosyllabic words from orthography to phonology and to simulate the loan word (regularity) effect. Finally, we present predictions for some benchmark effects in reading aloud, namely word frequency, length, and neighbourhood size effects.
GERMAN ORTHOGRAPHY AND PHONOLOGY

As with English, the German writing system is considered to be phonologically deep because it adheres to the principle of morpheme constancy (see Scheerer, 1987; for a comprehensive analysis of German phonology see Wiese, 1996). Morpheme constancy means that the spelling of morphemes is kept constant in spite of context-induced changes in their pronunciation (e.g., HEAL vs. HEALTH).

As summarised in Scheerer (1987), German has a complicated set of phonographic regularities that can be exploited during reading. For example, vowel length is marked either by putting an “h” after a vowel or by vowel gemination. For example, the vowel is long in both JAHR (year) and HAAR (hair). Lengthening by “h” is more frequent than gemination but occurs only in front of liquid consonants. Vowel length is never marked in front of b, d, f, and g. For example, the German word TAG (day) has a long vowel but this is not marked in orthography neither by gemination nor by inserting the letter “h” after the vowel. Vowels are typically shortened by geminating the following consonants. For example, the vowel in the German word BALL (ball) is short because it is followed by two consonants. Some consonants are never geminated, however (c, h, j, v, w, x).

With respect to the overall degree of regularity, German is said to have highly regular orthography-to-phonology correspondences. Irregularity seems to come mainly from loan words, proper names, and geographical terms. For any alphabetically written language, the degree of irregularity of that language can be measured once a set of grapheme–phoneme correspondence rules (GPCs) is specified for the language. The degree of irregularity is then defined as the percentage of words for which the rule pronunciation disagrees with the lexical pronunciation.

THE ENGLISH DRC

The architecture of the English DRC (Coltheart et al., 1993, submitted) is depicted in Figure 1. It can be broken into two main parts, the lexical and the nonlexical route.

In the lexical route, the orthographic levels (i.e., visual feature detectors, letter units, orthographic lexicon) are almost identical to those in the interactive activation model of McClelland and Rumelhart (1981). Each unit in the feature level represents one of a letter’s features, each unit in the letter level represents one letter of the alphabet, and each unit in the word level represents one word in the lexicon. The interactive activation model implements two major principles: The first principle is interactive
Figure 1. Overall architecture of the DRC.
activation—that is, activation spreads along bidirectional connections between units belonging to different levels. Compatible units have excitatory connections; they mutually activate one another. Incompatible units have inhibitory connections; they mutually inhibit. The second principle is within-level inhibition—that is, units within the same level mutually inhibit one another through inhibitory lateral connections. The phonological levels (phonological output lexicon, phoneme system) are equivalent to the orthographic levels, except that instead of letters, they contain phonemes, and instead of whole-word orthographic units they contain whole-word phonological units. There are only excitatory connections between the orthographic and phonological lexicon. That is, a given word in the orthographic lexicon does not inhibit all incompatible words in the phonological lexicon and vice versa. Note, however, that lateral inhibition within each level does a very similar job.

The nonlexical route deals with assembling phonology. This route operates as a serial mechanism that converts individual letters or letter groups into single phonemes via a grapheme–phoneme conversion procedure (the GPC rules). Letter information becomes progressively available to the nonlexical route. At the first cycle, no letters are available. After a constant number of cycles (10 in the simulations reported here), the first letter is assembled into a phoneme. After this, every 17 cycles another letter becomes available to the system. It has been shown that changing this parameter produces changes in the speed of the nonlexical route and thus in the impact of assembled phonology on lexical processing (see Rastle & Coltheart, 1999b). The dynamics which govern the activation flow of the model and more specific architectural details are explained in greater detail in a number of other papers (Coltheart et al., 1993, submitted; Coltheart & Rastle, 1994; Rastle & Coltheart, 1998, 1999a, b).

IMPLEMENTATION OF THE GERMAN DRC

The first step in implementing the German DRC was to change DRC’s vocabulary from English to German. This involved changing the content of the orthographic input and phonological output lexicon as well as the phoneme and letter units. As the model’s vocabulary, we used all monosyllabic and monomorphemic German words given in the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993). Loan words that were not in the German dictionary Duden (1982) as well as proper names and geographical terms were excluded. This selection resulted in 1448 word units in the orthographic lexicon and 1408 word units in the phonological
The 1448 orthographic word forms ranged from two to eight letters with an average word length of 4.5 letters. The phonological forms ranged from two to six phonemes with an average of 3.7 phonemes. Although monosyllabic words are rare in some European languages (e.g., Spanish, Italian), they are fairly common in German. Monosyllabic words in German account for 53.8 per cent of all word occurrences. Thus, they provide a fairly representative sample of all German words.

Word frequency in the model affects the rise of activation of each word unit. For the word units in the orthographic lexicon, this rise-of-activation was calculated on the basis of printed frequencies given in the CELEX database, for the word units in the phonological lexicon, spoken word frequencies from the same database were used for this computation. Frequencies of homographs were summed in the orthographic lexicon, frequencies of homophones were summed in the phonological output lexicon. Other than that, no changes in lexical processes were made compared to the English DRC. We expected no problems for crosslinguistic generalization of the DRC’s lexical processes because these processes are mainly governed by the dynamics of interactive activation which have been shown to produce stable effects in languages other than English, such as Spanish or French (e.g., Carreiras, Perea, & Grainger, 1997; Ziegler et al., 1998). However, the major question was whether a rule set could be obtained that would be able to assemble phonology by converting graphemes into phonemes.

**GERMAN GPC RULES**

In the original DRC, there are three major types of rules: single-letter, multiletter, and context-sensitive rules (in the present paper, we shall ignore phonotactic output rules). These three types of rules are grapheme-to-phoneme rules, i.e., none of the rules is bigger than the individual grapheme or phoneme. All rules are position specific, i.e., they apply to the beginning, the middle, or the end of the string. As for English, the German rule set was generated in the following way: (1) An appropriate database was selected that included the orthographic and phonological form of all monosyllabic words. As for the English model, CELEX was

---

1The number of whole-word phonological units is smaller than the number of whole-word orthographic units because of heterographic homophones that can have more than one orthographic representation for a single phonological representation. The inverse case, in which a single orthographic representation has more than one phonological representation (heterophonic homographs), is much rarer.
used. (2) All words were segmented into their individual phonemes and their corresponding graphemes. (3) For each grapheme in a given position, the corresponding grapheme–phoneme correspondence was extracted semi-automatically. In case a single grapheme mapped onto more than one phoneme, the most frequently occurring grapheme–phoneme correspondence was used. All rules are listed in Appendix A.

**Single-letter rules**

Single letter rules apply when a single letter maps into a single phoneme. There are 45 single letter rules in German and 39 in English. In fact, all single letters of the alphabet are also graphemes, i.e., they map onto one phoneme. In German, most of the one-letter graphemes map consistently into one and only one phoneme. However, there are exceptions. For example, the letter “b” maps into /b/ or /p/ depending on where in the string it occurs. The same is true for “d”, “g”, and “y”. By allowing rules to be position-specific, this kind of irregularity can be eliminated. The general rule behind this disambiguation is that voiced consonants at the end of a word become unvoiced. However, there are a few cases of true irregularities at this level that cannot be eliminated by position specificity. The most prominent is the grapheme “v” that sometimes maps into /v/ and sometimes into /f/. Because the v −> /f/ mapping is the most frequent, it is defined as the rule in the German DRC. Accordingly, words like VERS (/fərs/) are regular while words like VERB (/vərp/) are irregular.

**Multiletter rules**

There are only 48 multiletter rules in German as compared to 146 in English. More strikingly, the number of multiletter rules in German can further be reduced to a few very general rules (super rules). For example, the German DRC has currently separate rules for vowels that are lengthened by putting an “h” after the vowel (i.e., eh, ah, ih, oh, uh). However, in principle, all these individual rules could be replaced by a single super rule, which indicates that vowels are lengthened when followed by “h”. Similarly, using separate rules for vowel gemination (i.e., aa, ee, oo) overestimates the number of multiletter rules that are really needed to do grapheme-to-phoneme conversion in German. In sum, one of the major differences between German and English seems to lie in the fact that the nonlexical computation of phonology in English requires more and bigger multiletter rules than German. We shall come back to the implications of this finding in the discussion.
Context-sensitive rules

Context-sensitive rules are needed when preceding or following letters consistently determine the pronunciation of a particular grapheme. For example, “s” in the beginning of a word is mainly pronounced /s/. However, when followed by a vowel, it is pronounced /z/ and when followed by the plosives “p” or “t”, it is pronounced /ʃ/. Such regularities are accounted for by adding context-sensitive rules, such as s[V] → /z/ and s[p, t] → /ʃ/, where [V] stands for “when followed by any vowel” and s[p, t] stands for “when followed by the letters “p” or “t”.

German has 38 context-sensitive rules, whereas English has only 14. Thus, on the first glance, German has more than twice as many context-sensitive rules as English. However, a closer look shows that a large number of the context-sensitive rules could again be replaced by a few super rules. For example, a vowel followed by two or more consonants tends to be short (e.g., V[C][C] → short V), a vowel followed by one consonant tends to be long (e.g., V[C] → long V). This general rule reflects a tendency in languages towards isochrony, that is, the attempt to keep the duration of the phonological rime of the syllable constant. Thus, when a vowel is followed by several consonants in spoken language, it is shortened to keep the overall syllable duration constant (for a discussion see Lass, 1984, chap. 10). This general rule includes consonant gemination as a special case, that is, when a vowel is short in spoken language but only followed by a single consonant, the consonant is geminated in written language to indicate the shortening of the vowel. If we count this general rule as a single rule, the number of context-sensitive rules in German would be reduced to six.

MODEL EVALUATION

The German DRC was tested in two ways. First, we investigated the model’s capacity to pronounce all German monosyllabic words. This data allowed us to evaluate some general aspects of the model’s behaviour, such as its overall error rate, the percentage of correct rule applications, and the number of rule violations (i.e., the number of irregular words). Second, we tested the model’s ability to capture one of the major naming effects that has previously been investigated in German: the regularity or loan word effect.

Overall error rate

The model was presented with all 1448 monosyllabic words; it mispronounced only 16 of them (1.10 per cent). All errors were actually errors
to loan words, such as mispronunciations of words like JOB, CHIC, and CHARME. As a comparison, the overall error rate of the English DRC for all monosyllabic English words was 1.17 per cent. This percentage includes errors to nonhomophonic homographs for which at least one pronunciation must, by definition, be wrong. The remaining errors were almost always on low-frequency words with exceptional correspondences in early letter positions (see Rastle & Coltheart, 1999b).

**How often are rules correct?**

To evaluate the efficiency of the nonlexical route, it is useful to compare German and English with respect to the percentage of correct rule applications. This information is presented in Table 1. These statistics were generated by comparing the pronunciation generated from the model’s nonlexical route (via the set of GPC rules) with the pronunciation given in the CELEX database. If the two pronunciations were the same, all of the rules used to generate the word pronunciation were considered correct; if the two pronunciations were different, all of the rules used to generate the word pronunciation were considered incorrect. The percentage of correct rule applications also gives a first index about how regular German is compared to English. The more rules are correctly applied, the more regular the orthography–phonology mapping.

As can be seen in Table 1, German single-letter rules were used correctly about 88 per cent of the time, whereas English single-letter rules were used correctly about 80 per cent of the times. The biggest difference between German and English was with respect to multiletter rules. Not only does German have fewer multiletter rules than English, but the German rules are also more often correct than their English counterparts.

<table>
<thead>
<tr>
<th>Rule type</th>
<th>No. rules</th>
<th>% Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-letter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>German</td>
<td>45</td>
<td>88.5</td>
</tr>
<tr>
<td>English</td>
<td>39</td>
<td>81.8</td>
</tr>
<tr>
<td>Multiletter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>German</td>
<td>48</td>
<td>95.2</td>
</tr>
<tr>
<td>English</td>
<td>146</td>
<td>80.6</td>
</tr>
<tr>
<td>Context-sensitive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>German</td>
<td>38</td>
<td>87.5</td>
</tr>
<tr>
<td>English</td>
<td>14</td>
<td>75.5</td>
</tr>
</tbody>
</table>
(95 per cent versus 81 per cent for German and English, respectively). A closer comparison between German and English multiletter rules also shows that German has virtually no graphemes larger than two letters while English has many. Thus, it seems that German affords fewer, smaller, and more reliable multiletter rules. Finally, German has more context-sensitive rules than English. Again, they were correctly applied more often than their English counterparts. Averaged across the three rule types, German rules were correctly applied 90.4 per cent of the time, whereas English rules were correctly applied only 79.3 per cent of the time.

How many words are irregular in German?

Having specified the German GPC rules (see Appendix A), we can now give a rule-set-defined answer as to how many monosyllabic words are irregular in German. This was done in a simulation in which the German DRC’s lexical route was switched off. Thus, words were read by the nonlexical route only. Any word that is named incorrectly by the nonlexical route is, by definition, irregular; it violates the GPC rules.

From the 1448 words that were submitted to the German DRC with its lexical route switched off, 150 were read incorrectly by the nonlexical route. Therefore, irregularity in the mapping between orthography and phonology in German is 10.3 per cent according to this rule set. Interestingly, there were a number of systematic subtypes of irregularity. The largest type of irregularity (53 per cent) was due to subtle differences in vowel length. For example, the O in LOCH (hole) is short while it is long in HOCH (high). HOCH is irregular because it violates the rule that vowels followed by two consonants should be short. This group also includes a number of highly frequent function words. For example, the function words BIS (until) or MIT (with) should be pronounced with a long vowel according to rule but they are pronounced with a short vowel. The second largest type of irregularity (44 per cent) came from irregular loan words. Most of them are listed in Appendix B. They include words like JAZZ, JOB, FAIR, CREAM and so on. Finally, a fairly small percentage of words (3 per cent) did not fall in any of these categories (e.g., VOLT, ZIG). As a comparison, the English DRC mispronounced 17.94 per cent of all English monosyllabic words when reading was purely by the model’s nonlexical route.

In summary, contrary to common belief, the present analysis shows a considerable degree of irregularity in German orthography-to-phonology mapping. This is mainly due to intrusions of loan words into the German vocabulary and to unpredictable changes in vowel length (see earlier example). Irregularity in vowel length could be considered as subtle
irregularity because only a single phonetic feature (i.e., vowel length) is affected by this type of irregularity. It remains an empirical question whether this type of irregularity has the same effect as irregularity in English.

The loan word effect

Unlike English, for which a large empirical database concerning a variety of word recognition effects is available, the existing data on German word naming is rather meagre. However, one effect, the loan word effect, has previously been investigated in a naming task in German (Scheerer, 1987). Given that many loan words are irregular, the loan word effect is the German equivalent of the regularity effect. The regularity effect reflects the finding that low-frequency words with regular GPCs are named faster than those with irregular GPCs (e.g., Andrews, 1982; Baron & Strawson, 1976). The regularity effect has played a critical role in the development of word naming models in English (e.g., Coltheart et al., 1993; Plaut et al., 1996).

To test for the existence of regularity effects in German, Scheerer (1987) selected three groups of loan words: (1) regular loan words that did not contain any violation of German orthography (e.g., FILM, TEST); (2) regular loan words that violated German orthography; they contained at least one bigram that does not occur among native words (e.g., SKAT, TYP); (3) loan words with irregular GPCs \(^2\) (e.g., CHEF, TEAM). As shown in Table 2, Scheerer (1987) found that regular loan words (group 1) were not significantly different from native German words. However, regular loan words with orthographic violations (group 2) produced significantly longer latencies than native words. Finally, loan words with irregular GPCs (group 3) produced longer latencies and more naming errors (19.5 per cent) than any of the other groups.

The German DRC was tested in its ability to capture this effect while using the original parameter values of the English DRC. For this purpose, we selected among all German monosyllabic words those loan words that fall into the three categories described above. This resulted in a selection of 51 words in group 1, 35 words in group 2, and 66 words in group 3. These words are listed in Appendix B. All words were of fairly low frequency and there was no significant differences between the three groups in terms of word frequency, \(F(2, 149) = .12, p > .10\). In

\(^2\) Scheerer defined loan words as being GPC irregular when their pronunciation was listed in the *Duden* dictionary. In the *Duden*, pronunciations are given only for those words that would be incorrectly pronounced according to German rule.
addition, a group of 45 native words was selected that matched these loan words with respect to word frequency and word length.

The simulation results are presented in Table 2. The model accurately predicts the pattern obtained by Scheerer (1987). Planned comparisons showed that, in the model, no difference was obtained between regular loan words (group 1) and native German words, $F(1, 95) = .14, p > .10$. As in the human data, however, regular loan words with irregular orthography (group 2) and irregular loan words (group 3) differed significantly from native words, $F(1, 79) = 3.4, p < .05$ and $F(1, 110) = 42.3, p < .0001$, respectively. Also, the model accurately predicted the high error rate for loan words with irregular GPCs as observed in the human data. Together, it seems that the model does a good job in simulating the loan word effect.

### SOME PREDICTIONS FOR FUTURE RESEARCH

As mentioned previously, little research has been done in German with respect to some of the classic effects of word naming in English (e.g., word frequency, word length, or neighbourhood size effects). This makes it impossible to fully test the model on these variables. However, it may be useful to present the model’s predictions concerning these effects in an attempt to motivate future research in German. Predictions for these effects are presented in Table 3.

As can be seen in Table 3, when using four frequency classes (low, $\log F<1$; medium, $1<\log F<2$; high, $2<\log F<3$; very high, $3<\log F<4$), the model predicts a graded, log-linear, frequency effect for German

---

**TABLE 2**
The loan word effect in German. Mean latencies (in ms), errors (in %), and number of cycles for native words and three classes of loan words. Human data taken from Scheerer (1987, Table 2)

<table>
<thead>
<tr>
<th>Word classes</th>
<th>Human data</th>
<th>DRC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RTs</td>
<td>Errors</td>
</tr>
<tr>
<td>Native words</td>
<td>573</td>
<td>0.3</td>
</tr>
<tr>
<td>Loan words</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reg GPC/Reg Orth (<em>Test, Film</em>)</td>
<td>566</td>
<td>0.9</td>
</tr>
<tr>
<td>Reg GPC/Irreg Orth (<em>Skat, Typ</em>)</td>
<td>591</td>
<td>1.6</td>
</tr>
<tr>
<td>Irreg GPCs (<em>Team, Chef</em>)</td>
<td>634</td>
<td>19.5</td>
</tr>
</tbody>
</table>

Reg = Regular; Irreg = Irregular; Orth = Orthography.
naming. Such effects have previously been obtained in English (e.g., Forster & Chambers, 1973; Monsell, 1991). The DRC also predicts an inhibitory length effect for German. Naming latencies increase in a seemingly linear fashion with increasing word length. In English, length effects have been reported for naming nonwords and low-frequency words. No length effects were found for high-frequency words (Weekes, 1997). The German DRC predicts a facilitatory neighbourhood size effect\(^3\) for both high- and low-frequency words. Facilitatory neighbourhood size effects in naming have been consistently reported in English, although they seem to be restricted to low-frequency words (for a review, see Andrews, 1997). Finally, as shown previously, the German DRC predicts a regularity effect in German. Future research should investigate whether normal readers would show regularity costs for what we have called subtle irregularities, such as unpredictable vowel prolongations in minimal pairs (e.g., HOCH/DOCH, DACH/NACH, BART/HART).

### GENERAL DISCUSSION

In the present paper, we have generalised the DRC to German using the same parameter values as the English DRC. The model was evaluated for its ability to correctly read all monosyllabic German words and to simulate the loan word effect of Scheerer (1987). The model obtained satisfactory performance on both tests. These results support Scheerer’s

\(^3\)Neighbourhood size in German varies between 0 and 15 neighbours with a mean of 2.8 neighbours per word. Accordingly, in the simulations, words were defined low N if they had less than two neighbours and high N if they had more than three neighbours.

### TABLE 3

<table>
<thead>
<tr>
<th>F-effect</th>
<th>Length-effect</th>
<th>N-effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groups</td>
<td>DRC</td>
<td>Groups</td>
</tr>
<tr>
<td>Low</td>
<td>84.2 (.34)</td>
<td>three</td>
</tr>
<tr>
<td>Medium</td>
<td>81.9 (.28)</td>
<td>four</td>
</tr>
<tr>
<td>High</td>
<td>77.5 (.24)</td>
<td>five</td>
</tr>
<tr>
<td>Very high</td>
<td>72.8 (.36)</td>
<td>six</td>
</tr>
</tbody>
</table>

Neighbourhood size in German varies between 0 and 15 neighbours with a mean of 2.8 neighbours per word. Accordingly, in the simulations, words were defined low N if they had less than two neighbours and high N if they had more than three neighbours.
(1987) claim that the “dual route theory is a viable candidate for an orthography-invariant model of visual word processing” (p. 242).

One interesting aspect of the present model is its potential to motivate new research by providing a tool which allows researchers to anticipate the model’s quantitative and qualitative predictions before running an experiment. A number of predictions for some benchmark effects of word recognition were provided. In summary, according to the model, naming latencies in German should exhibit a facilitatory frequency effect, an inhibitory word length effect, and a facilitatory neighbourhood size effect.

There are a number of challenging questions with respect to the present implementation. One is whether the German and English versions of the model are sensitive to crosslinguistic differences despite the fact that the overall architecture and dynamics are identical. One difference between the German and the English DRC is the structure of the nonlexical route. German seems to require fewer rules than English and many of the individual rules seem to be reducible to a relatively small number of fairly general super rules. More specifically, German has fewer and smaller multiletter rules than English. This makes the interesting prediction that the grain size of the nonlexical computation is smaller in German than English. Thus, German readers can successfully use smaller chunks to compute phonology than English readers. One consequence may be that German readers exhibit a stronger length effect than English readers. In turn, if Germans use smaller chunks, it could be expected that effects of bigger grain sizes (e.g., body-rime effects) are weaker in German than in English.

Furthermore, our rule statistics support the possibility that German readers not only use smaller chunks than English readers but that these smaller chunks are more reliable (i.e. less irregular). Irregularity in German was about 10 per cent as compared to 18 per cent in English. For example, the English words *ball*, *cat*, and *hand* all have different pronunciations of the vowel “a” while their German equivalents *Ball*, *Katze*, and *Hand* have the same vowel pronunciation. The obvious prediction is that if German readers use smaller chunks to compute phonology and if these smaller chunks are more reliable (i.e., regular), then nonword reading or learning-to-read should be easier in German than in English. In fact, a recent crosslinguistic study has shown that word and nonword reading in children was faster and less error-prone in German than in English (Landerl, Wimmer, & Frith, 1997).

A more fundamental question is whether the DRC should be generalised to German at all. Coltheart et al.’s (1993) major justification for a dual-route architecture in English was the fact that neither a lexical nor a nonlexical system alone seemed sufficient to explain both nonword and exception word reading, as well as the double dissociation between
surface and phonological dyslexia. However, if a major part of German words (about 95 per cent if loan words are excluded) can be pronounced correctly using a limited set of general rules, one might argue that there is little need for a separate lexical system. The advantage of a simulation approach is that such a possibility can directly be tested by comparing the original model with a version of the model in which the lexical route is “switched off” (the relevant parameters are set to zero). Similarly, one could argue that because German has a small set of general rules that reliably predict pronunciations, the nonlexical route may operate more quickly for the German rule set than is the case for the English rule set. Again, this possibility can directly be tested by modifying the speed of the nonlexical route.

To summarise, the present paper showed that the DRC could be implemented for the German language. The model successfully simulates the loan word effect that can be seen as the equivalent of the regularity effect in English. More empirical data are now needed to explore whether the German DRC can capture word recognition and reading in as much detail as its English counterpart. Furthermore, the implemented DRC should provide a useful tool for investigating potential differences or similarities between German and English, such as the importance of a lexical system or the relative speed of nonlexical and lexical routes.

Manuscript received February 1999
Revised manuscript received October 1999

REFERENCES


---

4Keep in mind that the serial route operates from left to right, processing one letter at a time, with a fixed number of cycles in between each letter. Thus, reliability of the rules alone does not naturally speed up the nonlexical route.


Rastle, K., & Coltheart, M. (1999a). Lexical and nonlexical phonological priming in reading


**APPENDICES**

Appendix A

German GPC rules. Each rule presents a grapheme and its corresponding phoneme together with the position at which the rule applies (b = beginning; m = middle; e = end; a = all). For example, the rule $b \rightarrow /b/ (b)$ indicates that the grapheme $b$ maps into the phoneme $/b/$ at the beginning (b). In the context sensitive rules, the symbols [V] or [C] stand for any vowel or consonant, respectively (see also text).

**Single-letter rules**

\[
\begin{align*}
\text{b} & \rightarrow /b/ \ (b); \\
\text{p} & \rightarrow /p/ \ (me); \\
\text{k} & \rightarrow /k/ \ (a); \\
\text{d} & \rightarrow /d/ \ (b); \\
\text{l} & \rightarrow /l/ \ (a); \\
\text{g} & \rightarrow /g/ \ (b); \\
\text{h} & \rightarrow /h/ \ (a); \\
\text{j} & \rightarrow /j/ \ (a); \\
\text{k} & \rightarrow /k/ \ (a); \\
\text{l} & \rightarrow /l/ \ (a); \\
\text{m} & \rightarrow /m/ \ (a); \\
\text{n} & \rightarrow /n/ \ (a); \\
\text{p} & \rightarrow /p/ \ (a); \\
\text{q} & \rightarrow /k/ \ (a); \\
\text{r} & \rightarrow /r/ \ (a); \\
\text{s} & \rightarrow /s/ \ (a); \\
\text{t} & \rightarrow /t/ \ (a); \\
\text{v} & \rightarrow /v/ \ (a); \\
\text{x} & \rightarrow /x/ \ (a); \\
\text{y} & \rightarrow /y/ \ (b); \\
\text{z} & \rightarrow /z/ \ (a); \\
\text{a} & \rightarrow /a/ \ (be); \\
\text{e} & \rightarrow /e/ \ (be); \\
\text{i} & \rightarrow /i/ \ (be); \\
\text{u} & \rightarrow /u/ \ (be); \\
\end{align*}
\]

**Multiletter rules**

\[
\begin{align*}
\text{aa} & \rightarrow /a/ \ (a); \\
\text{ah} & \rightarrow /a/ \ (a); \\
\text{ai} & \rightarrow /a/ \ (a); \\
\text{au} & \rightarrow /au/ \ (a); \\
\text{ee} & \rightarrow /e/ \ (a); \\
\text{eh} & \rightarrow /e/ \ (a); \\
\text{ei} & \rightarrow /e/ \ (a); \\
\text{eu} & \rightarrow /eu/ \ (a); \\
\text{ff} & \rightarrow /f/ \ (a); \\
\text{ie} & \rightarrow /i/ \ (a); \\
\text{ieh} & \rightarrow /i/ \ (a); \\
\text{ih} & \rightarrow /i/ \ (a); \\
\text{kh} & \rightarrow /k/ \ (a); \\
\text{ll} & \rightarrow /l/ \ (a); \\
\text{mm} & \rightarrow /m/ \ (a); \\
\text{ng} & \rightarrow /n/ \ (a); \\
\text{oa} & \rightarrow /o/ \ (a); \\
\end{align*}
\]
Appendix B

Loan words in the CELEX database according to Scheerer’s (1987) classification.

**Regular loan words (no violation of orthography)**
AKT, BASS, BLUFF, BOSS, BRIE, BROM, DRINK, DROPS, FESCH, FILM, FLIRT, FLOR, JOD, JUST, KILT, KLAN, KLON, KLUB, KOKS, KULT, KUR, LOG, LORD, MOL, NORM, PAKT, PER, PIER, PINK, PLAN, PLUS, POMP, PORT, PRO, PUCK, PUR, QUARK, QUART, QUARZ, QUINT, RE, RUM, SCHAH, SCHEICH, SOL, SONG, SPRIT, TAFT, TRAM, TREND, VERS

**Regular loan words (with violations of orthography, i.e., illegal bigrams)**
BOX, CHLOR, CHOR, CHRIST, CHROM, CLAN, CLUB, FIX, FJORD, GEN, GNOM, JUX, KHAN, KREM, LAX, LUX, MOP, NERV, PAX, PHON, PNEU, PSALM, SKALP, SKAT, SKETCH, SKRIPT, SMART, SNOB, SPHINX, STOP, SWING, THAI, TWIST, TYP

**Irregular loan words (violations of GPCs)**
AIR, BAND, BEAT, BIT, BLUES, BOB, BON, BOOM, BOY, BRIDGE, CAMP, CHARME, CHEF, CHIC, CLOWN, CODE, CREME, FAIR, FAN, FLAIR, GAG, GIN, GROS, JAZZ, JEEP, JET, JOB, KODE, KORPS, LIVE, LUNCH, MATCH, PUMPS, QUAI, RANCH, REN, ROUGE, SAFE, SCHI, SET, SEX, SHOW, SKI, SLANG, SLIP, SLUM, SPIN, SPLEEN, SPOT, SPRAY, SQUAW, STEAK, TAB, TEAK, TEAM, TIP, TOAST, TOUR, TRIP, TWEED, TWEN, VAMP, VERB, YARD, YEN, ZEN