Journal of Experimental Psychology:
Human Perception and Performance
1994, Vol. 20, No. 6, 1197-1211

0096-1523/94/$3.00

Serial Processing in Reading Aloud: Evidence for Dual-Route Models of Reading

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The authors examined the regularity effect on reading aloud as a function of left-to-right phonemic position of irregularity in low-frequency exception words. Ss named 96 low-frequency exception words categorized into 5 conditions on the basis of the position (1st through 5th) of their 1st irregular grapheme-to-phoneme correspondence (GPC). Latencies and error rates for these words were compared with the rates for 96 matched GPC regular controls. Results showed that the cost of irregularity decreased monotonically over the 5 positions of irregularity. This result is offered as evidence for dual-route models of reading and against parallel distributed processing models of reading.

In dual-route models of reading aloud (Baron & Strawson, 1976; Coltheart, 1978, 1985; Coltheart, Curtis, Atkins, & Haller, 1993; Forster & Chambers, 1973), two procedures are used to compute pronunciations from print: a lexical procedure and a nonlexical procedure. The lexical procedure operates by (a) access to a word's representation in an orthographic input lexicon or visual word recognition system followed by (b) retrieval of that word's spoken form from a phonological output lexicon or spoken word production system. The nonlexical procedure operates by applying a set of letter-to-sound correspondence rules to a string of letters; this procedure is nonlexical in the sense that it requires neither access to the orthographic input lexicon nor retrieval from the phonological output lexicon.

The method most frequently adopted for investigating dual-route models has been the use of exception words, regular words, and nonwords as stimuli in reading-aloud experiments. The terms *exception* and *regular* can only be defined with reference to some set of rules of correspondence between orthography and phonology. For any such set of rules, regular words are those for which the pronunciation generated by applying these rules is the correct pronunciation, and exception words are those for which application of the rules yields an incorrect pronunciation.

Given the characterization of the lexical and nonlexical procedures defined by dual-route models, production of the correct pronunciations of exception words requires use of the lexical procedure, whereas production of the correct pronunciations of nonwords requires use of the nonlexical procedure. Application of the lexical procedure to a pronounceable nonword fails because, by definition, there are no representations for nonwords in the orthographic input lexicon. Application of the nonlexical procedure to an exception word yields a "regularization error"; the rules compute the pronunciation so that, for example, *pint* is pronounced as if it rhymed with *mint.* In the case of a regular word, both procedures generate the correct pronunciation, though, of course, by different means.

It follows from this analysis that exception words should suffer, in comparison to regular words, because for exception words conflicting pronunciations are produced, whereas for regular words the two procedures generate the same pronunciation. This expectation has been confirmed in various studies of naming latencies for regular and exception words. Usually, however, only relatively low-frequency exception words suffer a latency cost; naming latencies for high-frequency words are not affected by regularity (e.g., Paap & Noel, 1991; Seidenberg, Waters, Barnes, & Tanenhaus, 1984; Taraban & McClelland, 1987).

The dual-route interpretation of this interaction between word frequency and regularity follows from the widely accepted idea that the speed with which any lexical procedure operates depends on word frequency. When one reads aloud, the lexical processing of high-frequency words is sufficiently rapid that the lexical route generates their pronunciations before the nonlexical route can compute them. The lexical processing of low-frequency words, however, is sufficiently slow that at least sometimes it is not completed by the time the nonlexical route has generated a pronunciation. Here, there is scope for conflict between the outputs of the two routes. Such conflict occurs when the stimulus is an exception word but not when it is a regular word.

The most common theoretical model that deals with these pronunciation conflicts, the "horse-race" model (Norris & Brown, 1985; Patterson & Morton, 1985), postulates that the two routes race to produce a pronunciation, and the subject utters whatever pronunciation is generated by the winner of the race. This cannot be the correct analysis, however, because it predicts that regularity affects only

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This work was supported by Australian Research Council Grant AC9231176 awarded to Max Coltheart. We are grateful to Michael Haller, Robyn Langdon, and Alan Taylor for their assistance, and to Ken Forster and Jonathan Grainger for their comments on an earlier draft of this article.

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error rate, not latency. By this account, when the stimulus is an exception word and the nonlexical procedure wins the processing race, a fast regularization error, not a slow correct pronunciation, occurs. The latency disadvantage that is seen for low-frequency exception words, therefore, cannot be predicted by a simple horse-race model. Hence, what is needed is a subtler account of how the conflict between lexical and nonlexical processing is resolved.

The horse-race analysis assumes that the two processing routes are entirely independent. Such complete independence of the two procedures is not a necessary feature of dual-route models, however, and indeed is implausible, if completely independent means sharing no processing stages. The input to the letter–sound rule system is letter identities, as is the input to the orthographic input lexicon. Hence, the two routes share the same initial processing stage, a letter-identification stage, which delivers its output to two different destinations, the orthographic input lexicon and the letter–sound rule system.

The two routes also share a final processing stage. Because each route generates a pronunciation, the final stage of each route must be a level of phonemic representation, and there is no reason to suggest that each route has its own separate phonemic stage. When the two routes generate different pronunciations, the resulting conflict could occur at this common stage, and hence this may be the stage at which the conflict is resolved.

A computational version of the dual-route model has recently been developed, the dual-route cascade (DRC) model (Coltheart et al., 1993), which includes an explicit account of how this phonemic conflict is resolved in a way that generates slowed but correct naming responses for exception words. Because this model is relevant to various aspects of our article, it is described here in some detail.

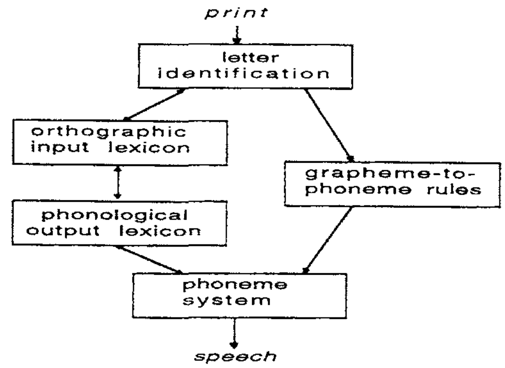

Figure 1. The overall architecture of the dual-route cascade model.

DRC Model of Visual Word Recognition and Reading Aloud

The DRC model is a dual-route model in the sense that it contains two procedures for converting print to speech, a lexical lookup procedure and a grapheme-to-phoneme (GPC) rule procedure. It is a computational model in the sense that it exists as a complete computer program that takes letters as input and yields a phonemic representation as output. The overall architecture of the model is presented in Figure 1.

Basic Principles of the DRC Model

Graded processing. Activation rises slowly in the various components of the model, rather than being an all-or-none affair. Therefore, word recognition or pronunciation is achieved after numerous processing cycles, rather than as soon as the stimulus is presented. Activation level is bounded within the range 0.0 to +1.0, and the equations of the model are such that activation of appropriate units is an ogival function of processing cycles.

Cascaded processing. As soon as there is any activation at all in any level of the model, this activation is communicated to adjacent levels. That is, information is passed between levels continuously, rather than waiting until processing in one level is completed before anything is transmitted to other levels.

Fully interactive processing. Every level contributes activation and inhibition to all of its adjacent levels. So, for example, when there is any activation at all in the phonological output lexicon, excitation and inhibition of units not only in the next processing stage (the phoneme system) but also in the previous processing stage (the orthographic input lexicon) will occur. This has extreme consequences: Any activation in the phoneme system will eventually find its way back upstream all the way to the letter identification system because of the bidirectionality of all the connections in the lexical side of the DRC model.

Architectural Details

The letter identification and word recognition components of the DRC model are not original to this model: They are a generalization of the interactive activation (IA) model of visual word recognition developed by McClelland and Rumelhart (1981) and Rumelhart and McClelland (1982).[1] Hence, in DRC, as in the IA model, there is a full set of 26 letter detector units for each possible position in input letter strings. All letter detector units are connected to all of the word detector units in the orthographic input lexicon. These letter-to-word connections are excitatory whenever the word possesses that particular letter in that particular position; the remaining letter-to-word connections are inhibitory. All of these letter-to-word connections are bidirectional.

The original IA model operated only with four-letter words; the DRC model operates for words of any length from two through eight letters. The ability to cope with

[1] For this reason, the DRC model should be able to simulate successfully the wide range of word-superiority data that the original IA model successfully simulated.

varying word lengths is achieved by adding to each set of letter detector units a unit coding absence-of-letter, which has excitatory links to all words that do not have a letter in the relevant position (e.g., the absence unit for Position 4 letters excites the units for all words with three or fewer letters) and inhibitory links to all words that do have a letter in this position. The orthographic input lexicon of the DRC model contains a unit for every one of the monosyllabic words in the CELEX linguistic database (Baayen, Piepenbrock, & van Rijn, 1993) containing at least two letters; there are 7,991 such words.[2] Each of these units has a resting activation level that is a scaled value of its frequency of occurrence in the CELEX database. These values range from −0.05 (for the lowest frequency) to 0.00 (for the highest frequency); therefore, the more frequent a word, the faster the rate at which activation rises across processing cycles in that word's unit when the word is presented to the model.

The phonological lexical output side of the model is likewise closely related to models developed by Dell (1986) and by Harley and MacAndrew (1992). The phonological output lexicon contains a unit for every one of the phonologically distinct monosyllabic words in the CELEX database; there are 7,127 such words. Fewer units are in the phonological output lexicon than in the orthographic input lexicon because of the existence of homophones; for example, the words *sale* and *sail* have separate representations in the orthographic input lexicon (because they are spelled differently) but a single common representation in the phonological output lexicon (because they are pronounced identically). Heterophonic homographs such as *lead* or *sow* are dealt with in the reverse way; there is one entry for any such word in the orthographic input lexicon that is connected to two entries in the phonological output lexicon, one for each of the two different pronunciations of such words. Apart from these homophones or homographs, the connections from the orthographic input lexicon to the phonological output lexicon are one-to-one; a word's unit in the orthographic input lexicon has a direct and bidirectional excitatory connection to its unit in the phonological output lexicon. There are no inhibitory connections between the two lexicons.

The phoneme level of the DRC model consists of six sets of phoneme units, one for each possible phonemic position in a pronunciation (no monosyllabic word in the CELEX database contains more than 6 phonemes). Each set of phoneme units contains 44 different phoneme units, plus a zero-phoneme unit. Every phoneme unit is connected to all of the word units in the phonological output lexicon. These phoneme-to-word connections are excitatory whenever the word possesses that particular phoneme in that particular position; the remaining phoneme-to-word connections are inhibitory. The zero-phoneme unit in the *n*th set of phoneme units has excitatory connections to all word units in the phonological output lexicon that have fewer than N phonemes and has inhibitory connections to all other words. All of these phoneme-to-word connections are bidirectional.

The models developed by Dell (1986) and Harley and MacAndrew (1992) have been applied to the explanation of slips of the tongue in normal speakers and paraphasic speech errors in aphasic speakers; because the phonological part of the DRC model is closely related to these models, it is thus likely that the DRC model will be competent to explain such effects too.

Plans are also afoot to implement a semantic system, which would have excitatory and inhibitory connections to and from the orthographic input lexicon and to and from the phonological output lexicon.

Parameters

The specific behaviors of the DRC model are controlled by the values assigned to the parameters of the model. As in the IA model, the strength of the excitatory connections between any two adjacent layers of the lexical side of the model is determined by an individual single parameter (with a separate parameter for each direction of the connections), and the strength of the inhibitory connections between any two adjacent layers is also specified by an individual single parameter (again, with a separate parameter for each direction of the connections). Within the four components of the lexical side of the model, there is full inhibitory interconnectivity of all units, and each of these four sets of lateral inhibitory connections has its own parameter determining the strength of the lateral inhibition.

The behavior of the nonlexical side of the model (the GPC rule system) is controlled by three parameters. One determines the strength of the activation of the phoneme system by the output of the GPC rules. The second determines the steepness of the ogival activation function governing the rise of this activation across processing cycles. The third determines the time (in processing cycles) that elapses before the next phoneme coming from the GPC procedure begins to activate the phoneme level of the model; this is needed because the GPC rules operate from left to right, so that the procedure delivers phonemes serially to the phoneme stage of the model.

The model has 24 parameters in all. These are not free parameters; each has a specific interpretation, because each controls a specific component of the model.

Lexical Decision and Reading-Aloud Tasks

The DRC model makes lexical decisions using the procedure proposed by Coltheart, Davelaar, Jonasson, and

[2] The DRC model is currently restricted to monosyllabic words for the following reason. Whereas it is clear what a sensible set of GPC rules for the nonlexical route of the model is (and indeed Coltheart et al., 1993, describe an algorithm that learns a complete set of such rules from exposure to a corpus of real words), it is not clear how stress is to be assigned nonlexically to a polysyllabic letter string. Until a procedure for the nonlexical assignment of stress is added to the nonlexical route of the DRC model, this route will generate pronunciations in which all syllables are stressed, and so when the input is polysyllabic the output of the nonlexical route will often be inappropriate. Work is currently in progress on the development of a nonlexical stress assignment procedure.

Besner (1977). It responds *YES* when any unit in the visual input lexicon has reached some criterial activation level. It responds *NO* when a criterial time (i.e., a criterial number of processing cycles) has elapsed without any unit in the visual input lexicon reaching the criterial activation level. As proposed by Coltheart et al. (1977), the value of this deadline is variable and is determined by the total activation occurring in the visual input lexicon. When, early in processing, this total activation is low, the deadline is reduced, and when the total activation is high, the deadline is extended (see Jacobs and Grainger, 1992).

The model decides on a pronunciation by applying a criterion to the activations of the phoneme units; when, within each of the six sets of phoneme units, either (a) there is a unit in the set whose activation exceeds a critical value (typically 0.90) or (b) none of the units in the set has an activation above the complement of this critical value (i.e., 0.10), then a complete pronunciation is regarded as having been computed. This pronunciation consists of just those phonemes with an activation value above the critical level. For any reasonable set of model parameters, after a sufficient number of processing cycles has elapsed there will be exactly one such phoneme in each of the first *N* sets of phoneme units, and none in the remaining sets, when the correct pronunciation contains *N* phonemes.

Simulations

We evaluate the DRC model by determining the success with which it can simulate effects obtained in a variety of experiments on visual word recognition and reading aloud. These simulations are done by varying the parameters of the model until a parameter set is found (if one can be found) under which the model's behavior exhibits the effect that human subjects have been found to exhibit. The behavior of the model here is measured by running the model on the same set of items as was used in the relevant experiment with human subjects. Ultimately, the model will be verified not just by showing that each of the effects in question can be simulated under some parameter set or other, but by showing that there is a single set of parameters under which all of these effects can be observed in the behavior of the model. If it proves impossible to identify such a single set of parameters, the model must be judged ultimately unsuccessful, even if every effect is successfully simulated under some particular parameter set. Jacobs and Grainger (1992) adopted the same attitude in their simulation work.

This program of simulations has only just begun, so complete results will not be available for some time. However, sample results in which some basic effects are studied with just a few representative stimuli have been obtained, and these are presented below.

Sample Results From DRC Simulations

Regularity Effects

Given the processing structure of the phonemic output system of the DRC model, it is easy to explain why regularity influences both error rates and latency of correct response in reading-aloud experiments. As lexical processing goes on, the lexical procedure causes the activation levels in the correct phoneme units to rise. The nonlexical procedure works similarly; activation levels rise in those phoneme units that correspond to the graphemes of the input string. The phonemes activated by the two procedures will be the same when the stimulus is a regular word, but they will differ when the stimulus is an exception word. As discussed above, the more frequent a word, the more rapidly the lexical procedure does its job; therefore, a pronunciation for a high-frequency word can be generated entirely by the lexical procedure before any activation from the nonlexical procedure begins to influence the phoneme stage. In this case, regularity cannot affect performance, because regularity effects only occur through conflict at the phoneme level between the activations generated lexically and nonlexically.

With appropriate parameter choice, however, input from the nonlexical route regarding a low-frequency word may reach the phoneme level before lexical processing has fully determined pronunciation. Consider the word *pint* as an example. The lexical route activates the phoneme /ɪ/ in the second position, but before activations at this level reach their criterial value the nonlexical route begins to activate a conflicting phoneme in the second-position set, the phoneme /i/. Because there is full inhibitory interconnection within any phoneme set, these two units inhibit one another, so the activation of each reduces the activation of the other. The activation of the correct unit, having begun earlier, is larger than the activation of the incorrect unit; thus, the correct unit eventually drives the incorrect unit down to an activation of zero. Before this happens, however, inhibition from the incorrect unit reduces the rate at which activation in the correct unit rises under the control of the lexical route. Correct activations eventually reach the criterial value, but the time (i.e., number of processing cycles) taken to reach this value will be increased because of the presence of conflicting information from the nonlexical route whenever the stimulus is a low-frequency exception word. Therefore, the pronunciation of these exception words will be delayed relative to the pronunciations of matched regular words, where no such inhibition will occur. If, instead, the stimulus is a regular word, the nonlexical input accelerates rather than decelerates the rise of the correct phonemic activations because all the desired phonemes will be activated from two sources.

With irregular words of still lower frequency, input from the nonlexical route may sometimes actually get to the phonemic output stage before any input from the lexical route arrives. In this case, the nonlexical route will dictate the ultimate pronunciation, though the time taken to generate this pronunciation will be lengthened if conflicting input arrives from the lexical route. Here, then, there will be an error effect rather than a latency effect. The dual-route analysis therefore offers an explanation of the interaction between regularity and frequency for both latencies and error rates.

This is a qualitative argument; it might not be translatable into quantitative terms. That is, it needs to be demonstrated whether there actually is a set of parameter values under which DRC's naming latencies will be unaffected by regularity for high-frequency words at the same time that they are longer for exception than for regular words when the words are low in frequency. It turns out to be easy to find such a set of parameters. For a parameter set that yields zero effects of regularity with high-frequency words, the model's naming latencies for a sample set of low-frequency regular and irregular words are shown in Table 1. The pronunciations generated by the model were correct in all cases here.

This mean difference of more than six processing cycles is substantial in DRC terms; in simulations with larger word sets, mean differences of three cycles between conditions are often highly statistically significant.

Can we be sure that these regularity effects are really due to the influence of the GPC route and not some confounding (e.g., orthographic) variable? An enormously valuable aspect of computational modeling, often not appreciated, is that it provides a method by which such questions can be definitively answered. This particular question can be answered by manipulating the strength of the influence of the GPC route (by varying one parameter of the model, strength of GPC activation). If the effect in Table 1 is genuinely a regularity effect, it should be exaggerated when the value of this parameter is increased. Table 2 shows the result of this parameter manipulation.

Note here that as GPC excitation is increased, naming latencies decrease for the regular words and increase for the exception words. If GPC excitation is sufficiently high, regularization errors[3] begin to occur with the exception words. Clearly, then, the different performance with the two types of word is a genuine regularity effect.

These three exception words are of similar frequencies and are all four letters long, but they do not behave in the same way: Performance with *tomb* is much better than performance with *chef* but much worse than performance with *glow*. Why are there these large naming-latency and error differences between different exception words of similar frequencies and lengths? We return to this question in the section titled *Serial and Parallel Processes in Text-to-Speech Translation*; we invite the reader to offer an answer to it before reading on.

Table 1
DRC's Naming Latencies (in Processing Cycles) for Low-Frequency Regular and Exception Words

Words	Latencies
Exception	
glow	28
chef	35
tomb	30
M	31
Regular	
dish	24
moss	24
plea	26
M	24.7

Note. DRC = dual-route cascaded (model).

Table 2
DRC's Latencies (in Processing Cycles) for Correct Naming Responses for Low-Frequency Regular and Exception Words, as a Function of the Strength of Activation From the Nonlexical Route

	Strength of excitation from GPC route		
Word	0.75	1.0	1.5
Exception			
chef	35	—	—
tomb	30	36	—
glow	28	29	33
Regular			
moss	24	23	22
plea	24	24	23
dish	26	25	23

Note. Dashes denote regularization errors (i.e., pronouncing the irregular word as the rules prescribe). DRC = dual-route cascaded (model); GPC = grapheme-to-phoneme correspondence.

Pseudohomophony Effects

A pseudohomophone is a nonword (such as *koat* or *phocks*) whose pronunciation is identical to that of some real word (such as *coat* or *fox*). This property of nonwords affects performance in both lexical decision and reading-aloud tasks.

The *NO* response in lexical decision tasks is slower and error rates are higher for pseudohomophone nonwords than for matched nonpseudohomophone nonwords (Coltheart et al., 1977; Rubenstein, Lewis, & Rubenstein, 1971). Coltheart, Patterson, and Coltheart (1994) found that this effect is restricted to pseudohomophones that are orthographically very similar to the words with which they are pseudohomophonic; thus, the effect is present with pseudohomophones like *koat* but not with pseudohomophones like *phocks*.[4]

Naming latency in reading-aloud tasks is shorter for pseudohomophones than for nonpseudohomophone nonwords (McCann & Besner, 1987; Taft & Russell, 1992).

Lexical decision. Figure 2 shows the activation of the unit for the word *coat* in the orthographic input lexicon in response to two nonword stimuli, the pseudohomophone *koat* and the orthographically matched nonpseudohomophone *foat*. It is clear that the pseudohomophone causes more activity in the orthographic input lexicon than the nonpseudohomophone, and hence, given the account offered earlier of how lexical decisions are made by the DRC model, the *NO* response will be slower to the pseudohomophone than to the nonpseudohomophone.

Where is this activation of the *coat* entry by the stimulus *koat* coming from? It is a consequence of the fully interac-

[3] A regularization error is an error in which an exception word is pronounced in the way prescribed by the GPC rules to which it is an exception.

[4] This result is paralleled by informal observations we have made when asking people about pseudohomophones; people readily agree that *koat* is a pseudohomophone, but often have difficulty in determining that *phocks* is a pseudohomophone.

tive character of the DRC model. Once *koat* has activated its three phonemes in the phoneme system, through input from the GPC system, the phonological representation for the word *coat* in the phonological output lexicon will receive strong activation through DRC's excitatory links from phoneme level to phonological output lexicon, and so in turn strong activation will be transmitted back to the orthographic unit for *coat* in the orthographic input lexicon and, indeed, through this to the letter unit for C in the letter detectors for Position 1. (Might this be the basis for what Taft, 1982, has described as grapheme–grapheme rules?)

When activation of the *coat* entry in the orthographic input lexicon is measured with the alternative pseudohomophone *kote* as input, using the same parameter values, one finds no activation at all—the *coat* entry does not respond. Hence, the model will have difficulty making a lexical decision with the orthographically similar *koat* but not with the orthographically dissimilar *kote*—as is the case with human subjects in lexical decision experiments.

Why is *coat* activated only by an orthographically close pseudohomophone? This is due to the inhibitory connections from the letter detectors. With the pseudohomophone *kote,* three of the four stimulus letters—*k, t,* and *e*—will be inhibiting the *coat* entry, and that keeps it inactive. With the stimulus *koat,* only one letter—the *k*—will be having an inhibitory effect, and this allows the excitation that has come all the way downstream from the phoneme system to activate the *coat* entry. The substantial activation of the *coat* entry by the control nonword *foat* is due solely to the excess of excitation over inhibition coming from the letter level.

Naming latency. Both McCann and Besner (1987) and Taft and Russell (1992) have shown that pseudohomophones are named faster than control nonwords. A subset of 36 of the McCann–Besner pseudohomophones, plus their nonword controls, was submitted to the model and its naming latencies determined. The human and model data for these items are shown in Table 3.

Post hoc analyses indicated that the orthographic similarity of a pseudohomophone to its base word did not affect the pseudohomophone advantage in either the human or the model data.

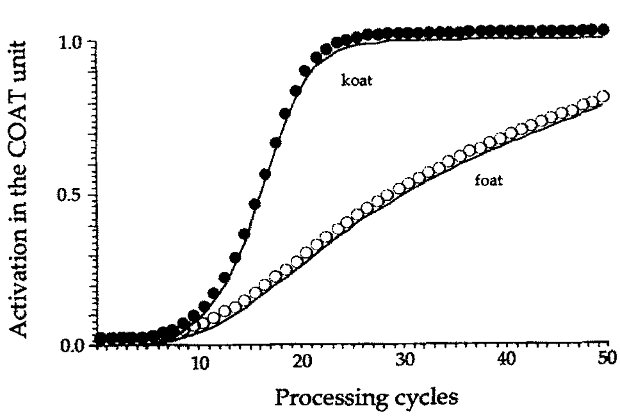

Figure 2. Activation of the unit for *coat* in the visual input lexicon in response to the stimuli *koat* and *foat.*

Table 3
Effect of Pseudohomophony on Nonword Naming Latency in Human Subjects and in the DRC Model

Word type	Naming RT (ms)[a]	Cycles[b]
Pseudohomophones	591	23.67
Nonpseudohomophones	642	27.08

Note. For naming reaction time (RT), $p = .0009$; for cycles, $p < .0001$. DRC = dual-route cascaded (model).
[a] Human subjects; data are from McCann and Besner (1987).
[b] DRC model.

McCann and Besner (1987) suggested that this pseudohomophone advantage in naming is due to the action of connections from the phonological output lexicon to the phoneme system; the effect of these connections will be to increase activation at the phoneme level when the set of phonemes being activated at that level comprises the phonological form of a word that is present in the phonological output lexicon. DRC can be used to test this directly: The strengths of just this set of connections can be set to zero. When this is done, nonwords and pseudohomophones are still named correctly, but there is no longer a pseudohomophone advantage, which confirms McCann and Besner's explanation of this advantage.

Masked Priming Effects

We have not yet begun simulation work on masked primary effects. However, according to what has just been said about the DRC model and pseudohomophone effects, nonlexically derived phonological representations of printed stimuli gain access to the visual word recognition system very early on in processing, certainly earlier than the point at which lexical decisions are made or a reading-aloud response occurs. Suppose that, at that point, the stimulus whose nonlexical phonology has had some effect within the visual word recognition system is replaced by a new printed stimulus. This is the DRC analogue of masked priming. When this happens, the response of the model to the target stimulus will not be starting from a state of zero activation of all units in the visual word recognition system, as would normally be the case. Instead, the starting point will be the pattern of partial activations that had been evoked by the priming stimulus, and this will include phonologically mediated activation of the unit for the target word if the prime were a homophone or a pseudohomophone of the target. Hence, we are optimistic about the capacity of the DRC model to simulate phonological masked priming effects such as those reported by Perfetti and Bell (1991) and Ferrand and Grainger (1992).

Neighborhood Size (N) Effects

The *N* of a letter string is the number of different real words that differ from that letter string by just one letter (Coltheart et al., 1977); for example, *jazz* and *ilge* have no neighbors (thus *N* values of zero), whereas *meat* and *sare* have many neighbors (thus high *N* values). Lexical decision times are affected by *N*.

NO *to nonwords is slower when N is high than when it is low.* Table 4 (see also Coltheart et al., 1977) compares data from human subjects responding to nonwords in a lexical decision task to data from the DRC model when it is making *NO* responses in a lexical decision task using the variable-deadline procedure described earlier; in both cases, *NO* latencies are slower when *N* is high than when it is zero.

YES *to words is faster when N is high than when it is low (especially for low-frequency words).* Table 5 (see also Andrews, 1992) illustrates the interaction between word frequency and *N* as it affects *YES* response latency in lexical decision experiments.

As Figure 3 shows, *N* does not affect activation for higher frequency words (high-*N store* vs. zero-*N doubt*), but for lower frequency words (high-*N crave* vs. zero-*N psalm*) activation rises more rapidly (and so the *YES* response will be made more quickly) for words whose *N* value is high. What is the mechanism responsible for the facilitated effect of *N* on *YES* latencies? Andrews (1992) proposed that it is top-down feedback from word detectors to letter detectors. If so, the difference between the *crave* and *psalm* plots should disappear if the parameter in the DRC model that controls the strength of the excitatory connections from words to letters is set to zero; that is what happens.

Regularity Effect in Reading Aloud

An Alternative to the Dual-Route Approach

The parallel distributed processing (PDP) model of reading aloud proposed by Seidenberg and McClelland (1989) includes a single procedure for computing phonology from orthography, which it is asserted, can correctly transcode both exception words and nonwords. Hence, they offer this model as evidence against a basic tenet of dual-route models (namely, that two different procedures are used by human readers to read exception words and nonwords correctly). The accuracy with which this model computes phonological output from orthographic input, after training, is influenced both by word frequency (how often a word is presented during training) and by regularity, and these two factors interact, so that the model, like people, shows a greater regularity effect when word frequency is low than when it is high.

Table 4
Comparison of Data From Human Subjects and From DRC Model for NO *Responses in a Lexical Decision Task*

Response latency	High-*N* nonwords (e.g., *sare*)	Zero-*N* nonwords (e.g., *ilge*)
Human (ms)	798	701
DRC (cycles)	77	67

Note. Human data are from Michie, Coltheart, Langdon, and Haller (1994). DRC = dual-route cascaded (model); *N* = neighborhood size.

Table 5
Effects of Neighborhood Size (N) and Frequency on Latency of Correct YES *Responses in a Lexical Decision Task*

Word frequency	High *N*	Low *N*	*N* effect
High	660	670	10
Low	710	755	45

Note. Human data are from Michie, Coltheart, Langdon, and Haller (1994).

Seidenberg and McClelland (1989) therefore argued that the interaction between regularity and frequency can no longer be taken as evidence for the traditional type of dual-route model of reading, because a radically different model—a model with a single route that can read both exception words and nonwords—is capable of explaining this interaction. However, there are a number of difficulties with their claim. First, the output of their model in response to any orthographic input is a phonological error score—a measure of the extent of mismatch between the phonological representation that the model computes and the correct phonological representation—and it is by no means clear how the model's phonological error scores could be mapped onto response latencies (Besner, Twilley, McCann, & Seergobin, 1990). Second, in a general critique of the Seidenberg and McClelland (1989) model, Coltheart et al. (1993) have argued that there are a number of basic facts about reading that this model has not been able to explain; if these arguments are correct, then the model as a whole should be rejected.

These difficulties, however, are specific to the particular PDP model of oral reading proposed by Seidenberg and McClelland (1989), rather than to some general class of PDP models. Hence, the objections raised in the previous paragraph do not necessarily apply to the PDP model described by Plaut, McClelland, and Seidenberg (1993) and Plaut and McClelland (1993). Their model differs from the Seidenberg and McClelland (1989) model in the form of input representation of orthography and output representation of phonology that it uses. However, their model resembles the Seidenberg and McClelland model in that it too includes a single procedure for computing phonology from orthography which can correctly transcode both exception words and nonwords. Furthermore, their model can simulate the interaction between regularity and frequency.

Hence, there exist two quite different kinds of model, the dual-route model and the PDP model, which can explain the basic Regularity × Frequency interaction. We have therefore sought some new approach to the study of regularity effects, some approach that will allow contrasting predictions to be derived from the DRC and the PDP models. We have done this by attempting to identify an aspect of the regularity effect about which all forms of the dual-route model will make the same prediction and about which all forms of the PDP model will make a different prediction. This would allow us to adjudicate, not between some particular dual-route model and some particular PDP model, but instead between two broad classes of models.

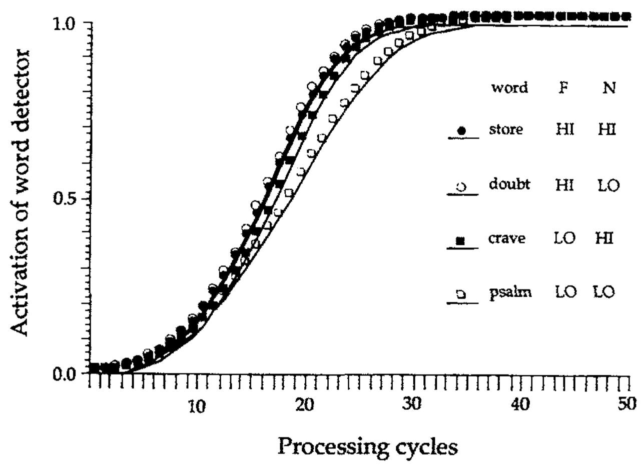

Figure 3. Activation of specific units in the visual input lexicon as a function of frequency (*F*) and neighborhood size (*N*) of the stimulus word.

Serial and Parallel Processes in Text-to-Speech Translation

As noted above, one of the two processing procedures in dual-route models is a grapheme–phoneme conversion procedure. In such models, it is assumed that this procedure operates serially, from left to right, across a grapheme string:

> Delivery of the assembly process's "opinions" about segmental phonology may well be more spread out over time, reflecting its essentially left-to-right operation, and perhaps be delivered in smaller packets (e.g., syllable onsets, rimes). (Monsell, Patterson, Graham, Hughes, & Milroy, 1992, p. 464)

> We assume that the assembly process delivers information in a cascade-fashion, so that assembled information related to the left part of (long) words is available earlier than assembled information for the right part. (Content & Peereman, 1993, p. 224)[5]

> . . . Suppose that construction of the nonlexical response . . . operates in a strict left-to-right manner. (Forster & Davis, 1991, p. 19)

As discussed earlier, the GPC procedure of the DRC model operates serially, left-to-right across the input string.

In contrast to this serial-processing property of dual-route models, it is intrinsic to the PDP models of Seidenberg and McClelland (1989) and of Plaut et al. (1993) and Plaut and McClelland (1993) that phonemic output is computed in parallel. Whether the input is an exception word, a regular word, or a nonword, activation of the correct phonemes at the model's phonemic output stage occurs in parallel across the set of phoneme units.

The presence of a serial procedure in dual-route models but not in the PDP models permits the derivation of contrasting predictions from the two classes of model.

According to dual-route models, the relative timing with which lexical and nonlexical information reach the phonemic output stage accounts for the regularity effect; the effect occurs when processing of an exception word at the phonemic stage is still in progress when conflicting information arrives from the nonlexical procedure. Similarly, the timing of lexical and nonlexical input explains the Regularity × Frequency interaction. The timing of the arrival of information from the lexical procedure depends on word frequency, so high-frequency exception words can be processed fully at the phonemic output stage before any information from the serially operating nonlexical procedure reaches that stage. The lexical processing of low-frequency words is slower, and so it is possible for information about these words coming from the nonlexical procedure to arrive at the phoneme system before processing of lexically derived information by that system is complete.

If the regularity effect found with low-frequency words occurs because of conflict at the phonemic stage between lexical and nonlexical phonemic information, and if nonlexical phonemic information reaches that stage serially, left-to-right, it obviously follows that the later in the phoneme string the conflicting information lies, the higher the probability that lexical processing will be completed before the conflicting information reaches the phonemic stage. Therefore, dual-route models predict that the size of the effect of regularity on naming latency of exception words depends on where in that exception word the first irregular GPC occurs: The later this correspondence occurs in an exception word, the smaller the regularity effect.

In contrast, for PDP models simulating the effect of regularity on naming latency, the left-to-right serial position of the irregular correspondence can make no difference, because activation of phonemes occurs entirely in parallel in these models.

Earlier, we presented DRC simulation data in which the model generated pronunciations for three low-frequency exception words (*chef, tomb,* and *glow*) and three matched regular words, and pointed out that the model's pronunciation latencies were longer for the exception words. We also raised the following question: "These three exception words are of similar frequencies and are all four letters long, but they do not behave in the same way: Performance with *tomb* is much better than performance with *chef* but much worse than performance with *glow.* Why are there these large naming-latency and error differences between different exception words of similar frequencies and lengths?" The answer should now be clear. The word *chef,* which generated the largest exception effect, is exceptional at its first phoneme; the next largest effect was for *tomb,* which is exceptional at its second phoneme; the smallest effect was for *glow,* which is exceptional at its third phoneme. Thus, the size of the exception cost in DRC's naming latencies diminishes as the position of the exceptional GPC moves from left to right through exception words.

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[5] Both of these articles allude to the possibility that the units that are delivered left-to-right by the assembly process might be larger than phonemes. The assembly process of the DRC model (Coltheart et al., 1993), however, generates solely phonemic units.

Hence, it is of interest to discover whether the cost of irregularity for low-frequency exception words in naming latency experiments with human subjects is related to the location in the exception words of their first irregular GPC. Discovering this will allow adjudication between two broad classes of models of reading aloud.

Effects of Position of Irregularity on Naming Latency

Some suggestive data already exist concerning effects of position of irregularity. Jared and Seidenberg (1990, Experiment 2) studied the effect of regularity on the naming latencies of two- and three-syllable words. They found that for high-frequency words, latencies and error rates were unaffected by regularity. For low-frequency words, however, exception words were named more slowly or with a higher error rate than regular words, and there was a tendency for these effects to be larger when the exceptional correspondences were in the first syllable (e.g., *diesel* or *cellist*) than when they were in the last syllable (e.g., *mocha* or *corsage*). Jared and Seidenberg argued, however, that this effect was not necessarily a true left-to-right effect; it could instead have been due to a consistency effect at the level of the (orthographically defined) syllable. The first syllables of words with first-syllable exceptional correspondences had on average 6.3 "enemies"—other words that began with that same letter sequence and in which the critical GPC was different. For words with final-syllable exceptional correspondences, the mean number of enemies was 4.3. Hence, they asserted that their finding that regularity effects are largely confined to the initial syllables of (low-frequency) words could have arisen either because of the influence of some kind of left-to-right translation process or because of a confounding of syllabic position with number of enemies.

Content (1991, Experiment 2) varied regularity and frequency in a word-naming latency experiment in French. Both variables affected naming latency, but there was no interaction between them. Error rates did reveal this interaction, with the effect of regularity on error rate being larger for low-frequency words. In a post hoc analysis, Content found that for both latencies and error rates, regularity effects were seen when the relevant phoneme was in initial or medial position, but not when it was in final position.

Content and Peereman (1993) report a post hoc analysis of regularity effects in a naming latency experiment in French that varied word frequency, regularity, and the nature of filler items (either high-frequency words or pronounceable nonwords). They analyzed the size of the regularity effect as a function of whether the irregular GPC was early (Phonemic Positions 1 through 3) or late (Phonemic Positions 4 through 6) in the exception word. In the latency data, position of irregularity did not interact with the size of the regularity effect, nor was there a triple interaction between regularity, frequency, and position of regularity, although the latency means exhibited trends in such directions; however, regularization errors were significantly more frequent when the irregularity was early in the irregular word than when it was late, and this effect interacted with the nature of the filler items (a larger effect of position of irregularity when the fillers were nonwords).

Also relevant here, even though not involving the variable of regularity, is the masked priming work of Forster and Davis (1991). When a target word to be read aloud was preceded by a brief masked priming nonword that differed from the target by only its first or its last letter, they found that naming latency for the target word was shorter when the prime and target had the same first letter (e.g., *bellom–bellow*) than when they had the same last letter (e.g., *dellow–bellow*); this effect was only seen with low-frequency target words. They argued that this priming effect was coming from the nonlexical phonological recoding of the nonword masked prime; if so, the fact that a common first phoneme produced more priming than a common final phoneme is evidence that the phonological recoding of nonwords is accomplished by a serial (left-to-right) rather than parallel process.

The three regularity studies obtained results on the position-of-irregularity effect solely from post hoc analyses, and in all three cases the authors draw attention to possible difficulties with these analyses. Nevertheless, the evidence they report strongly suggests that the effect is a genuine one, and this conclusion is consistent with the masked priming data from Forster and Davis (1991).

Strategic Effects in Reading Aloud

The main aim of our study was to determine whether the position-of-irregularity effect can be demonstrated in an experiment specifically designed for this purpose. The study also had a second, subsidiary, aim. In an early paper on the dual-route model, Coltheart (1978) suggested that "subjects can control the extent to which they use the lexical lookup and [GPC] strategies in tasks requiring them to pronounce aloud words and/or nonwords .... The presence of nonwords increases the use of the [GPC] strategy; the absence of exception words increases the use of GPC procedures" (p. 204). A number of subsequent studies have examined this suggestion. The basic technique of these studies is to manipulate a subject's use of either route by varying the nature of filler items in naming latency experiments. If there are many nonwords in the experiment, GPC processing should be relatively emphasized; if there are many exception words in the experiment, processing through the lexical route should be relatively emphasized. To be more precise, these strategic effects, if they occur, do not necessarily imply that subjects are capable of exerting strategic control over both routes of dual-route models. They imply that strategic control of at least one of the routes is possible (because the relative influence of the two routes can, of course, be varied by increasing or decreasing the activity of just one of the routes).

Tabossi and Laghi (1992) found that the effect of semantic priming on naming latency for words was present when all the items in the experiment were words, but was abolished if the materials included nonwords. When all the items were words, a lexical strategy for reading aloud should predominate, and of course semantic priming only occurs if the lexicon is in use. The inclusion of nonwords requires use of the nonlexical strategy for reading aloud; because the words and subjects in this experiment were Italian, which has no exception words, a nonlexical strategy would also allow correct reading aloud of all words but would not allow semantic priming effects to occur. Hence, Tabossi's results may show that subjects strategically emphasize the lexical or the nonlexical strategies in response to the demands of experiment materials.

Baluch and Besner (1991) studied naming latencies in Farsi, as a function of whether filler items were words or nonwords. For Farsi words that are written "transparently" (i.e., written in a way that would allow them to be read aloud by nonlexical rules), they found that two effects that depend on lexical access (the effects of word frequency and of semantic relatedness) were reduced when nonwords were included as fillers, which again suggests that the relative contribution of the lexical procedure to reading aloud is reduced when the stimuli include nonwords.

Monsell et al. (1992) report two experiments comparing naming performance in pure blocks of nonwords or exception words to performance in blocks of randomly mixed nonwords and exception words. For exception words, naming was slower when there were nonwords in the experiment than when no nonwords were present; this was only the case, however, with high-frequency exception words. Regularization errors were more frequent with low-frequency than with high-frequency exception words, and were more frequent when the materials included nonwords. For nonwords, they found that naming was faster when there were no low-frequency words to be named; the presence or absence of high-frequency words did not affect nonword naming latency.

Content and Peereman (1993) report a similar experiment in which they investigated naming latencies for words, varying the regularity (randomized variable) and frequency (blocked variable) of these words, and also the nature of filler items. Fillers were either nonwords or words of the same frequency as the target words. For word naming latencies, they found that, whereas nonword naming slowed performance for all words, high-frequency words were disproportionately slowed compared with low-frequency words. Moreover, for high-frequency words, nonword naming emphasized the regularity effect and increased regularization errors. Regularity did not interact with filler type or with word frequency.

All of these experiments suggest that subjects can strategically vary the degree to which they use lexical and nonlexical pathways in response to the types of items they must read aloud. It is not at all clear how reading models that do not distinguish between lexical and nonlexical pathways, such as the PDP models described above, might attempt to explain such effects.

Because regularity effects are attributed to the nonlexical pathway, it follows that the size of these strategic effects might vary as a function of the relative dependence upon the two pathways that subjects strategically choose. If it is the case that the size of the regularity effect depends on the phonemic position of the irregularity, then one measure of the size of the effect will be the slope of the function relating cost of irregularity to position of irregularity. Hence we might expect the slope of this function to be steeper when the experiment includes nonwords (emphasizing the nonlexical pathway) than when all the items are words. (Here, use of the nonlexical pathway is not necessary.)

In summary, then, our experiment had two aims: (a) to determine whether the size of the regularity effect seen on naming latencies for low-frequency words is influenced by where in an exception word the irregularity occurs, and (b) to determine whether, if this position effect is indeed obtained, it is influenced by the nature of filler items (nonwords vs. words) in the way that would be expected if it is possible for subjects to exert strategic control over relative speeds of processing by lexical and nonlexical pathways.

We therefore designed a naming latency experiment using low-frequency exception words and matched regular words as stimuli. The exception words contained an irregular correspondence for either their first phoneme (e.g., *chaos*), their second (e.g., *deadly*), their third (e.g., *crooked*), their fourth (e.g., *famine*), or their fifth (e.g., *esprit*). As we have explained, dual-route models predict that the size of the regularity effect will diminish monotonically across these five conditions, whereas the PDP models discussed earlier predict that regularity effects will be independent of position of irregularity; the model developed by Norris (1994) also predicts such independence.

The key sets of exception and regular words were presented for naming under two conditions: randomly intermingled with nonwords (stressing the use of the nonlexical route) or randomly intermingled with high-frequency exception words (stressing the use of the lexical route). If we do obtain position-of-irregularity effects, comparisons of the size of these effects in the two conditions will provide information about the extent to which strategic control over lexical and nonlexical processing in reading aloud is possible.

Method

Subjects

Forty-three first-year Macquarie University (Sydney, New South Wales, Australia) students participated in the experiment; 20 were assigned to the nonword filler condition, and 23 were assigned to the irregular-word filler condition. All had normal or corrected-to-normal vision, and all were native Australian-English speakers. Subjects received course credit for participating.

Stimuli

Ninety-six target words, each with highly irregular GPCs, were chosen from the Medical Research Council Psycholinguistic Database (Coltheart, 1981). All words had two syllables, between four and seven letters, and frequencies between 1 and 20 in the norms of Kuçera and Francis (1967). In addition, all irregular target words had been pronounced correctly during preliminary testing by at least 80% of pilot subjects from the same subject pool.

Irregular target words were categorized into five conditions based on the position of the first irregular GPC. Twelve words were irregular at the first phoneme, 30 at the second phoneme, 17 at the third phoneme, 23 at the fourth phoneme, and 14 at the fifth phoneme. For each of the five sets of irregular words, a matched set of regular words was selected (see Appendix).

Regular words were matched to irregular words on the number of letters and the initial phoneme. The initial phoneme matching almost always involved identical initial phonemes; in the few cases where this was not possible, phonemes from the same phonetic class (e.g., both fricatives) were used. All the regular words had two syllables, between four and seven letters, and frequencies between 1 and 20 in the norms of Kuçera and Francis (1967). The need to select by position of exceptional phoneme and match on initial phoneme made it very difficult to match exactly across conditions on word frequency and neighborhood size; these variables were therefore dealt with by means of analysis of covariance (see the Results section).

For the nonword filler condition, 192 nonwords were generated. All nonwords were orthographically legal and pronounceable. For the irregular-word filler condition, 192 high-frequency irregular words were selected. All irregular words had one or two syllables, between four and seven letters, and a Kuçera and Francis (1967) frequency of 100 or greater.

Apparatus and Procedure

Stimulus presentation and data recording were accomplished by using DMASTR software[6] running on a DeltaCom 486 PC. Responses were timed using a voice key that was fitted to each subject; the microphone was held at a constant distance from the mouth throughout the experiment by means of a voice key headset. Subjects were seated approximately 16 in. from the computer monitor. They were instructed to read aloud each item on the monitor as quickly and as accurately as possible. The experimenter recorded mispronunciations by hand. Subjects were given 10 practice trials. Word and nonword presentation was preceded by 900-ms fixation brackets spaced eight characters apart. A word or nonword then appeared in lowercase on the screen for a maximum of 4,000 ms. Naming of the item triggered the immediate presentation of the fixation brackets. In total, subjects named 96 low-frequency irregular words, 96 matched regular controls, and 200 fillers, either nonword or irregular word depending on condition. Stimuli were presented in a different random order for each subject.

Results

Reaction times under 200 ms and over 1,200 ms were discarded. When an error was made to an irregular word, its reaction time and the reaction time to its matched regular word were discarded, and conversely for errors to regular words. Reaction times for the nonword fillers in Condition 1 and irregular-word fillers in Condition 2 were discarded, and the remaining data points falling outside the second standard deviation were winsorized to the second standard deviation boundary, individually for each subject. Table 6 shows the mean latency of correct responses as a function of regularity, position of irregularity, and filler condition. Table 7 shows mean error rates broken down in the same way.

The mean latencies of correct responses were analyzed by an analysis of covariance with three factors (filler condition, regularity, and position of irregular phoneme) and three covariates (neighborhood size, $\log_{10}$ word frequency, and number of letters).

Table 6
Mean Correct Naming Latencies as a Function of Regularity, Filler Condition, and Position of Irregularity

	Position of irregularity				
Filler	1	2	3	4	5
Nonword					
Irregular	554	542	530	529	537
Regular	502	516	518	523	525
Exception					
Irregular	545	524	528	526	528
Regular	500	503	503	515	524

The regularity effect was significant both by subjects and by items, $F_1(1, 43) = 134.17$, $p < .005$, and $F_2(1, 192) = 29.51$, $p < .0005$. The Regularity × Position interaction was also significant in both analyses: $F_1(4, 172) = 20.08$, $p < .0005$, and $F_2(4, 192) = 2.86$, $p = .025$.

No other effects in this analysis of covariance approached significance by both subjects and items. Position was significant by subjects but not by items: $F_1(4, 172) = 2.87$, $p = .025$, and $F_2(4, 192) = 0.50$, $p = .739$. Condition was significant by items but not by subjects: $F_1(1, 42) = 0.20$, $p = 0.657$, $F_2(1, 192) = 10.83$, $p = .001$. No other effects were significant by either analysis; in particular, the Condition × Regularity interaction and Condition × Position interaction, and the three-way interaction of these variables, all yielded $p > .33$ for both analyses. Hence, there was no evidence whatsoever that the effects of regularity were modulated by filler condition.

Figure 4 shows the size of the regularity effect (after adjustment for the effects of the three covariates) as a function of position of irregularity. As predicted by the DRC model, this effect declines monotonically across positions, from 59 ms at Position 1 down to 6 ms at Position 5. These results are fitted well by the linear regression equation in the figure, which had an intercept of 65.1 ms, and a slope of −12.7 ms per increment of position; the value of R^2 was 0.924.

Planned comparisons of the significance of the regularity effect at each of the five positions were carried out for subject data and for item data, collapsed across the filler condition variable, with the following results:

Position 1: The regularity effect was significant both for subjects and for items: $F_1(1, 42) = 91.40$, $p < .005$, and $F_2(1, 19) = 5.85$, $p = .026$.

Position 2: The regularity effect was significant both for subjects and for items: $F_1(1, 42) = 58.73$, $p < .005$, and $F_2(1, 55) = 15.33$, $p < .005$.

Position 3: The regularity effect was significant both for subjects and for items: $F_1(1, 42) = 26.49$, $p < .005$, and $F_2(1, 29) = 4.23$, $p = .049$.

Position 4: The regularity effect was significant for subjects, $F_1(1, 42) = 5.06$, $p = .030$, but not for items.

[6] We thank Ken Forster for providing this software.

Table 7
Mean Naming Error Percentages as a Function of Regularity, Filler Condition, and Position of Irregularity

	Position of irregularity				
Filler	1	2	3	4	5
Nonword					
Irregular	13.8	11.8	12.9	8.5	3.9
Regular	1.7	1.2	0.3	0.9	1.1
Exception					
Irregular	12.7	10.4	13.8	7.9	2.8
Regular	1.1	0.6	1.0	1.5	0.0

Position 5: The regularity effect was not significant on either analysis.

Discussion

Our experiment focused on two aspects of reading (serial processing and strategic effects), and we discuss these in turn.

Serial Processing

As discussed earlier, the DRC model (and dual-route models in general) predicts that the size of the regularity effect on word naming latency should decrease monotonically as a function of position of irregularity, whereas PDP models such as those of Seidenberg and McClelland (1989), Plaut, McClelland, and Seidenberg (1993), Plaut and McClelland (1993), and Norris (1994) predict that the regularity effect will be independent of position of irregularity. Because a monotonic decline of the regularity effect as a function of position was clearly documented in our experiment, we offer our results as evidence for dual-route models and against PDP models.

Are there any natural modifications to these PDP models that might allow them to accommodate our results? It is hard to see what these could be; introduction of any type of serial processing procedure would mean that such a model was no longer a purely parallel processing model. Of course, the ultimate execution of a vocal response must be serial, but that serial process is subsequent to the formation of a phonological representation. It is the formation of that representation that the PDP models view as a process operating in parallel across all the phonemic positions of the representation; it is that view with which our results conflict.

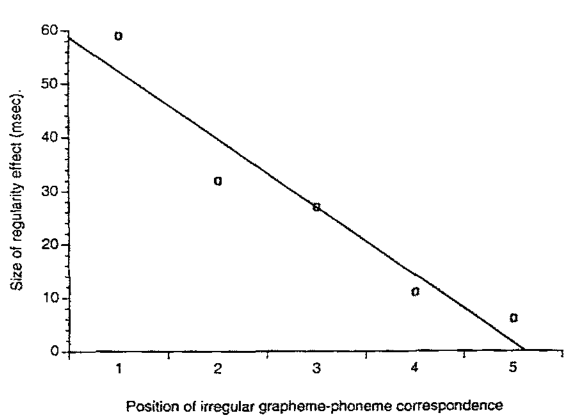

Figure 4. Size of the regularity effect as a function of position of irregularity.

One way of attempting to deal with the problem of serial order in the context of PDP models is to use recurrent networks (Jordan, 1986). Dell, Juliano, and Govindjee (1993) have developed a PDP model of phonological word production that uses recurrent network architecture: "Given a lexical input, say some encoding of the word CAT, the network's goal is to generate the features of the first segment /k/ across the output units, then /æ/, then /t/, and then it should 'stop', that is, generate neutral activation values of 0.5 for all the output features" (p. 157). One could imagine this kind of recurrent network as a back end to the PDP models of reading aloud, a mechanism that would translate the phonological representations computed by such models into a sequentially ordered utterance. However, this still would not offer such models a means by which our results could be explained. The effect of regularity of spelling–sound correspondence must be an effect on the time taken to compute a complete phonological representation, not on the time taken to execute it serially after it has been fully computed. To claim otherwise would be to claim that the phonological representations computed from exception words were in some way different from those computed from regular words. It is perhaps conceivable that there might be an activation-strength difference between the representations of exception words and the representations of regular words, after these have been computed in ways proposed by the PDP reading models. However, it is not conceivable that this activation-strength difference occurs only for exception words whose exceptionality is in one of the early positions in the word.

We thus persist in our view that the results we have obtained are inconsistent with the PDP reading models. A simulation by any such model of the relationship we have found between the size of the regularity effect and the position of the irregularity will show that our view is wrong.

Strategic Effects

On the basis of previous work, we expected that the use of nonword fillers in our naming latency experiment would lead subjects to emphasize the use of the nonlexical route as much as they could and that the use of high-frequency exception words as fillers, with no nonwords at all in the materials, would lead subjects to neglect the use of the nonlexical route as much as they could. If this strategy effect occurred, then effects of regularity on naming latencies and error rates should be larger in the nonword filler condition than in the exception-word filler condition. This result was not obtained; in our experiment, filler condition did not interact with any other variable, in either subject or item analyses. Why did we not obtain the strategic effect that we had been led to expect from the results of previous work?

We discuss two possibilities: that we should have used low-frequency exception words rather than high-frequency exception words as fillers; and that we should have used high-frequency exception words rather than low-frequency exception words as targets.

Filler-Word Frequency

It could be argued that introducing high-frequency exception words as fillers would in fact not have the effect of inducing subjects to minimize use of the nonlexical route for reading aloud, even though the nonlexical route would respond incorrectly to all such words. If the lexical processing of high-frequency words is always faster than nonlexical processing, then the errors on high-frequency exception words that are made by the nonlexical route would be irrelevant: By the time the nonlexical route has computed a (wrong) pronunciation, the correct pronunciation has already been uttered. If so, there would be no need to deemphasize the use of the nonlexical route here, because it is not harming performance. On this reasoning, the correct type of fillers to use would be low-frequency exception words. There must be overlap of processing times between the lexical processing of low-frequency words and nonlexical processing (otherwise there would be no regularity effect for low-frequency words); therefore, the presence of many low-frequency exception words would lead to a large error rate, and the only way to reduce this error rate would be to make less use of the nonlexical route—which should reduce the size of the regularity effect seen with the target words. Thus, the way to reduce the use of the nonlexical route would be to introduce low-frequency (not high-frequency) exception words as fillers. This reasoning seems plausible; it also seems consistent with the results of Monsell et al. (1992). They found that nonword naming was slower when the nonwords were mixed with low-frequency exception words (we have proposed here that it is advantageous to slow down nonlexical processing) than when there were only nonwords to be named. The presence of just high-frequency exception words mixed with the nonwords (here, we have argued, there is no need to slow down nonlexical processing) did not affect nonword naming latency.

Monsell et al. (1992) also found that naming of exception words was slower when nonwords were present than when there were no nonwords, which is also consistent with what we have been arguing; the introduction of nonwords would of course enhance any effects that reflect use of the nonlexical route (such as regularity effects). Unfortunately, however, our argument predicts that only the naming of low-frequency exception words should be sensitive to the presence or absence of nonwords, whereas Monsell et al. found the opposite: It was only the naming of high-frequency exception words that was affected by this manipulation.

Target-Word Frequency

We refer the reader to Monsell et al. (1992) for arguments that led these authors to expect that any strategic adjustments of a subject's reliance on the nonlexical route would influence the naming of high-frequency exception words, rather than the naming of low-frequency exception words. If this is so, then it might have been better for us to use high-frequency rather than low-frequency exception words as target stimuli. However, their arguments seem to entail that nonlexical processing would very often finish before lexical processing for low-frequency exception words. Hence, such words should very often be mispronounced (regularized); the observed error rates for low-frequency exception words in naming-latency experiments (such as ours, for example) are not as high as the arguments of Monsell et al. (1992) would lead us to expect.

We do not want to propose that strategic manipulation of one or both reading routes never happens, given that we have referred earlier to several results that suggest that it does happen. However, we do not know why it did not happen in our experiment, and a full account of the conditions that govern the possibility of such strategic manipulations therefore remains to be formulated.

What is clear, however, are the theoretical implications of our main finding: The size of the regularity effect on word naming latency decreases as a function of position of irregularity. The PDP models we have referred to predict that the size of the regularity effect will be unrelated to position of irregularity. The DRC model predicts the decline in the size of the regularity effect as a function of position that we observed.

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Appendix

The 96 Irregular (Irreg.) Words and Their 96 Matched Control Regular (Reg.) Words Used in the Experiment

Irreg.	Reg.
Position 1	
elite	ankle
epoch	eagle
omelette	exploit
unite	ethic
usurp	unfit
chamois	shampoo
chaos	comic
chorale	convict
oven	edit
earthy	escort
honour	outlet
hourly	arcade
Position 2	
booking	bundle
bouquet	blemish
canine	cradle
castle	cantor
covet	clinic
facet	fable
deadly	dispel
fasten	fabric
footing	foolish
goody	garlic
hearty	hectic
cuisine	confine
khaki	kiosk
leaden	limpid
penal	pelvis
phoenix	ferment
rabies	ramble
rating	radish
ravine	relish
rebuild	railway
receipt	ransack
seismic	sibling
siding	septic
souffle	seaside
tidal	timid
touchy	tactic
tulip	tepid
duet	digest
puny	peanut
pupil	poodle
Position 3	
abbey	anvil
alley	acrid
cosmos	candid
crooked	compact
orient	outlaw
psychic	seaweed
react	relic
ruin	rabid
signor	sawdust
stifle	staple
stylish	sparkle
swarthy	startle
visage	vanish
anguish	argon
adage	arsenic
basil	bandit
cliche	candle
Position 4	
barley	banish
baggage	brigade
cabbage	compost
comrade	catfish
cottage	canteen
famine	format
forfeit	filbert
galley	gamble
hockey	humble
languid	lactate
memoir	mentor
pigeon	punish
rabbi	robin
racquet	rampage
rustle	runway
sojourn	steeple
volley	vortex
whistle	weekday
wrestle	wrinkle
homage	hurdle
milieu	morbid
moisten	mundane
parquet	pumpkin
Position 5	
bandage	bagpipe
chutney	germane
debris	dismay
esprit	enzyme
festive	fertile
fictive	flemish
redwood	ripple
trestle	torment
trolley	trustee
vestige	verdict
biscuit	blemish
salvage	stumble
vantage	varnish
whiskey	wedlock

Note. The classification of a word as regular or irregular was determined objectively, as follows. The grapheme–phoneme rule learning algorithm described in Coltheart et al. (1993) was applied to a database of approximately 4,000 monosyllabic words and their Australian pronunciations. This yielded a set of Australian grapheme-to-phoneme correspondence (GPC) rules. When the GPC-applying algorithm of the dual-route cascaded (DRC) model (Coltheart et al., 1993) was applied to the 96 words classified here as irregular, none of these words were correctly translated; all are regularized. When the GPC-applying algorithm of the DRC model (Coltheart et al., 1993) was applied to the 96 words classified here as regular, 100% of these words were correctly translated (counting as correct a few cases of words where vowels may be reduced, at least in casual speech, but are given their full value by the GPC procedure).

Received January 31, 1994
Revision received April 1, 1994
Accepted April 15, 1994 ■