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Priming and Attentional Control of Lexical and Sublexical Pathways During Naming

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A modified priming task was used to investigate whether skilled readers are able to adjust the degree to which lexical and sublexical information contribute to naming. On each trial, participants named 5 low-frequency exception word primes or 5 nonword primes before a target. The low-frequency exception word primes should have produced a greater dependence on lexical information, whereas the nonword primes should have produced a greater dependence on sublexical information. Across 4 experiments, the effects of lexicality, regularity, frequency, and imageability were all modulated in predictable ways on the basis of the notion that the primes directed attention to specific processing pathways. It is argued that these results are consistent with an attentional control hypothesis.

Words afford a number of distinct processing pathways, or codes (e.g., orthography, phonology, semantics, and morphology). Most current models of word reading (e.g., Coltheart, Curtis, Atkins, & Haller, 1993; Plaut, McClelland, Seidenberg, & Patterson, 1996; Zorzi, Houghton, & Butterworth, 1998) include two major pathways for the pronunciation of visually presented words aloud. In dual-route models (e.g., Coltheart, 1978; Coltheart et al., 1993), the sublexical route produces pronunciations according to spelling to sound rules, whereas the lexical route maps the whole word onto a lexical representation that has the appropriate pronunciation stored with it. In this way, the sublexical route is particularly well suited for the pronunciation of nonwords (e.g., FLIRP), whereas the lexical route is essential for the pronunciation of exception words that do not follow these rules (e.g., PINT). Parallel distributed processing (PDP) models represent orthographic, phonological, and semantic information in separate systems (e.g., Plaut et al., 1996). Because spelling-to-meaning mappings are more arbitrary than spelling-to-sound mappings, semantic information tends to be more word specific and is particularly important for low-frequency exception words (Seidenberg, 1995; Strain, Patterson, & Seidenberg, 1995). For ease of explication we refer to word-specific information as "lexical" and information about spelling-to-sound mappings as "sublexical" throughout, reserving discussion of how this distinction is instantiated in the two classes of models for the General Discussion section.

Recently, there has been a good deal of debate as to whether skilled readers have attentional control over the degree to which lexical and sublexical information contribute to naming performance (Balota, Law, & Zevin, 1999; Balota, Paul, & Spieler, 1999; Baluch & Besner, 1991; Lupker, Brown, & Colombo, 1997; Jared, 1997; Monsell, Patterson, Graham, Hughes, & Milroy, 1992; Simpson & Kang, 1994; Tabossi & Laghi, 1992). Clearly, there are situations in which it might be desirable to attend selectively to one or another aspect of visually presented text. For example, reading isolated words aloud from a computer screen does not require the same attention to meaning as reading a novel or a journal article. The question addressed in the current research is whether readers can bias their processing style at a very basic level to meet task demands within the context of an experiment. For brevity, we refer to this as the "attentional control" hypothesis and now turn to a brief review of the extant literature.

Evidence for the Attentional Control Hypothesis

One approach that has been used to investigate the attentional control hypothesis is to bias processing pathways with list composition manipulations. Generally, in this type of experiment, performance in blocks composed entirely of one type of stimulus (pure blocks) is compared with performance in blocks containing various kinds of stimuli (mixed blocks). Differences in performance between the two blocks are attributed to participants' relying more on stimulus-appropriate processing in the pure blocks than in the mixed blocks. Interestingly, the more powerful demonstrations of attentional control of processing pathways have been in orthographies with varying levels of orthographic depth (in Farsi, Baluch & Besner, 1991; in Korean, Simpson, & Kang, 1994; and Kang & Simpson, 1998; and, in Turkish, a

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shallow orthography, Raman, Baluch, & Sneddon, 1996) with the list context paradigm.

As an example of the list context manipulation across different levels of orthographic depth, consider the Simpson and Kang (1994) study. In Korean, there are two different scripts, *Hangul* and *Hanza*, each representing a different level of orthographic depth (Frost, Katz, & Bentin, 1987). In the *Hangul* alphabet, constituents are completely regular, to the extent of lacking any context-sensitive rules. In contrast, the *Hanza* script involves a system of ideographs derived from the Chinese system whose forms are almost entirely uninformative regarding phonology. Thus, the *Hanza* script is much deeper than the *Hangul* script. Simpson and Kang (1994) compared performance on orthographically shallow stimuli in pure blocks containing only *Hangul* words, mixed blocks containing a high proportion of nonwords, and mixed blocks containing a high proportion of *Hanza* words. A small (21 ms) frequency effect was observed in the pure block. When nonwords were included in a list of *Hangul* words, they eliminated the effect of word frequency (low-frequency words were actually 8 ms faster than high-frequency words), suggesting that the inclusion of nonword stimuli biased participants to depend on sublexical conversion of spelling to sound at least to a greater extent than in blocks composed entirely of *Hangul* words. Conversely, the inclusion of *Hanza* words resulted in a relatively large frequency effect (60 ms) for the same *Hangul* word stimuli. This suggests that the presence of orthographically deep words, which do not easily afford direct translation of spelling to sound, induces a greater reliance on frequency-sensitive, lexical-semantic processing. A similar experiment in Italian (Tabossi & Laghi, 1992) demonstrated that semantic priming effects in a naming task were diminished when nonwords were included in the stimulus list. Interestingly, they failed to replicate this interaction in English with less regular stimuli. As noted above, results consistent with these findings have also been obtained in Farsi (Baluch & Besner, 1991) and in Turkish (Raman et al., 1996).

Although the results from list context manipulations appear relatively consistent in studies that have used comparatively shallow orthographies, the results from English and French are a bit more controversial. First consider the Monsell et al. (1992) study. Monsell et al. found list composition effects in English using nonword and exception word stimuli. High-frequency exception words were pronounced reliably faster in pure blocks than when they were mixed with nonwords. This, and a decrease in regularization errors were taken as evidence that participants allocated more attention to lexical information in pure blocks. In the mixed blocks, this strategy would be counterproductive because half of the stimuli (nonwords) must be processed sublexically, thereby slowing responses to exception words. There was no evidence of a list composition effect on response latencies for the low-frequency exception words. However, the tendency to produce regularization errors was greater for the low-frequency exception word stimuli when these items were mixed with nonwords than in pure blocks of low-frequency exception words. Regularization errors occur when participants pronounce the irregular grapheme or graphemes in an exception word in a way that is incorrect but consistent with other words (e.g., pronouncing PINT so that it rhymes with HINT). The pattern of regularization errors for low-frequency exception words is thus congruent with the response latency data from the high-frequency exception words. That is, participants allocated more attention to lexical information in pure blocks and thus made fewer regularization errors. It should be noted, however, that the *proportion* of errors that were regularizations did not change across contexts. That is, all kinds of errors were more frequent in the nonword context block, making the increase in regularization errors difficult to interpret. Content and Peereman (1992) found similar results in French. Rather than blocking stimuli by type, however, they introduced either nonword or high-frequency word "fillers" into blocks of exception and regular words. They found that the regularity effect was largest in the nonword filler condition, supporting the notion that the presence of the nonwords increased the reliance on sublexical spelling to sound mappings, thereby magnifying the regularity effect.

Coltheart and Rastle (1994) observed a somewhat different result in a similar list composition paradigm with English stimuli. When high-frequency exception word and nonword fillers provided the context for low-frequency exception and regular word targets, they observed no evidence of an interaction between filler type and the regularity effect. They explained this pattern by suggesting that lexical access is accomplished so quickly for high-frequency words that there is little opportunity for an influence of sublexical processing. Possibly, attention is shifted to the lexical route (or away from the sublexical route) only under conditions when competition from sublexical processing interferes with performance on many stimuli in a block. Indeed, in a later experiment (Rastle & Coltheart, 1999), results consistent with the attentional control hypothesis were found when low-frequency rather than high-frequency exception words were used as fillers. Interestingly, these later results were partially simulated by slowing down the grapheme-to-phoneme system of the Coltheart et al.'s (1993) Dual-Route Cascaded (DRC) model.

The support these results provide for the attentional control hypothesis has recently been reinterpreted within an alternative framework by Lupker et al. (1997) and by Jared (1997). We refer to this alternative hypothesis as the "deadlines" hypothesis. The deadlines hypothesis can explain much of the relevant data from experiments in English and French equally as well as the attentional control hypothesis. According to the deadlines hypothesis, participants adjust a timing criterion for initiation of responses based on their response latency on previous trials. For example, in a block containing both stimuli to which very fast responses are possible and stimuli that generally elicit slower responses, the criterion for initiating a response will be set at an intermediate point. Consequently, faster responses will tend, on average, to be slower in mixed blocks than in pure blocks and normally slow responses will tend to be faster. This hypothesis predicts that high-frequency exception words will be produced relatively slowly when mixed with nonwords, as observed by Monsell et al. (1992), simply because the nonwords in their experiments tended to produce slower responses, and not because of increased attention to sublexical processing. The deadlines hypothesis also predicts a reciprocal pattern for nonword stimuli: These items should be produced more quickly when mixed with high-frequency exception words than in pure blocks. This is the pattern observed in the Monsell et al. data. The data from Rastle and Coltheart's (1999) experiments are also explained equally well in terms of the deadlines hypothesis. They found that words irregular at the first position (e.g., CHEF) are produced more slowly than words with irregularities at later positions (e.g., GLOW, see also Coltheart & Rastle, 1994; Cortese, 1998). Consistent with the deadlines hypothesis, nonwords and regular words were also produced more slowly in the presence of the relatively slow first-position irregular than third-position irregular words. This is particularly damaging to an attentional control account of these data, because the actual simulation in which the phonological route was slowed down produced a context by lexicality interaction not observed in the behavioral data.

Independent support for the deadlines hypothesis has come from a number of experiments by Lupker, Brown, and Colombo (1997) and Jared (1997). For example, in one experiment (Lupker et al., Experiment 3) high- and low-frequency exception words were presented in either pure blocks of a single frequency range or mixed blocks of both high- and low-frequency words. Consistent with the deadlines hypothesis, high-frequency exception words were produced more slowly when mixed with low-frequency exception words, and vice versa. Results from Jared's (1997) study are similarly problematic for the attentional control hypothesis. In these experiments, high- and low-frequency consistent and inconsistent words (Jared, McCrae, & Seidenberg, 1990) were presented in the context of either nonword or low-frequency exception word filler stimuli. Participants in the low-frequency exception word filler condition were generally faster than participants in the nonword filler condition. In no instance, however, was the size of the consistency effect for either high- or low-frequency stimuli dependent on filler type, as would be predicted by the attentional control hypothesis. Of course, one must be cautious in rejecting the attentional control hypothesis based on these null results, because it is at least possible that a stronger manipulation might modulate attentional control.

The current controversy has generated substantial evidence for both the deadlines hypothesis and the attentional control hypothesis. Despite the accumulating support for the attentional control hypothesis from shallower orthographies (Baluch & Besner, 1991; Raman, Baluch, & Sneddon, 1996; Simpson & Kang, 1994; Tabossi & Laghi, 1992), much of the evidence from earlier findings in relatively deep orthographies (e.g., Content & Peereman, 1992; Monsell et al., 1992) appears to be reinterpretable in terms of the deadlines hypothesis. The goal of the current research is to provide a stronger test of the attentional control hypothesis in English. We should point out here that results consistent with the attentional control hypothesis will not necessarily be inconsistent with a deadlines account. Although the deadlines account raises serious questions about earlier evidence that has been interpreted in terms of attentional control, it should be possible to observe attentional control phenomena under circumstances that do not lend themselves to a deadline account.

There is already a good deal of evidence that the different tasks used to study word recognition call on different sets of processes (e.g., Balota & Chumbley, 1984, 1990; Balota et al., 1999; Jacobs & Grainger, 1994; Stone & Van Orden, 1993). It is important to consider whether conditions within a single task can modulate the degree to which different sources of information contribute to responses. Changing the contribution of different processes while holding the response constant may yield a clearer picture regarding the role of attention in modulating relevant processing codes.

The Present Study

In light of the considerable evidence from other languages, it seems plausible to suggest that similar effects could be found in English with more powerful manipulations. The languages in which these effects are the strongest tend to have shallow orthographies. In a deeper orthography, the role of attentional control may be more difficult to observe. The allocation of attention to different sources of information is measured in terms of the strength of main effects supported by the pathways that use that information. If multiple pathways contribute to a single effect, it is less clear how interactions are to be interpreted. In a shallow orthography, mappings from orthography to phonology are so regular that the influence of variables like frequency and lexicality may be wholly the result of other, lexical-level processing (Frost et al., 1987; Seidenberg, 1995). In a quasi-regular orthography, like English, however, frequency of occurrence may influence the association of spelling to sound for a given item (Harm & Seidenberg, 1999; Plaut et al., 1996) and possibly the application of context-sensitive rules (Rosson, 1985; Norris, 1994). Thus, it is not surprising that effects in English are more subtle than in other, shallower orthographies.

It is also possible that in earlier list composition experiments, attentional control effects were diluted by the fact that some of the target stimuli were preceded by other targets, which may have disrupted any increased dependence on specific sources of information fostered by the fillers. One way to minimize this problem is to control the structure of the trials such that each target is preceded by a set of primes designed to accentuate the contribution of lexical or sublexical information. In the current study, we used a priming procedure in which each trial consisted of five primes followed by a target. Trials were blocked by prime type, so that in each block, 100 primes of the same type were presented. The rationale was to create a situation in which dependence on the most efficient pathway for processing the prime stimuli would be maximally beneficial.

Experiment 1

The first experiment was a necessary step to determine whether the present manipulation is sufficiently powerful to modulate performance. In this experiment, we presented low-frequency exception words and nonwords as targets. Examples of the stimuli that participants encountered and the sequence of events on a given trial are presented in Figure 1. The attentional control hypothesis predicts that nonword primes should direct attention to sublexical processing, which should in turn impair performance on low-frequency exception word targets, compared with nonword targets. The low-frequency exception word primes should have a similar effect on nonword targets, compared with exception word targets because these items should encourage dependence on lexical-semantic information, which is generally not beneficial for nonword reading. The prediction of the deadlines hypothesis depends crucially on how latencies to the two prime types differ from each other. If responses to one type of prime are dramatically slower than those to the other, the deadlines hypothesis predicts that all targets in that condition will be produced more slowly. On the other hand, if the difference in overall response latency between prime types is small, the deadlines hypothesis makes no prediction.

Method

Participants. Thirty-three Washington University undergraduates participated in this experiment as partial fulfillment of a course requirement. All were native speakers of English and had normal or corrected-to-normal vision.

Stimuli. One hundred low-frequency exception words and 100 nonwords served as primes in all experiments. The low-frequency exception words had a mean frequency of 4.42 ($SD = 6.14$) occurrences per million with a range from 0 (BROOCH, CLEANSE, SINEW, and SWAB were not listed) to 34 (Kučera & Francis, 1967). All words were irregular by single graphemes (Venezky, 1970), and all were inconsistent (Glushko, 1979). In addition, 62 of the exception words were of the type labeled *strange* by Waters and Seidenberg (1985). The nonwords were generated such that each matched a given low-frequency exception prime for initial phoneme and letter length. The same primes were used in all 4 experiments. Target stimuli for this and the remaining experiments are presented in the Appendix.

The targets in this experiment consisted of a list of 20 low-frequency exception words and a list of 20 nonwords matched for onset phoneme, length in letters, Coltheart's N, and bigram frequency. The t tests on these variables revealed no significant difference between target types for letter length, N, or bigram frequency, all ts (38) < 1.2. Properties of these targets and also for targets used in subsequent experiments are listed in Table 1. Eight practice trials and four buffer trials were also constructed. Practice trials consisted of two trials in each cell generated by crossing Prime Type × Target Type. Buffer trials consisted of one trial of each type and always contained the same prime type as the block they preceded.

Equipment. The experiment was controlled by a PC with a 133 mHz processor running in DOS mode. The 17-in. monitor was set to 40-column mode for the presentation of stimuli. We used a Gerbrands G1341T voice key connected to the PC's real-time clock to collect response latencies and response durations to the nearest

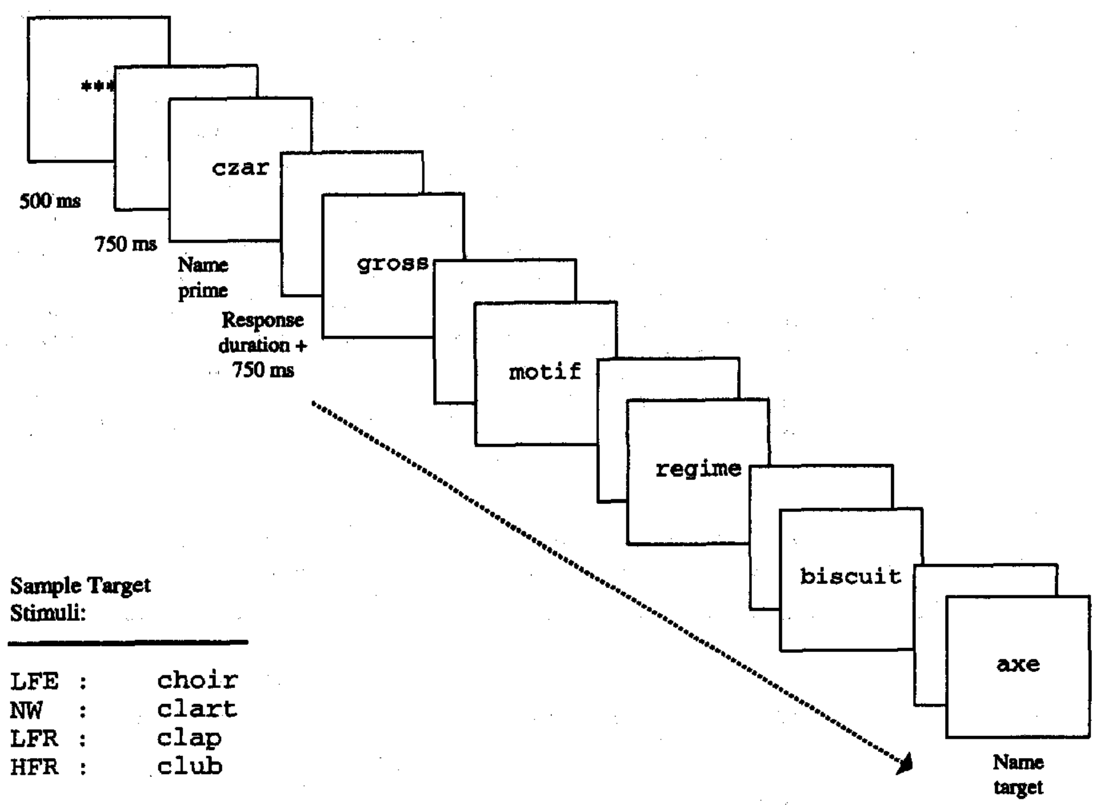

Figure 1. The paradigm used in all four experiments. A series of either low-frequency exception word (shown) or nonword primes are presented and named, followed by a target.

Table 1
Stimulus Characteristics of Targets for Experiments 1–4

	Experiment							
	1		2		3		4	
Variable	LFE	NW	HFR	LFR	LFE	LFR	HI	LI
Number of letters	5.25	5.36	3.95	3.95	5.25	5.25	5.30	5.15
Frequency	4.20	—	476.20	1.75	4.20	3.85	4.17	4.80
Coltheart's N	3.00	1.94	8.85	8.90	3.00	3.45	3.62	3.96

Note. LFE = low-frequency exception words; NW = nonwords; HFR = high-frequency regular words; LFR = low-frequency regular words; HI = high-imageable words; LI = low-imageable words.

ms. The same equipment was used throughout, except that in Experiments 3 and 4, we used a PC with a 166 mHz processor.

Procedures. Participants received instructions explaining the mode of presentation and were encouraged to respond as quickly and as accurately as possible. Stimuli were presented one at a time at the center of the CRT in white lowercase letters against a black background. The following events occurred on each trial: (a) A warning tone was presented for 250 ms, (b) a fixation point (three asterisks) was presented for 500 ms, (c) the screen went blank for 750 ms, and (d) a stimulus was presented until the participant named it, after which steps (c) and (d) were repeated for each of the five primes and target; the offset of each response served as the initiation point for the subsequent delay. After the presentation of the six stimuli for each trial, the experimenter scored the trial in one of four ways: (a) all stimuli were correctly pronounced, (b) dysfluency or extraneous noise error triggered the offset of the target word, (c) regularization of the target word occurred, or (d) an error of any kind occurred on the primes. If an error was made on at least one prime and the target on a given trial, it was scored as a prime error.

We presented participants with a block of 8 practice trials and subsequently with 40 experimental trials divided into two blocks of 20. Each block of trials included 10 low-frequency exception word targets and 10 nonword targets. In addition, each experimental block began with two buffer trials. Prime type was blocked (nonword vs. low-frequency exception word primes), and block order was counterbalanced so that half of the participants saw the low-frequency exception word block first, while the other half saw the nonword block first. We counterbalanced target type across prime type so that each target was preceded by both low-frequency exception words and nonwords across participants, and no prime or target was repeated for a given participant. Within a block, targets and primes were randomly ordered anew for each participant.

Results

To ensure that the current analyses were not unduly influenced by extreme response latencies, we used the following screening procedures for all experiments. First, we calculated an overall mean and standard deviation for each participant's naming performance. Any observation more than 2.5 *SDs* above the mean or greater than 1,500 ms was treated as an outlier. Also, any response less than 2.5 *SDs* below the mean or less than 250 ms was treated as an outlier. The overall percentage of outliers was 1.4%. We then calculated means for each cell for response latencies (excluding errors and outliers), errors (excluding outliers, regularizations, e.g., pronouncing PINT to rhyme with HINT, and errors produced on primes), and regularization errors on low-frequency exception word targets. Regularization errors were not possible for nonwords.

We conducted separate analyses of variance (ANOVAs) on errors and response latencies both for participants and for items. For the participants analyses, we conducted a 2 (prime type) × 2 (target type) ANOVA for each within-participant dependent measure. For the items analyses, we conducted a 2 (prime type) × 2 (item type) mixed-factor ANOVA for each dependent measure. All effects reported as significant have a p value less than .05. We excluded 1 participant from the analysis because of elevated error rates and a mean response latency more than 2.5 *SDs* above the mean for the remaining participants.

Response latencies. As shown in Table 2, the Prime Type × Target Type interaction predicted by the attentional

Table 2
Mean Response Latencies (RT), Percentage of Dysfluency Errors (DE), and Percentage of Regularization Errors (RE) for Experiment 1 as a Function of Prime Type and Target Type

	Prime type								
	LFE			NW			Priming effect		
Target	RT	DE	RE	RT	DE	RE	RT	DE	RE
LFE	630	7	9	634	6	19	4	1	10***
NW	658	6	0	632	3	0	26*	3	0
Lexicality effect	−28**	1	9	2	3	19			

Note. LFE = low-frequency exception words; NW = nonwords.
*$p < .05$. **$p < .01$. ***$p < .001$.

control hypothesis was observed. Specifically, nonword targets were produced 26 ms more quickly when preceded by nonword primes than when preceded by exception word primes. Latencies to low-frequency exception words appear to be relatively uninfluenced by prime type. The main effect of prime type predicted by the deadlines hypothesis was observed only for nonword targets.

The above observations were supported by the above-described ANOVAs. Specifically, although the main effects of prime type, $F_1(1, 31) = 2.58$, $MSE = 4{,}007.04$, $p = .12$, $F_2(1, 38) = 6.05$, $MSE = 4{,}872.09$, $p < .02$, and target type, $F_1(1, 31) = 3.32$, $MSE = 5{,}443.91$, $p = .078$, $F_2(1, 38) = 1.44$, $MSE = 5{,}240.37$, were only marginally reliable, there was a highly reliable Prime Type × Target Type interaction, $F_1(1, 31) = 10.18$, $MSE = 1{,}724.16$, $p < .005$, $F_2(1, 38) = 6.39$, $MSE = 6{,}319.31$, $p < .02$. Post hoc t tests indicated that nonwords were significantly slower when primed by low-frequency exception words than when primed by nonwords, $t_1(31) = 12.34$, $p < .001$, $t_2(19) = 8.31$, $p < .01$. Although low-frequency exception words did appear to show the reciprocal pattern, this effect was not reliable, both $ts < 1$.

Dysfluency errors. As shown in Table 2, we distinguished between two different types of errors. The first type, called dysfluency errors (DE), included both dysfluencies and possible voice-key errors. No reliable effects of prime or target type were observed in the dysfluency errors.

The second type of error involved regularization errors (RE) on targets, when participants pronounced a word based on the typical spelling to sound correspondence instead of the correct pronunciation (e.g., pronouncing PINT such that it rhymes with HINT). Of course, the later type of error was possible only on low-frequency exception words. According to the attentional control hypothesis, if participants were relying more on sublexical spelling to sound correspondences in the nonword prime condition, compared with the low-frequency exception word prime condition, then one might expect an increase in regularization errors on low-frequency exception words that followed nonword primes. As shown in Table 2, this is precisely the pattern that was obtained. Specifically, the percentage of regularization errors for low-frequency exception word targets was greater for the nonword prime condition than for the exception word prime condition, $t_1(31) = 12.46$, $p < .001$, $t_2(19) = 8.07$, $p < .01$.

Finally, because of the larger number of prime errors excluded, the number of regularization errors in the exception word prime condition may be underestimated in this regularization error analysis. We addressed this concern by conducting a second analysis in which the number of regularization errors was divided by the total number of target errors for each participant in this condition. This gives us a way of measuring whether the *proportion* of errors that are regularizations is greater in the nonword prime condition, as the attentional control hypothesis would predict. Indeed, this is the case: In the exception word prime condition, 41% of errors are regularizations, whereas in the nonword prime condition, 66% of the errors are regularizations.[1] This difference is significant, $t_1(31) = 6.91$, $p < .02$, $t_2(19) = 4.52$, $p < .05$.

Prime response latencies. Response latencies for nonword primes ($M = 622$) were faster than for low-frequency exception word primes ($M = 636$). This result approached significance by participants and by items, $F_1(1, 31) = 3.65$, $MSE = 31{,}202$, $p = .065$, $F_2(1, 198) = 2.75$, $MSE = 534.7$, $p < .1$. No other effects approached significance.

Prime errors. There was a relatively high (32%) error rate on low-frequency exception word prime trials. However, one must remember here that each prime trial included five primes, and in most cases these error estimates reflect a single error on one of the five primes on a given trial. Thus, an error rate of 32% actually reflects a 6% error rate per item, that is, 32% distributed over five primes, which is quite comparable to the error rates on the low-frequency exception word targets. The only effect to reach significance in the analysis of the prime trials is that low-frequency exception word primes generated substantially more errors than their nonword counterparts, $t_1(31) = 55.27$, $MSE = 534.73$, $p < .001$, $t_2(198) = 91.37$, $MSE = 4.19$, $p < .001$. Nonword primes had a mean error rate of 11%.

Because errors on primes trials might modulate response latencies to the targets, in this and all subsequent experiments, we conducted additional analyses in which response latencies to the targets were excluded when participants made errors on primes. The pattern of results in all cases is essentially the same as those for the analyses in which these observations were excluded. Specifically, all results reported as significant when prime errors are included remain significant when these trials are excluded.

Discussion

The results of Experiment 1 provide support for the attentional control hypothesis. Nonword targets produced faster response latencies when preceded by a set of nonword primes than when preceded by a set of low-frequency exception word primes. This is consistent with the notion that nonword primes bias attention to sublexical information that would be more useful for the pronunciation of nonword targets and actually disruptive for low-frequency exception word targets. This latter disruptive effect was nicely exemplified in the regularization errors to the low-frequency targets. Specifically, low-frequency exception word targets produced a substantial increase in regularization errors (relying on sublexical information to pronounce the word), when these items followed nonword primes compared with low-frequency exception word primes. Of course, if the nonword primes biased attention to sublexical information, this should produce regularization errors for words that do not normally follow common spelling-to-sound correspondences.

[1] Note that these proportions are smaller than one would expect given the participant means in Table 2. This is because the proportions were computed item-wise. Because some items were never regularized in either condition, several zeros were entered into the analysis, resulting in slightly lower proportions.

The difference in reaction times across prime types was small (14 ms), and thus the deadlines hypothesis makes no explicit prediction. Studies in which an actual response deadline has been instituted (Kello & Plaut, 1998; Lupker, Taylor, & Pexman, 1997) have found that response deadlines of up to 50 ms have little or no effect on the quality of participants' responses. We point out as well that responses to primes were produced at about the same speed as responses to targets. The difference in reaction times was quite small (14 ms), and therefore an unembellished deadlines hypothesis does not predict an effect of prime type on target processing.

Experiment 2

Although the results from Experiment 1 are consistent with the attentional control hypothesis, there is a relatively simple alternative account of the data. It is possible that the effects of prime type were not due to switching of processing pathway per se, but were due to a type of expectancy effect. That is, when participants read a list of primes of a given type, they may generate an expectancy for the same type of stimulus on the target trial. This would produce slower or less accurate responses overall when the presented target does not match the expectancy. This could be independent of whether the expected stimulus type and the presented stimulus depended on different sources of information. In Experiment 2, we examined the influence of prime type on the effect of stimulus regularity, that is, the finding that exception words produce slower response latencies than regular words. Because this effect is larger for low-frequency words than high-frequency words (e.g., Andrews, 1982), we included only low-frequency exception words and low-frequency regular words in Experiment 2. In this case, the attentional control hypothesis predicts that the regularity effect should be larger in the nonword prime condition, because of the greater attention to sublexical information, a less efficient processing strategy for low-frequency exception word stimuli as compared with low-frequency regular-consistent word stimuli.

Method

Participants. Thirty-two Washington University undergraduates participated in this experiment as partial fulfillment of a course requirement. All were native speakers of English and had normal or corrected-to-normal vision.

Stimuli. The targets included 20 low-frequency exception words and 20 low-frequency regular consistent words. The exception words in this experiment were identical to the ones used as targets in Experiment 1. We matched the two lists for onset phoneme, letter length, word frequency, positional bigram frequency and Coltheart's N. Results from t tests revealed no significant difference between target types for letter length, word frequency, N, or bigram frequency, $t(38) < 1$ for all tests.

Results

The screening procedure identified 4.5% of the responses as outliers.

Response latencies. The mean response latencies, percentage of dysfluency errors, and regularization errors as a function of prime type and target type are shown in Table 3. Here one can see that low-frequency regular targets produced faster response latencies than low-frequency exception word targets overall. More important, as predicted by the attentional control hypothesis, this regularity effect is larger for nonword prime trials (43 ms) than for low-frequency exception word prime trials (27 ms).

The above observations were supported by the ANOVAs. Specifically, there were reliable main effects of target type, $F_1(1, 31) = 50.6$, $MSE = 40{,}194.71$, $p < .001$, $F_2(1, 38) = 10.75$, $MSE = 31{,}875.22$, $p < .005$, and more important, there was a reliable interaction of target regularity with prime type in both the participant and item ANOVAs, $F_1(1, 31) = 4.17$, $p = .05$, $F_2(1, 38) = 5.34$, $p < .03$.

Dysfluency errors. As shown in Table 3, dysfluency errors tended to be higher on low-frequency exception word targets. This result was reliable, $F_1(1, 31) = 9.77$, $MSE = 4.13$, $p < .005$, $F_2(1, 38) = 5.5$, $MSE = 0.009$, $p < .05$.

Turning to the regularization errors (which could occur only for the low-frequency exception words), the results are again consistent with the attentional control hypothesis. Specifically, the percentage of regularization errors was higher when the exception word targets followed the nonword primes than when these items followed the exception word primes. This difference was highly reliable by both participants and by items, $t_1(31) = 17.7$, $p < .001$, $t_2(19) = 18.2$, $p < .001$. As in Experiment 1, we conducted a second analysis examining the proportion of errors that were

Table 3
Response Latencies (RT), Percentage of Dysfluency Errors (DE), and Percentage of Regularization Errors (RE) for Experiment 2

	Prime type								
	LFE			NW			Priming effect		
Target	RT	DE	RE	RT	DE	RE	RT	DE	RE
LFE	574	7	11	572	8	22	2	−1	11***
LFR	547	5	0	529	3	0	18*	2	0
Regularity effect	27***	2***	11	43***	5***	22			

Note. LFE = low-frequency exception words; LFR = low-frequency regular words; NW = nonwords.
*$p < .05$. ***$p < .001$.

regularizations in either condition. The percentage of regularization errors in the exception word prime condition (49%) was again lower than that in the nonword prime condition (77%). This difference was significant, $t(31) = 8.28, p < .01$.

Prime response latencies. Responses to nonword primes were again faster ($M = 559$) than responses to low-frequency exception word primes ($M = 577$). The main effect of stimulus type on response latency was reliable, $F_1(1, 31) = 11.48, MSE = 57{,}710.36, p < .005, F_2(1, 38) = 4.5, MSE = 33{,}258.42, p < .05$. No other effects approached significance.

Prime errors. There were again more errors on low-frequency exception word prime trials (31%) than on nonword prime trials (11%). The main effect of prime type on errors was also reliable, $F_1(1, 31) = 75.61$, $MSE = 658.13$, $p < .001$, $F_2(1, 198) = 107.4$, $MSE = 5.97$, $p < .001$. No other reliable effects were observed.

Discussion

The results from Experiment 2 again provided support for the attentional control hypothesis. Specifically, the regularity effect was larger when attention was biased toward sublexical information via the nonword primes, compared with when attention was directed toward lexical information via the low-frequency exception word primes. Of course, the regularity effect is presumably due to competition arising from the sublexical level for the exception words. In addition, as in Experiment 1, the low-frequency exception words produced an increase in regularization errors when primed by nonwords. This again is predicted by the attentional control hypothesis, because nonwords should bias sublexical information that could lead to regularization errors. Finally, it is noteworthy that Experiment 2 included a partial replication of the conditions from Experiment 1 (specifically, the low-frequency exception word targets), and the results clearly replicated in both response latencies and regularization errors across experiments. Specifically, the proportion of regularization errors in the nonword prime condition was twice as large as in the low-frequency exception word prime condition. Also replicating Experiment 1, response latencies were not significantly effected by prime type. We suggest that this is the result of a speed–accuracy trade-off. That is, in the nonword prime condition, the more difficult words were twice as likely to be regularized and were thus not available to participate in the response latency analysis. Again, we note that an unembellished deadlines account cannot fully accommodate these data.

Experiment 3

In Experiment 3, target stimuli were high- and low-frequency regular-consistent words. If readers depend more heavily on direct translation of graphemes to phonemes when primed by nonwords, it should be possible to reduce the frequency effect for regular-consistent words by presenting these items in a nonword context. For example, in the DRC model (Coltheart et al., 1993) frequency effects arise entirely from the lexical route. The predictions from PDP models (e.g., Plaut et al., 1996) regarding frequency effects are a bit less clear because frequency effects can arise in both direct and semantically mediated translation of spelling to sound. However, as discussed above, semantically mediated translation should be more sensitive to frequency because spelling-to-meaning translations are more arbitrary than spelling-to-sound mappings, at least for monomorphemic words. Because spelling-to-meaning mappings are largely unsystematic, learning the meaning of a particular string does not receive much benefit from experience with similar strings, and thus the frequency of individual items plays a greater role in this pathway.

Method

Participants. Seventy-two Washington University undergraduates participated in this experiment either to fulfill a course requirement or for a monetary reimbursement of $5. We excluded 4 participants from the analysis because their mean reaction time was more than 2.5 *SD*s greater than the mean for all participants or because the sum of their correct responses was 2.5 *SD*s less than the mean.

Stimuli. Two lists of targets were composed, one containing only high-frequency ($M = 476.2$) regular-consistent words and the other containing only low-frequency ($M = 1.75$) regular-consistent words. We matched the two lists for onset phoneme, letter length, positional bigram frequency, and Coltheart's *N*, $t(38) < 1$ in all cases.

Results

Using the screening procedures described above, 4.8% of all responses were treated as outliers.

Response latencies. Table 4 displays the mean response latencies and dysfluency errors as a function of prime type and target type. As shown, low-frequency words were overall slower than high-frequency words. More important, as predicted by the attentional control hypothesis, the word-frequency effect appears to be larger in the prime condition that directs attention to the lexical pathway (i.e., the low-frequency exception word condition), compared with the prime condition that directs attention to the sublexical pathway (i.e., the nonword prime condition).

Table 4
Response Latencies (RT) and Percentage of Dysfluency Errors (DE) for Experiment 3

	Prime type					
	LFE		NW		Priming effect	
Target	RT	DE	RT	DE	RT	DE
LFR	544	9	528	6	16***	3**
HFR	521	5	515	5	6	0
Frequency effect	23***	4**	13***	1		

Note. LFR = low-frequency regular words; HFR = high-frequency regular words.
$^{**}p < .01$. $^{***}p < .001$.

The ANOVAs yielded a main effect of frequency, $F_1(1, 71) = 47.77$, $MSE = 22{,}650.27$, $p < .001$, $F_2(1, 38) = 6.07$, $MSE = 6{,}562.06$, $p < .02$, along with a main effect of prime type that was significant by participants, $F_1(1, 71) = 7.56$, $MSE = 9{,}025.47$, $p < .01$, and marginally significant by items, $F_2(1, 38) = 3.95$, $MSE = 2{,}502.79$, $p = .054$. The interaction between prime and target type was significant by participants, $F_1(1, 71) = 4.18$, $MSE = 1{,}837.16$, $p < .05$, but not by items, $F_2(1, 38) < 1$, $MSE = 322.74$.

Dysfluency errors. Errors on targets were again considered separately from errors on primes. The main point to note regarding the target error data is that the pattern of errors is correlated with response latencies per cell. The main effect of prime type, $F_1(1, 71) = 6.62$, $MSE = 2.92$, $p < .02$, $F_2(1, 38) = 7.51$, $MSE = 0.01$, $p < .01$, and target type both reached significance, $F_1(1, 71) = 7.26$, $MSE = 4.75$, $p < .02$, $F_2(1, 38) = 4.8$, $MSE = 0.01$, $p < .05$. However, the interaction between prime type and target type was not significant, $F_1(1, 71) = 1.92$, $MSE = 1.53$, $F_2(1, 71) = 3.05$, $MSE = 0.00$, $p = .088$.

Prime response latencies. Mean response latencies for primes were again slower in the low-frequency exception word prime condition (599) than in the nonword prime condition (577). This difference was significant both by participants and by items, $F_1(1, 71) = 19.5$, $MSE = 178{,}907.64$, $p < .001$, $F_2(1, 198) = 10.18$, $MSE = 72{,}300.48$, $p = .001$. No other reliable effects were observed.

Prime errors. Low-frequency exception word primes produced more errors than nonword primes, $F_1(1, 71) = 199.03$, $MSE = 267.96$, $p < .001$, $F_2(1, 198) = 150.15$, $MSE = 6.32$, $p < .001$. The mean error rates were 34% and 14% for exception words and nonwords, respectively. No other differences were observed.

Discussion

The results from Experiment 3 are again broadly consistent with the attentional control hypothesis. Specifically, in the nonword prime block, low-frequency regular-consistent words benefited from the additional attention to direct translation of graphemes to phonemes, thereby decreasing the word-frequency effect. On the other hand, in the low-frequency exception word prime block, the additional attention to lexical information produced a relatively large frequency effect.

It is interesting that although the frequency effect was smaller in the presence of nonword primes than in the presence of low-frequency exception word primes, a frequency effect was observed in both instances. We believe it is likely that frequency effects are not exclusively a result of lexical information. This is certainly an assumption of the PDP models (Plaut et al., 1996; Seidenberg & McClelland, 1989), and, although it has not been built into the DRC model (Coltheart et al., 1993), it does not directly conflict with the basic dual-route framework (see, e.g., Rosson, 1985).

Experiment 4

Although the results of Experiment 3 provided some support for the attentional control hypothesis, the effects were not quite as large as those obtained in Experiments 1 or 2. Unlike frequency, which may be related to both lexical and sublexical information, imageability is strictly a feature of the meanings of words. Highly imageable words are assumed to be more fully represented in the semantic system because of frequent experience with their referents (de Groot, 1989). Imageability effects in single-word naming, however, have been a source of some controversy (see review in Balota, Ferraro, & Connor, 1991). Recently, interest in imageability in word recognition has been renewed by results suggesting that its primary influence is on low-frequency exception words (Cortese, Simpson, & Woolsey, 1997; Strain et al., 1995). Because it is difficult to generate a pronunciation for these words in the orthography-to-phonology pathway, the semantic system is recruited to aid in producing a pronunciation. Extending this logic to the present priming paradigm, if participants are able to allocate more attention to semantics in the low-frequency exception word prime condition, compared with the nonword condition, then there should be a larger imageability effect in this condition than in the nonword condition.

Method

Participants. Thirty-six Washington University undergraduates participated in this experiment either to fulfill a course requirement or for a $5 reimbursement.

Stimuli. The same primes were used as in Experiments 1, 2, and 3.

We constructed two lists of targets, drawing largely from the lists reported in Strain et al. (1995) and Cortese et al. (1997). Additional stimuli were taken from a list generated by Cortese et al. and normed by Kansas University undergraduates. To ensure that the same imageability ratings were applicable to the current sample, 26 Washington University undergraduates rated each word for imageability on a scale from 1 to 7 using the standard Carroll, Davies, and Richman (1971) instructions. The mean rating for high-imageable words was 6.18 ($SD = 0.42$), whereas the mean for low-imageable words was 2.83 ($SD = 0.74$). The two lists formed nonoverlapping distributions. All of the target stimuli in this experiment were regular-consistent words. We matched the two lists for frequency, Coltheart's N, number of letters, onset phoneme, and summed bigram frequency, $t(38) < 1$ in all cases.

Results

Using the screening procedures reported above, a total of 5.4% of all observations were treated as outliers.

Target response latencies. Table 5 displays the mean response latencies, and dysfluency errors as a function of target type and prime type. As shown in this table the results are quite consistent with the attentional control hypothesis. Specifically, there is a clear imageability effect that is localized for the low-frequency exception word prime condition, with no evidence of such an effect for the nonword prime condition. The results from the ANOVAs yielded a main effect of prime that was only marginally

Table 5
Response Latencies (RT) and Percentage of Errors (DE) for Experiment 4

	Prime type					
	LFE		NW		Priming effect	
Target	RT	DE	RT	DE	RT	DE
LI	539	9	516	6	23	3
HI	518	7	517	5	1	2
Imageability effect	21***	2	−1	1		

***$p < .001$.

significant by participants and did not approach significance by items, $F_1(1, 35) = 3.95$, $MSE = 5{,}028$, $p = .055$, $F_2(1, 38) < 1$, and a main effect of imageability that was significant by participants but only marginally by items, $F_1(1, 35) = 5.47$, $MSE = 3{,}480.42$, $p < .03$, $F_2(1, 38) = 1.92$, $MSE = 3{,}131.59$, $p = .17$. Most important, the interaction of imageability with prime type was reliable by both participants and by items, $F_1(1, 35) = 8.14$, $MSE = 4{,}025.80$, $p < .01$, $F_2(1, 38) = 4.22$, $MSE = 1{,}567.84$, $p < .05$.

Dysfluency errors. As shown in Table 5, targets following exception word primes generated more errors than those following nonword primes. The main effect of prime type was marginally significant by participants, but not by items, $F_1(1, 35) = 2.78$, $MSE = 0.16$, $p = .1$, $F_2(1, 38) = 1.63$, $MSE = 0.01$, $p = .2$. Low-imageable words were also more likely to generate errors, compared with high-imageable words. The main effect of target type was reliable in the items analysis, but not by the participants analysis, $F_1(1, 35) < 1$, $F_2(1, 38) = 4.49$, $MSE = 0.04$, $p < .05$. There was no evidence of an interaction between prime type and target type, both Fs < 1.

Prime response latencies. Nonword primes ($M = 550$) were again reliably faster than exception word primes ($M = 576$), $F_1(1, 35) = 16.43$, $MSE = 121{,}583.71$, $p < .001$, $F_2(1, 38) = 5.27$, $MSE = 34{,}387.83$, $p < .03$.

Prime errors. Exception word primes again produced more errors (30%) than nonwords primes (11%), $F_1(1, 35) = 107.62$, $MSE = 663.17$, $p < .001$, $F_2(1, 38) = 141.152$, $MSE = 6.61$, $p < .001$. No other reliable effects were observed.

Discussion

The imageability effect was larger in the low-frequency exception word prime condition than in the nonword prime condition. Again, these results support the attentional control hypothesis. On exception word prime trials, attention should have been directed toward semantic information, which would produce a benefit for high-imageable over low-imageable words. Note that low-imageable words are actually produced more slowly in the low-frequency exception word prime condition, suggesting that semantically mediated processing is generally slower than direct spelling-to-sound conversion for stimuli that are low frequency, low in imageability, and orthographically consistent. The disparity between high- and low-imageable words was not present when attention was biased to the sublexical translation of spelling to sound. These results are quite consistent with the results of Strain et al. (1995) and Cortese et al. (1997). In those studies, the imageability effect was largest when targets demanded a higher degree of semantic processing due to their unusual spelling-to-sound correspondences. In the current manipulation, the imageability effect was present only when the *context* encouraged a greater involvement of semantics. Moreover, the complete absence of an imageability effect in the nonword prime condition suggests that readers are able to largely ignore semantic information in a naming task when the context allows direct translation of spelling to sound for all stimuli.

General Discussion

The present series of experiments examined whether skilled readers have attentional control over the degree to which lexical and sublexical information contributes to naming performance. In each experiment, the main effect of a different stimulus variable was modulated by the presence of nonword or low-frequency exception word primes. The interactions between prime type and the targeted variables were consistent in all cases with an attentional control hypothesis. Specifically, results were consistent with the hypothesis that participants are able to adjust the relative contribution of lexical and sublexical information depending on the context created by low-frequency exception word primes or nonword primes. In Experiment 1, low-frequency exception words were produced more accurately when primed by other low-frequency exception words than when primed by nonwords, and nonwords were produced more quickly when primed by other nonwords than when primed by exception words. In Experiment 2, the regularity effect was larger under nonword priming than under exception word priming conditions. In Experiment 3, the frequency effect was larger in the exception word priming condition than when the same stimuli were primed by nonwords. In Experiment 4, targets that produced an imageability effect when primed by exception words did not produce an imageability effect when primed by nonwords. Therefore, the present results suggest that skilled readers are sensitive to the task demands instantiated by low-frequency exception word and nonword stimuli and are able to modulate their attention to the appropriate information accordingly.

Results from earlier attentional control experiments in quasi-regular orthographies (e.g., Monsell et al., 1992) have been unable to distinguish between the attentional control hypothesis and the deadlines hypothesis. We believe the hypothesis that skilled readers are able to set a deadline for producing a response is, in theory, orthogonal to whether or not they are able to modulate the influences of the processes that contribute to naming performance. In fact, we are quite sympathetic to the perspective that temporal deadlines play a role in reaction time experiments in general. However, in the current experiments, the deadlines hypothesis and the attentional control hypothesis were unconfounded, because of the small (14–28 ms) difference in response latency between prime types. Furthermore, latencies to primes in both conditions were uniformly either similar to or slightly slower than target latencies, precluding the argument that different response deadlines were set according to prime condition.

Orthographic Depth and Attentional Control

As we noted above, the most consistent evidence for attentional control has come from languages with relatively shallow orthographies (Raman et al., 1996; Tabossi & Laghi, 1992) and from languages that have distinguishable scripts, one of which is very shallow and the other relatively deep (Baluch & Besner, 1991; Simpson & Kang, 1994). This is broadly consistent with the orthographic depth hypothesis (Frost et al., 1987). For example, in their initial experiments, Frost et al. did not find any influence of frequency on naming performance in Serbo-Croatian, whereas they did observe frequency effects in a lexical decision task. Conversely, Hebrew readers showed large frequency effects under both conditions. Frost et al. viewed this as evidence that readers of shallower, more consistent orthographies use direct translation of spelling to sound as their default process for reading, whereas readers of deeper orthographies are in general more dependent on lexical information. It is intriguing that readers of a shallow orthography appear more able to disregard frequency-sensitive lexical information than readers of a deeper orthography when task demands (e.g., naming vs. lexical decision; Andrews, 1982) make this a viable strategy. This same flexibility may be responsible for the relative ease with which attentional control effects are elicited in a shallow orthography as compared with deeper orthographies.

Although the orthographic depth hypothesis was initially framed in terms of the dual-route framework, it is not inconsistent with PDP models of visual word recognition (Seidenberg, 1995). In a quasi-regular system like English, one-to-one relationships between graphemes and phonemes are clearly not universal, and so other levels of analysis (e.g., word body, whole word) contribute to performance. The contribution of word frequency to nonsemantic translation of spelling-to-sound falls from the structure of the language system, and not inherently from the architecture of the cognitive system. In a completely regular or shallow orthography, strong direct connections could arise between individual graphemes and the corresponding phonemes, eschewing the influence of word frequency on the translation of spelling to sound. Frequency effects should thus be more sensitive to task demands in shallower orthographies, where they are more centrally located in the semantic system, than in deeper orthographies, where they arise from both semantic and nonsemantic processing. Indeed when we manipulated imageability in Experiment 4 (a manipulation clearly localized in the semantic system), the results better approximate those found for frequency in shallower orthographies. Specifically, there was a complete eradication of imageability effects in the nonword prime condition.

Implications for Modeling

Up to this point, we have referred to "lexical" and "sublexical" information without discussing the form such information might take. Importantly, different classes of models make different claims regarding this distinction, with important consequences for interpreting the current results. We first discuss the dual-route model, in which the lexical–sublexical distinction is explained as the action of two distinct, dedicated pathways. Next, we consider PDP models, which represent orthography, phonology, and semantics in separate systems that share common representational and processing attributes. Within this section we also discuss implications for resonance models such as those proposed by Van Orden and Goldinger (1994). For each class of model we discuss possible mechanisms of attentional control.

Dual-route models. In a dual-route model (Coltheart, 1978; Coltheart et al., 1993; Forster & Chambers, 1973) the sublexical route is the primary means for generating a pronunciation for nonwords (Andrews & Scarratt, 1998). It is normally assumed that the sublexical route is not sensitive to word frequency and produces "regularized" pronunciations for all exception words. Correct pronunciations for exception words are achieved via the lexical route, which is frequency sensitive. It is clear how this framework accounts for the results of Experiments 1 and 2. The increased proportion of regularization errors under nonword priming was the result of a greater (or faster) contribution of the sublexical route. Nonword priming also increased the size of the regularity effect in response latencies, because regular words can be processed by either route, whereas exception words can be processed only by the lexical route. In order to account for the modulation of the imageability effect in Experiment 4, one must bear in mind Besner and Bourassa's (1995) point that "dual-route" models are in fact "three-route" models—the third route being a semantic one. In most models of this type (e.g., Monsell et al., 1992), semantic information is accessed via the lexical route. Thus, any task demands that direct attention to the lexical route will increase the involvement of the semantic system. For example, when large numbers of exception words must be processed, one would expect a larger imageability effect as in Experiment 4.

The one result that poses a problem for this version of the dual-route account is the failure to eliminate the frequency effect in the nonword condition of Experiment 3. Both high- and low-frequency regular words can be processed equally well by the sublexical route, and the speed with which they are processed is not frequency dependent. So why should a significant frequency effect remain when the sublexical route is so clearly favored by the task demands? A possible answer comes from Rastle and Coltheart's (1999) simulation data. When they slowed down the sublexical route in the DRC model, they found a List Context × Lexicality interaction, such that performance on nonwords suffered more from a slower sublexical route than low-frequency regular words. Our results across experiments are broadly consistent with this interaction. Nonwords in Experiment 1 were slower by 36 ms in the exception word prime condition, whereas low-frequency regular words were slowed down by only 16 and 18 ms in Experiments 2 and 3, respectively. Thus, it may be possible to explain the results from the first three experiments in terms of the relative speed of the sublexical route. The interaction is weakest in Experiment 3 because no matter how much of a boost the sublexical route gets from the nonword context, the lexical route still plays a significant role (indeed this must be true in all of the first three experiments, as participants were able to pronounce most of the exception words correctly). In order to explain the results from Experiment 4, however, it must be further assumed that, although lexical information predominates under most conditions, semantic information is somehow involved only when attention is directed to the lexical route. Furthermore, caution must be exercised in comparing effect sizes between Experiment 1 and the following experiments, because response latencies were nearly 100 ms slower overall in Experiment 1.

Rastle and Coltheart (1999) manipulated the speed of the grapheme-to-phoneme route "by hand" in order to simulate attentional control phenomena. In order to address the current task and others like it, it may be useful to consider a separate control mechanism that feeds back to the word-recognition system. For example, in the DRC model (Coltheart et al., 1993), the phoneme system might provide some input to a control mechanism that represents the degree of conflict or the ratio of contributions between the lexical and sublexical routes on a given trial. The control mechanism might use this information to modulate parameters upstream and improve performance by, for example, slowing down phonological processing when it creates too much interference for sets of low-frequency exception word primes. When task demands change again, this will be reflected in the phoneme system, and the control mechanism can change the gain on the outputs from the two routes accordingly.

PDP models. In PDP models, lexical and sublexical information are not, strictly speaking, processed by separate pathways. Regular words, nonwords, and exception words can all be pronounced by applying probabilistic constraints governing spelling-to-sound mappings (Seidenberg & McClelland, 1989). Low-frequency exception words are very difficult to process purely on the basis of orthography-to-phonology mappings, however, because pronouncing them correctly requires violating generalizations based on many words with similar spellings but different pronunciations. Thus, semantic information plays a greater role in the naming of low-frequency exception words than it does for other stimuli (Cortese et al., 1997; Plaut et al., 1996; Seidenberg, 1995; Strain et al., 1995). This framework provides for a somewhat more complicated but equally effective account of the attentional control phenomena.

Whereas exception word primes should encourage greater dependence on semantic information, nonword primes encourage direct mapping from orthography to phonology. Given that the orthography-to-phonology pathway produces the correct response for exception words under most circumstances, some background is necessary to explain why this results in an increase in regularization errors. Kawamoto and Zemblidge (1992) demonstrated that early in processing, simple recurrent networks favor responses that are consistent with their general knowledge at a gross level. At some point, constraints from context begin to exert an effect and the model quickly converges on a context-appropriate response. Their model was developed to explain homograph ambiguity, but the analogy to pronouncing irregular words is clear. Early in processing, a pronunciation consistent with the model's general spelling to sound knowledge will tend to be active. For example, the I in PINT might at first activate /I/, because this is the most frequent mapping for this letter. Then, as constraints from the surrounding context (the other letters of the word) resolve, the model converges on the correct pronunciation. To pronounce a nonword correctly, it is not necessary to wait for constraining information to be resolved. Thus, if a participant who has just read a number of nonwords is suddenly faced with an exception word, a response might be produced before the incorrect (i.e., "regular") pronunciation has been overtaken by the correct (i.e., "irregular") one. This explains the pattern of results in Experiment 1 and Experiment 2. Nonwords and low-frequency regular words both benefit from faster, noisier (i.e., less constrained by context information from the whole word) mappings from spelling to sound, whereas low-frequency exception words are more prone to regularization errors in this condition.

Results from simulations by Kello and Plaut (1998) complicate this interpretation somewhat. They found that adjusting the "gain" on hidden units between orthography and phonology (in effect, encouraging fast, noisy mappings from spelling to sound) did *not* result in an increased proportion of regularization errors in a model with no semantic system. It is interesting that they did find this effect when they performed a similar manipulation with a model that had been trained with a semantic system. Thus it seems that the division of labor between direct and semantically mediated translation of spelling to sound may be an important part of a PDP interpretation of our findings. That is, increasing the gain on orthography to phonology hurts low-frequency exception word performance only if the model has learned to depend on semantics for these words. We suggest that this second model with semantic input best describes the situation in our human participants.

The modulation of the imageability effect in Experiment 4 is best expressed as an increase in attention (or perhaps "gain") to the semantic system. Normally, imageability effects are not observed for short, regular-consistent words (Cortese et al., 1997; Strain et al., 1995). However, if a preponderance of difficult low-frequency exception words puts a premium on semantic information, the semantic system may become more actively involved in the pronunciation of words whose phonology is relatively easy to compute from their orthography. It is conceivable that these results could be modeled by manipulating the gain between orthography and semantics (or between semantics and phonology).

Finally, the relative weakness of the results in Experiment 3 also fits neatly with the PDP account of word naming. Because the same frequency-sensitive learning algorithm is applied to all mappings, direct and semantically mediated translation from spelling to sound are both frequency modulated. Just as frequency effects are more pronounced for exception words because there are fewer words that share spelling-to-sound correspondences with them, frequency effects are still more pronounced in orthography-to-semantics mappings because (at least for morphologically simple words) words that share spelling patterns *rarely* have similar meanings (Harm, 1998). Thus, it is not surprising that robust frequency effects were observed in both conditions. In fact, the PDP account predicts an interaction only to the extent that there is a difference in the relative influence of frequency on the semantically mediated and direct pathways.

Thus, all four experiments may be described in terms of adjustments to the relative contributions of direct and semantically mediated spelling-to-sound translation in a PDP model. It is possible to consider a control system similar to the one we proposed for the DRC model above. Indeed, such systems have been implemented in connectionist models of other domains and tasks (Cohen, Dunbar, & McClelland, 1990; see also Kanne, Balota, Spieler, & Faust, 1998; Schneider & Detweiler, 1987).

The relationship of PDP models to dynamical systems approaches suggests another possibility. In a model that keeps track of its own state, behavior at each point in time is partly determined by the state of the system at the previous point in time (e.g., Elman, 1990). Thus, if the system has just produced a response stressing orthography-to-semantics mappings, increased activity (or coherence in the sense of Van Orden & Goldinger, 1994) in the semantic system could increase the contribution of semantics to future responses. Alternatively, one could hypothesize that participants set a threshold for the coherence of the pattern produced by the reading system as a whole and use this as a "deadline" for responding. In the exception word prime condition, the threshold would be set higher, because the involvement of semantics (and the fact that the stimuli are largely familiar) allows a greater degree of coherence, whereas in the nonword condition, the threshold would be set lower (see Gibbs & Van Orden, 1998, for a similar explanation of attentional control effects in lexical decision). Of course, an implemented model would be necessary to ascertain whether such an approach would work.

We conclude that readers are sensitive to the processing demands presented by different stimuli in a word-naming task and that they are able to adjust their dependence on different sources of information accordingly. Our results are interpretable in terms of both dual-route and PDP models of word recognition and, we believe, provide an interesting data point for future modeling endeavors. Ultimately, both approaches are meant to describe the reading system, but in order to make contact with the human data, implemented models must be somewhat rigidly tied to the task they are designed to simulate (e.g., naming in the case of Coltheart et al., 1993, and Plaut et al., 1996). Exploring how dependence on different sources of information influences performance within the context of the naming task might be an important step toward extending current models of word naming to other reading-related tasks.

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APPENDIX

Target Stimuli Used in Experiments 1-4

Table A1
Target Stimuli for Experiment 1

Low-frequency exception words	Nonwords
asthma	alkon
axe	arp
beige	blirp
catsup	castoon
choir	clart
corsage	conster
famine	farwin
forage	frental
gin	hompret
hospice	jert
lapel	lunko
morale	munders
nuance	nermon
pint	plome
plaid	ploss
salmon	santel
sew	sart
soot	stote
trough	timp
wallow	wemple

Table A2
Target Stimuli for Experiment 2

Low-frequency exception words	Low-frequency regular words
asthma	abound
axe	ash
beige	birch
catsup	canker
choir	cascade
corsage	clench
famine	crane
forage	fennel
gin	ferret
hospice	hacksaw
lapel	jar
morale	leafy
nuance	marble
pint	napkin
plaid	peak
salmon	perch
sew	sage
soot	sap
trough	scurvy
wallow	weasel

Table A3
Target Stimuli for Experiment 3

High-frequency regular words	Low-frequency regular words
back	ban
big	bunt
came	clap
car	cot
club	din
did	fawn
fact	fern
fear	gust
goal	hark
hand	hefty
happy	jest
just	kite
paper	pacer
set	sage
side	sap
still	soy
sun	steed
time	taper
total	tilt
year	yelp

Table A4
Target Stimuli for Experiment 4

High-imageable words	Low-imageable words
blade	bribe
cliff	cleft
clam	clue
coffin	custom
duck	deed
ditch	daze
groin	gait
mattress	madness
pepper	parry
pickle	pious
sack	sane
sandal	stanza
scarlet	figment
snail	fraud
spike	scorn
trout	truce
trumpet	traitor
weed	wisp
witch	whence
wreck	wrest

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