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Quick, Automatic, and General Activation of Orthographic and Phonological Representations in Young Readers

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Second through 6th graders were presented with nonword primes (orthographic, pseudohomophone, and control) and target words displayed for durations (30 and 60 ms) that were brief enough to prevent complete processing. Word reading skills were assessed by 3 word and nonword naming tasks. Good readers exhibited more orthographic priming than poor readers at both durations and more pseudohomophone priming at the short duration only. This suggests that good readers activate letter and phonemic information more efficiently than poor readers. Good readers also exhibited an equal amount of priming at both durations, whereas poor readers showed greater priming at the longer duration. This suggests that activation was not under strategic control. Finally, priming was reliable for both high- and low-frequency targets. This suggests that readers activate consistent information regardless of target word characteristics. Thus, quick, automatic, and general activation of orthographic and phonological information in skilled readers results from the precision and redundancy of their lexical representations.

The role of phonological activation during the early stages of visual word recognition is perhaps the most actively debated issue in current research in reading. Some researchers have argued that phonological activation is more accurately characterized as a quick, automatic, and general process (Lukatela & Turvey, 1994a, 1994b; Perfetti & Bell, 1991; Van Orden, 1987), whereas others have claimed that phonological activation can be late, strategic, and rule based (Coltheart, 1978; Paap & Noel, 1991). Despite the centrality of this debate in the adult literature, there has been little research examining whether phonological activation is quick, automatic, and general in children. The present study attempts to fill this gap by examining age and naming-ability differences in orthographic and phonological priming in children. The issues that we examine in this study are important for refining our theories of reading development as well as for designing educational practices. Those who have argued that phonological activation can be late, strategic, and rule based have postulated models of visual word recognition with multiple mechanisms (Coltheart, 1978; Paap & Noel, 1991). Quick, automatic, and general phonological activation would be more consistent with single-mechanism accounts of visual word recognition (Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989). In addition, the finding of quick, automatic, and general activation in young readers would support the importance of phonological awareness in learning to read (Wagner, Torgesen, & Rashotte, 1994; Wagner et al., 1997).

What Develops in Visual Word Recognition?

There are at least two possible ways in which phonological activation could change over the course of development. One possibility is that phonological activation decreases as reading acquisition progresses. For example, Backman, Bruck, Hebert, and Seidenberg (1984) found that younger and poor readers produced more errors on exception, regular inconsistent, and ambiguous words and that errors on these words decreased with ability level and age more than errors on regular words. They interpreted this finding as reflecting that poor readers used phonological information more in the initial decoding of words than did good readers. However, this interpretation is compromised by their finding that older and good readers produced more regularization errors for words and nonwords than did the younger and poor readers. Doctor and Coltheart (1980) argued that there is an age-related decrease in phonological recoding and that "phonological recoding is not a significant process for skilled reading" (p. 204). They

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based this argument on the finding that younger readers were less skilled than older readers at detecting homophone foils such as *blew* and pseudohomophone foils *bloo* in meaningful sentences such as "The sky is ______." However, this finding could be interpreted as reflecting the younger children's reliance on semantics rather than phonology when reading sentences (West & Stanovich, 1978) or as reflecting the younger children's less stable orthographic representations that are necessary to verify correct spellings (Perfetti & McCutchen, 1982). In addition, the age-related decrease of errors in pronunciation and detection found by Backman et al. (1984) and Doctor and Coltheart (1980) does not necessarily mean that reading development is marked by a reduction in phonological recoding. Indeed, older and more skilled readers may just be more accurate in their use of orthography–phonology relationships.

A different possible developmental trajectory, and the one that we support, is that reliance on phonological information increases across development. Only skilled readers are able to use phonological information to automatically influence the earliest stages of word recognition. Perfetti (1992) argued that an essential component of developing automatic and efficient visual word recognition processes is to increase the precision and redundancy of orthographic and phonemic connections. *Precision* refers to the accuracy in the mapping between a reader's orthographic and phonological representations. Children's initial lexical representations are not precise, because they often contain inappropriate mappings or because their representations are incomplete. For example, the orthographic representation *dok* may be used to access the phonological representation for *duck*. Early representations are less likely to contain vowels than consonants because vowels have more variable grapheme–phoneme correspondences (Liberman, Shankweiler, Orlando, Harris, & Berti, 1971). *Redundancy* refers to the degree to which there are sublexical and lexical connections between orthographic and phonemic forms (see also Ehri, 1992). Initially, children's orthographic and phonemic representations are sparsely interconnected. For example, early lexical representations are more likely to include only initial and final letters (Marchbanks & Levin, 1965). With development, orthographic and phonemic representations become redundantly interconnected. Skilled readers have mappings between individual letters and the pronunciations of words, but they also appear to have higher level mappings between orthography and phonology. For example, skilled readers may have mappings between onsets like *st* and rimes like *ake* and whole-word representations like *stake* (see Bowey, 1990). We argue that the ability to flexibly and rapidly use these redundantly interconnected orthographic and phonological representations for word recognition is the hallmark of skilled reading.

If changes in the quality of mappings between letter strings and phonological patterns mark progress in learning to read, we would want to better understand what brings about such changes. Many correlational and training studies have shown that later reading achievement is predicted best by earlier phonological knowledge, as measured by phoneme segmentation, phoneme deletion, and phoneme blending (see Wagner et al., 1994; Wagner et al., 1997). Jorm and Share (1983) proposed that phonological decoding attempts during reading are in fact the main learning mechanism that brings about knowledge of whole-word spellings. It appears that the acquisition of reading skill itself is enabled by the use of phonological information.

Research on children that makes direct contact with the research issues and paradigms of adult word identification is sparse. Only two single-word priming studies with children have directly examined the relative influences of orthographic and phonological processes in visual word recognition. Goswami (1990) studied 5- and 6-year-old children's use of three different analogical primes for reading target words. The prime types were orthographic–phonological (e.g., *most–post*), orthographic (e.g., *most–cost*), and phonological (e.g., *most–toast*). The largest priming effects (percentage correct reading) were found for the orthographic–phonological primes, but there was also a significant priming effect for the phonological primes. It should be noted, however, that Goswami's manipulation did not cleanly separate the effects of orthography and phonology. For example, the orthographic and orthographic–phonological primes did not have the same degree of orthographic similarity with the target (three out of four letters) as did the phonological primes (three out of five letters). Hansen and Bowey (1992) provided "on-line" evidence for the importance of phonology in word reading when they found that fourth graders exhibited significant decreases in naming latencies to target words, when primes, presented for 500 ms, shared the final trigram (rime unit) with the target words (e.g., *weed–seed*). However, word initial trigram primes did not facilitate the recognition of target words regardless of whether they had the same (e.g., *lean–leap*) or different (e.g., *pine–pink*) grapheme–phoneme correspondences. This suggests that there is something special about the rime of a word that facilitates visual word recognition in children (see also Treiman, 1994).

These two studies suggest that orthographic and phonological priming occur for developing readers. However, none of this research can tell us whether priming effects change with age and whether priming effects are quick, automatic, and general. As a result, the current developmental literature does not come into close contact with the debate in the adult literature about the role of phonological activation in lexical recognition. Most research investigating the time course, control, and generality of phonological activation has been conducted on adults.

Evidence for a Central Role for Phonology in Adult Readers

The brief-exposure paradigm, which limits the amount of processing that can occur, is especially useful for exposing the prelexical stages of word identification (Berent & Perfetti, 1995). In this paradigm a target word is followed by a backward prime, and when both target and prime are presented at durations of less than 55 ms, there is a disruptive backward priming effect on identification accuracy (see also Perfetti & Bell, 1991; Perfetti, Bell, & Delaney, 1988). This disruptive backward priming effect is reduced when the prime is orthographically similar or phonologically identical to the target word. For example, with the target word *rake,* an orthographic prime could be *ralk* and a pseudohomophone (phonological) prime could be *raik.* A pseudohomophone is a nonword that has the pronunciation of a real word but no corresponding orthographic representation. In this paradigm, recognition accuracy of target words preceded by control primes is very low, but identification rises significantly with orthographic and pseudohomophone primes. This suggests that partial orthographic and phonological information from the prime is being combined prelexically with partial information from the target to bring about correct identification.

Research using other paradigms with adults also points to a quick, automatic, and general role of phonology in visual word recognition. Lukatela and Turvey (1991, 1993, 1994a) found equal associative priming effects in naming latency to target words (e.g., *frog*) following pseudohomophone primes (e.g., *tode*) and homophone primes (e.g., *towed*) as compared with directly related primes (e.g., *toad*). Homophones are words that have the same pronunciation but different orthographic representations and meanings (e.g., *towed* and *toad*). These studies showed semantic priming effects despite the fact that only the phonological form, and not the orthographic form, was consistent with the meaning of the target. Studies using a semantic categorization task also suggest that visual word recognition is automatically influenced by phonology. This task requires participants to determine whether a word is a member of a given category, such as "part of the human body." These studies show that the rate of false positives and their latency is greater for pseudohomophones, such as *noes,* and homophones, such as *knows,* than for graphemic controls, such as *nise* (Jared & Seidenberg, 1991; Van Orden, 1987; Van Orden, Johnston, & Hale, 1988). In this paradigm, readers automatically use the phonological information even though it hurts their categorization performance.

The case for phonological activation being quick, automatic, and general is also supported by parallel distributed processing models (Plaut et al., 1996; Seidenberg & McClelland, 1989). In these models, patterns of activation in the orthographic and phonological systems settle quickly because of the quasiregular relationship between orthography and phonology in English. On the other hand, the relationship between semantics and phonology or orthography is not as systematic so the semantic system settles more slowly than the other systems. In other words, the self-consistency of letters to sounds is greater than the self-consistency of letters to meanings or sounds to meanings, and therefore, there is rapid interactive convergence of orthographic and phonological information during word recognition (Van Orden & Goldinger, 1994; Van Orden, Pennington, & Stone, 1990). The rapid interactive convergence of orthographic and phonological information during visual word recognition in adults may result from the precision of and redundancy between their orthographic and phonological representations.

Background of Present Investigation

Using the brief-presentation identification paradigm, Perfetti and Bell (1991) found that the phonemic similarity of pseudohomophone primes, such as *raik,* presented for over 45 ms facilitates the recognition accuracy of targets, such as *rake,* presented for 30 ms over and above the influence of orthographic similarity as indicated by orthographic primes, such as *ralk.* Perfetti and Bell also conducted a control experiment in which they presented the target words for 30 ms without primes. They found that identification accuracy was 26%, which was at least 10% less than the identification accuracy in the orthographic and pseudohomophone priming conditions. This suggests that partial phonological or orthographic information from the primes was being combined in a prelexical stage with partial information from the targets to produce correct identification. Finally, they found that pseudohomophone priming was independent of target word frequency. This suggests that phonological activation was general across word types.

To address the role of orthographic and phonological activation in the acquisition of reading skill, we used the brief-presentation identification paradigm. For experimental purposes, we assessed reading skill for both words and nonwords using measures of naming speed and accuracy. We take accuracy and speed with which words can be named as a rough estimate of the effective access to quality word representations. We were interested in whether naming speed, naming accuracy, and age are unique predictors of the magnitude of orthographic and pseudohomophone priming in the experimental task. Naming accuracy may explain more variance in priming because of the large variation in reading ability within an age group. We were also interested in whether priming effects are influenced by item characteristics, such as the frequency of the target and the orthographic similarity between prime and target. In summary, each experiment consisted of a 2 (orthographic similarity: high, low) × 2 (frequency: high, low) × 3 (prime: pseudohomophone, orthographic, control) design with age or naming ability as independent predictors of the priming effects.

In Experiment 1, second, fourth, and sixth graders were presented with prime–target pairs with a 30-ms presentation duration for each stimulus. If word representations develop in accord with the principles of precision and redundancy, older and good readers should exhibit rapid activation and coherence of orthographic and phonological information during the course of word identification. Accordingly, older and good readers should make better use of briefly exposed orthographic and pseudohomophone primes than younger and poor readers. In Experiment 2, we used a longer prime and target duration (60 ms) to examine the time course of activation. We expect that the longer presentation durations in Experiment 2 would allow all readers to effectively activate orthographic and phonological information to aid in word identification. On the basis of previous results with brief-duration identification paradigms (Lukatela & Turvey, 1994a, 1994b), we also expect reliable orthographic and pseudohomophone priming for both low- and high-frequency target words. This is in contrast to some models of visual word recognition which argue that phonological information influences the recognition of only certain types of words (Coltheart, 1978; Paap & Noel, 1991). Finally, we expect that prime–target pairs with high orthographic similarity should exhibit larger orthographic priming effects than those with low orthographic similarity. More letters in common provide more consistent priming information and less conflicting or interfering information.

Experiment 1

Method

Participants

Twenty-one second graders (mean age = 8.1 years, *SD* = 0.4 years), 21 fourth graders (mean age = 9.8 years, *SD* = 0.4 years), and 23 sixth graders (mean age = 12.0 years, *SD* = 0.5 years) participated in this study. These students came from two different private schools in the Pittsburgh, Pennsylvania metropolitan area. Second through sixth graders were chosen for this study because this age range marks a period of rapid reading acquisition. All participants received three naming tasks, along with the experimental task involving orthographic and pseudohomophone priming. One second grader was eliminated from all analyses, because she did not answer any of the words on the experimental task correctly.

Materials and Procedure

All materials administered to the participants were presented on identical 15-in. MultiScan Macintosh monitors controlled by a 540c Macintosh laptop computer or a 5300c Macintosh PowerPC laptop computer. All tasks described hereinafter were presented with PsyScope (Cohen, MacWhinney, Flatt, & Provost, 1993). Three naming measures were administered to all children: word identification task, nonword task, and exception word task.

Naming tasks. The word identification and nonword subtests from the Woodcock Reading Mastery Tests—Revised (Woodcock, 1987) were administered to all children. The word identification task contained 96 items with approximately 80% regular and 20% irregular words. The beginning words were easy words, such as *play;* as the task proceeded, the test included more difficult items, such as *zeitgeist.* Test administration was stopped when the participant pronounced 6 consecutive words incorrectly. The nonword subtest was a naming measure containing 40 nonwords. It began with easy nonwords, such as *dat,* and progressed to more difficult nonwords, such as *byrcal.* Each child was also administered an exception word task (Adams & Huggins, 1985), which required the child to read aloud 45 exception words. The task started with easy words, such as *ocean,* and ended with more difficult words, such as *baroque.* For all naming measures, if the children did not answer within 10 s, the time disappeared, as their answer was considered incorrect. If the child responded within 10 s, a button box detected his or her voice and erased the word from the computer screen. If the child stuttered and tripped the button box prematurely, but then pronounced the word correctly, the answer was scored as correct, but the premature reaction time (RT) was considered as missing data. Similarly, if the child pronounced the word correctly but did not trip the button box, then the answer was scored as correct, but the missing RT was considered as missing data. This recording procedure was used for all of the voice detection measures. Inappropriate voice onset detection accounted for less than 4% of the RT data.

The RT data for the naming tasks were subjected to two types of data elimination. First, all RTs greater than 5 s were eliminated. This resulted in the following percentage of eliminated trials: word identification task, 0.6%; nonword task, 0.8%; and exception task, 1.9%. The 5-s cutoff level gave participants ample time to name the item; any response after this cutoff would have artifactually inflated RT. The second form of data trimming for RTs involved eliminating items if fewer than 80% of the participants, regardless of grade level, pronounced them correctly. It was important to eliminate from consideration those words that were generally beyond the ability level of students at a given grade level. This criterion meant that naming RTs represent reaction time to words generally familiar to all children. With this criterion, the word identification task included 48 items from the original pool of 96; the nonword task included 13 items from the original pool of 40, and exception word task included 12 items from the original pool of 45. Therefore, RTs were based on a maximum of 73 items. Even for second graders, who tended to have lower accuracy levels, the RTs were based, on average, on about 84% of these 73 items.

Experimental task: Orthographic and pseudohomophone priming. The experimental task involved 15 practice trials followed by a series of 120 word identification trials. Each trial began with the display of a fixation cross, and the participant was asked to press a button when he or she was ready to begin the trial. At that point, the fixation cross disappeared and the trial began. Each trial consisted of a brief presentation of a nonword prime (30 ms), followed immediately by a brief presentation of a real word target (30 ms), which was then immediately followed by a mask of the form: XXXXX (500 ms). There was no interstimulus interval (ISI) between prime and target or between target and mask. Primes were always presented in uppercase, and targets were always presented in lowercase, so that any observed priming effects would have to be attributed to an abstract letter representation and not a lower level, case-specific visual representation. The pattern mask was used to disrupt the processing of the target. Without the pattern mask, performance on this task would have been near ceiling for the more advanced readers, because of luminance persistence of the target on the computer monitor. All stimuli were presented in white letters on a black background in 16-point Courier font. All words were four (1.6 cm) or five (2 cm) letters in length. The participants' task was to write down the target word after each trial. They were encouraged to guess the identity of the target if they were not sure. No partial credit was given. We are assuming that the participant's written response reflects access to orthographic and phonological forms, although other factors, such as knowledge of common letter patterns, may have influenced the translation from a mental representation to a written word.

There were within-item and between-item variables in the priming task. The within-item variables were the three prime types. The pseudohomophone primes were phonologically identical to the targets (e.g., *tume–tomb*); the orthographic primes shared the same overlapping letters with the target words as pseudohomophone primes but different nonoverlapping letters (e.g., *tams–tomb*); and the control primes shared no letters in common with the target (e.g., *usan–tomb;* see the Appendix for a complete list.) There were three counterbalancing lists, so that across participants each prime preceded each target an equal number of times. This meant that the three groups of participants corresponding to the three counterbalancing lists received a different list of prime–target pairs. The prime and target were matched on length. This matching is an important control but has not been done in other pseudohomophone priming studies (Lukatela & Turvey, 1994b; Perfetti & Bell, 1991). The pseudohomophones (interspersed with their orthographic controls) were also pilot tested on a group of 10 undergraduate students. To be included in the experimental list, at least 8 out of 10 students had to pronounce the pseudohomophones according to their real word counterpart.

The between-item variables were orthographic similarity between prime and target and target frequency. Orthographic similarity was defined on the basis of the formula developed by Van Orden et al. (1988). This prime–target similarity metric takes into account identical letters in the same position, in adjacent positions, and in the first and final positions. Our orthographic similarity value (os = .52) was exactly the same for the orthographic and pseudohomophone primes and was similar to, but slightly lower than, those found in other studies (e.g., Van Orden et al., 1988, os = .62 to .68). The low-frequency words had a mean Kucera and Francis (1967) frequency level of 11.5 in a million. The high-frequency words had a mean frequency level of 167 in a million.

Results

Individual-Difference Independent Variables

Table 1 displays the correlations between the individual naming measures and age (all $ps < .001$, unless otherwise noted). Accuracy scores on the three naming tasks, $r(65) = .87$, as well as RTs on the three naming tasks, $r(65) = .78$, were highly intercorrelated, so accuracy or RTs for the word identification, nonword, and exception word measures was averaged separately into two mean naming measures (naming accuracy and naming RT). Naming accuracy was negatively correlated with naming RT, and this was relatively uniform for all individual naming measures, $r(65) = -.58$. Finally, there were modest correlations of age with the individual naming measures, $r(65) = .57$. We calculated separate analyses with naming accuracy, naming RT, and age as predictors of orthographic and pseudohomophone priming because these

Table 1
Correlation Coefficients Between Individual Naming Tasks (Accuracy and RT) and Age for Experiment 1

Variable	1 %	1 RT	2 %	2 RT	3 %	3 RT	4
1. Word identification							
%	—						
RT	−.66*	—					
2. Exception words							
%	.94*	−.73*	—				
RT	−.55*	.87*	−.64*	—			
3. Nonwords							
%	.86*	−.54*	.80*	−.43*	—		
RT	−.57*	.72*	−.59*	.74*	−.54*	—	
4. Age	.67*	−.53*	.72*	−.43*	.48*	−.38	—

Note. RT = reaction time.
* $p < .001$.

measures appeared to be indexing slightly different underlying abilities.

Table 2 presents the means and standard deviations for the individual naming measures and the combined naming measures in Experiment 1 for the younger and older students based on a median split. There were clear age differences in accuracy and RT on all measures. However, there were large standard deviations within age groups for accuracy and RT. Groupings that were based on a median split of accuracy or RT resulted in larger mean differences and smaller standard deviations between good and poor readers than groupings that were based on age. The three grades were grouped into two age groups in Experiment 1 to allow for easy comparison with Experiment 2, which had two age groups (third vs. fifth graders). This age dichotomy also allowed for easy comparison with analyses calculated on high- versus low-naming-accuracy children.

Table 2
Means (and Standard Deviations) of Accuracy (%) and RT (in Milliseconds) for the Individual and Combined Naming Tasks for the Younger and Older Children in Experiment 1

Variable	Younger (n = 34)	Older (n = 32)
Word identification		
%	54.9	71.1
	(10.2)	(10.2)
RT	740	560
	(217)	(81)
Exception words		
%	39.6	69.9
	(16.9)	(15.8)
RT	927	618
	(485)	(86)
Nonwords		
%	51.9	67.8
	(17.7)	(14.7)
RT	955	728
	(354)	(175)
Total		
%	48.8	69.6
	(14.0)	(16.4)
RT	874	635
	(324)	(101)
Age		
M	8.6	11.4
SD	(0.7)	(0.9)

Note. Younger < 9.75 years old; older > 9.75 years old. RT = reaction time.

Experimental Design and Analysis Strategy

We present the results of two of our individual difference or between-subjects variables: age and naming accuracy. Naming RT analyses are not presented here (or in Experiment 2) because naming RT was entirely redundant with naming accuracy in accounting for variance in priming. Age and naming accuracy were treated as continuous regressor variables to more accurately represent underlying ability differences. Because this design requires an analysis focusing on a continuous subject variable, only subject analyses could be computed.

There were two within-subject independent variables: orthographic similarity and word frequency. We were interested in whether priming effects depended on the amount of orthographic overlap between the prime and target or on the frequency of the target.

There were two dependent variables of interest in the priming task: orthographic priming and pseudohomophone priming. Orthographic priming was calculated as the difference between accuracy in the orthographic and control conditions. Because the orthographic primes have overlapping letters and sounds with the target, we must attribute these priming effects to a combination or orthographic and phonemic overlap. Pseudohomophone priming was calculated as the difference between accuracy in the pseudohomophone and orthographic conditions. Because the pseudohomophone primes had the same level of orthographic similarity to the targets as did the orthographic primes, it is possible to view the pseudohomophone priming effects as resulting purely from phonological priming. Planned comparisons were computed separately for the orthographic and pseudohomophone priming dependent variables, and these results are presented in different sections.

In summary, orthographic and pseudohomophone priming dif-

Table 3
Experiment 1: Means (and Standard Deviations) for Accuracy in the Pseudohomophone (Pseudo), Orthographic (Ortho), and Control Priming Conditions for High- and Low-Orthographic-Similarity Prime–Target Pairs (OS) and for High- and Low-Frequency Targets (FQ)

	Older			Younger		
OS/FQ	Pseudo	Ortho	Control	Pseudo	Ortho	Control
High						
High	74.3	67.7	32.2	40.1	38.9	15.4
	(18.3)	(19.6)	(21.2)	(28.4)	(25.6)	(16.8)
Low	66.3	51.1	25.9	27.2	26.3	15.1
	(25.2)	(18.8)	(19.1)	(27.8)	(25.5)	(16.5)
M	70.2	59.5	28.7	33.5	32.2	15.1
	(19.5)	(16.9)	(17.5)	(26.2)	(23.4)	(15.2)
Low						
High	63.0	45.6	27.5	31.1	27.3	14.6
	(19.9)	(17.6)	(22.1)	(26.7)	(20.4)	(15.2)
Low	54.3	35.3	23.1	21.9	14.8	13.5
	(27.0)	(22.6)	(19.3)	(21.3)	(18.0)	(18.3)
M	61.1	41.7	26.5	28.1	23.6	14.0
	(19.3)	(16.4)	(16.7)	(22.2)	(18.5)	(14.1)
M	65.2	50.7	27.6	30.2	28.0	14.0
	(18.2)	(16.2)	(15.9)	(21.5)	(20.5)	(13.1)

Note. Older > 9.75 years old; younger < 9.75 years old. However, age was treated as a continuous regressor variable in the analyses of covariance presented in the text.

ference scores were submitted to a 2 (orthographic similarity: high, low) × 2 (frequency: high, low) analysis of covariance (ANCOVA) with either age or naming accuracy as independent regressor variables. ANCOVAs were calculated separately for age and naming accuracy. After the ANCOVA analyses, hierarchical regression analyses were computed to determine whether age or naming accuracy accounted for unique variance in the magnitude of orthographic and pseudohomophone priming collapsed across orthographic similarity and frequency. This collapsing is justified because age and naming accuracy produced essentially the same results in the ANCOVA analyses.

Age Analyses

Table 3 presents the means and standard deviations for the high- and low-orthographic prime–target pairs and for the high- and low-frequency targets in the pseudohomophone, orthographic, and control priming conditions for the younger and older children. These means are presented as raw scores for ease in interpretation. However, remember that the statistical analyses were calculated on difference scores (d) for orthographic and pseudohomophone priming.

Pseudohomophone priming. The most important finding was that, as predicted, older children (d = 15%) benefited more from pseudohomophone priming than did younger children (d = 2%), $F(1, 260) = 20.71$, $p < .001$. Presumably, older children's quick access to quality phonological representations allowed them to use this information for target identification more than younger children. In addition, high-orthographic-similarity pairs (d = 6%) benefited less from pseudohomophone priming than low-orthographic-similarity pairs (d = 12%), $F(1, 260) = 5.33$, $p < .05$. Low-orthographic-similarity pairs showed more priming because the smaller amount of orthographic overlap allowed for more phonological priming. All other main effects and interactions were not significant ($Fs < 2.4$, $ps > .12$). The pseudohomophone priming effect was not influenced by target frequency; there was reliable priming for both high- and low-frequency targets. This suggests that phonological activation is a general process involving all word types.

Orthographic priming. As predicted, older children (d = 23%) also exhibited more orthographic priming compared with younger children (d = 14%), $F(1, 260) = 20.14$, $p < .001$. In contrast to pseudohomophone priming, however, high-orthographic-similarity pairs (d = 24%) benefited more from orthographic priming than low-orthographic-similarity pairs (d = 15%), $F(1, 260) = 27.90$, $p < .001$. The high-orthographic-similarity pairs showed more priming because the larger amount of letter overlap allowed for more orthographic priming. Finally, high-frequency targets (d = 23%) benefited more from orthographic priming than low-frequency targets (d = 13%), $F(1, 260) = 17.11$, $p < .001$. Although orthographic priming was not independent of target frequency, there was reliable priming for high- and low-frequency targets, suggesting that orthographic priming is general across word types. All interactions were not significant ($Fs < 1.5$, $ps > .21$).[1]

[1] We used absolute differences in the orthographic and pseudohomophone priming analyses because absolute effect sizes are easier to interpret than relative effect sizes. However, relative effect sizes would have produced essentially the same results. Because our dependent variable was identification accuracy, which was bounded at the upper and lower ends of the distribution, we defined relative pseudohomophone priming in the following way: (pseudohomophone % correct − orthographic % correct)/

Table 4
Experiment 1: Means (and Standard Deviations) for Accuracy in the Pseudohomophone (Pseudo), Orthographic (Ortho), and Control Priming Conditions for High- and Low-Orthographic-Similarity Prime–Target Pairs (OS) and for High- and Low-Frequency Targets (FQ)

	High naming			Low naming		
OS/FQ	Pseudo	Ortho	Control	Pseudo	Ortho	Control
High						
High	75.6 (15.9)	69.9 (16.0)	33.4 (23.4)	39.3 (27.9)	37.6 (25.9)	14.0 (12.7)
Low	65.5 (26.9)	53.3 (19.5)	30.4 (19.2)	28.6 (28.1)	24.3 (22.1)	10.5 (10.7)
M	70.3 (19.1)	61.6 (14.3)	31.8 (18.3)	33.7 (26.2)	30.5 (22.2)	12.0 (9.7)
Low						
High	64.7 (22.3)	47.8 (15.1)	28.1 (21.1)	30.5 (23.9)	25.0 (18.7)	14.2 (16.8)
Low	53.8 (26.5)	38.5 (22.0)	26.2 (18.7)	22.2 (22.1)	12.3 (15.8)	11.5 (17.5)
M	62.0 (20.8)	44.6 (15.1)	27.4 (15.9)	27.8 (20.1)	21.0 (16.1)	13.5 (14.8)
M	66.3 (18.1)	53.6 (14.3)	29.4 (16.1)	29.8 (20.2)	25.6 (18.2)	12.2 (10.6)

Note. High naming > 63% accuracy on combined word-naming measure; low naming < 63% accuracy on combined word-naming measure. However, naming accuracy was treated as a continuous regressor variable in the analyses of covariance presented in the text.

The priming difference scores for orthographic and pseudohomophone priming collapsed across frequency and orthographic similarity were then plotted as a function of age. There was a strong linear relationship between age and orthographic priming, $r(65) = .42$, $p < .001$, and between age and pseudohomophone priming, $r(65) = .49$, $p < .001$. There was no evidence that these relations were influenced by the presence of outliers, and there was no evidence of nonlinearity in the relation.

Naming Accuracy Analyses

Table 4 presents the means and standard deviations (raw scores) for the high- and low-orthographic-similarity prime–target pairs and for the high- and low-frequency targets in the pseudohomophone, orthographic, and control priming conditions for the high- and low-naming-accuracy children.

Pseudohomophone priming. This analysis yielded the same significant results as with age. High-naming-accuracy children ($d = 13\%$) benefited more from pseudohomophone priming than did low-naming-accuracy children ($d = 4\%$), $F(1, 260) = 18.85$, $p < .001$. Low-orthographic-similarity pairs ($d = 12\%$) benefited more from pseudohomophone priming than did high-orthographic-similarity pairs ($d = 6\%$), $F(1, 260) = 4.99$, $p < .05$. All other main effects and interactions were not significant ($Fs < 2.1$, $ps > .14$).

Orthographic priming. This analysis yielded essentially the same results as with age. High-naming-accuracy children ($d = 24.2\%$) exhibited more orthographic priming than did low-naming-accuracy children ($d = 13\%$), $F(1, 260) = 31.53$, $p < .001$. Low-orthographic-similarity pairs ($d = 12\%$) produced less orthographic priming than did high-orthographic-similarity pairs ($d = 24\%$), $F(1, 260) = 30.36$, $p < .001$. High-frequency items ($d = 22\%$) benefited more from orthographic priming than did low-frequency items ($d = 13\%$), $F(1, 260) = 18.34$, $p < .001$. However, in contrast to the age analyses, the orthographic similarity effect was qualified by an interaction between naming accuracy and orthographic similarity, $F(1, 260) = 4.13$, $p < .05$. Orthographic priming for the high-similarity pairs increased more with naming accuracy than priming for the low-similarity pairs. All other main effects and interactions for orthographic priming were not significant ($Fs < 1$).

The priming difference scores for orthographic and pseudohomophone priming, collapsed across frequency and orthographic similarity, were then plotted as a function of naming accuracy. There was a strong linear relationship between naming accuracy and orthographic priming, $r(65) = .61$, $p < .001$. There was also a significant, but weaker, linear relationship between naming accuracy and pseudohomophone priming, $r(65) = .40$, $p < .001$.

(100 − orthographic % correct). This formula is equal to the proportion of incorrectly identified items in the orthographic condition that are correctly identified in the pseudohomophone priming condition. The relative amount of pseudohomophone priming for the older children was 20%, whereas the relative amount of pseudohomophone priming for the younger children was 3%. It is clear that the older children were exhibiting more priming than the younger children. Similarly, relative orthographic priming was defined as (orthographic % correct − control % correct)/(100 − control % correct). Relative orthographic priming produced similar results to absolute priming. Because the relative and absolute formulas produced essentially the same results, only the absolute priming results are presented here.

In sum, the age and naming accuracy analyses produced exactly the same results, except that there was a significant interaction between naming accuracy and orthographic similarity for orthographic priming. It appears that most of the developmental differences in priming can be accounted for by naming ability.

Unique Variance Explained by Age and Naming Accuracy

As noted earlier, naming accuracy and age were moderately correlated. To determine the degree of redundancy between these measures in terms of their prediction of the magnitude of priming, we calculated hierarchical regressions separately for orthographic or pseudohomophone priming with naming accuracy and age as predictors. Both age and naming accuracy explained unique variance in pseudohomophone priming. Age explained a significant amount of variance in pseudohomophone priming, $t(260) = 2.20$, $p < .05$, $R^2 = .18$, when entered on the second step after naming accuracy. Naming accuracy also explained a significant amount of variance, $t(260) = 2.13$, $p < .05$, $R^2 = .17$, when entered on the second step after age. However, age contributed only redundant information with naming accuracy in predicting the magnitude of orthographic priming. Age did not explain a significant amount of variance in orthographic priming, $t(260) = 0.80$, $p = .42$, when entered on the second step after naming accuracy. Naming accuracy explained a significant amount of variance, $t(260) = 3.27$, $p < .01$, $R^2 = .39$, when entered on the second step after age. Therefore, it appears that most of the developmental difference in priming effects can be accounted for by differences in naming ability.

In our study, naming-ability differences were unavoidably confounded with age differences. Naming accuracy was higher in the older group than in the younger group, so the number of participants in each cell of an Age × Ability factorial design would be too unbalanced for a meaningful analysis. Because of this, we could not determine statistically whether naming-accuracy differences in priming were different for younger and older children. However, considering that there was a linear relationship of age and naming accuracy with the magnitude of priming, we would expect naming accuracy to explain a similar amount of variance in younger and older children, but that the overall priming effect would be larger for older children.

Discussion

Experiment 1 yielded two major findings. The first major finding is that good readers benefited from both orthographic and pseudohomophone priming more than poor readers. To the extent that these priming effects reflect levels of activation, we suggest that activation of orthographic and phonological information is a function of reading skill. We argue that the more precise and redundant lexical representations of good readers allow them to more efficiently activate representations for words and grapheme–phoneme correspondences at these very short presentation durations, and this results in larger priming effects.

The second major finding is that age differences also accounted for a unique component of the variance in pseudohomophone priming. There is some aspect of the developmental process other than naming ability that accounts for additional variance in the magnitude of pseudohomophone priming. The lack of predictive power of naming ability may be because our naming instruments are not perfect measures of children's knowledge of orthographic and phonological forms or because of some other age-related factor. For example, research shows that word recognition abilities are related to rapid temporal processing of visual forms (Eden, Stein, Wood, & Wood, 1995; Lovegrove, Martin, & Slaghuis, 1986), so it may be that children with higher perceptual ability will show greater priming effects as a result of their increased ability to perceive rapidly presented visual forms.

Our results suggest that phonological activation influences prelexical processes in visual word recognition in both older children and good readers. Pseudohomophone priming occurred even at a 30-ms presentation duration that did not allow complete processing of the prime or target. The short presentation duration required that phonological and orthographic information from the prime and target be integrated during the prelexical period in order for the target word to be correctly identified. The level of identification in the inconsistent control condition was about 30%, which was much lower than the level of about 60% identification in the two consistent orthographic and pseudohomophone conditions. The difference between the consistent and inconsistent conditions suggests that the good readers were using the consistent priming information to produce correct identification.

Larger effects for pseudohomophone than for orthographic primes may be because children process pseudohomophones more like real words than other nonwords. For example, Laxon, Smith, and Masterson (1995) found that 7- to 11-year-old children pronounced pseudohomophones more accurately than nonwords that did not sound like words. In addition, Hansen and Bowey (1992) found that fourth graders were more accurate at reading nonwords when the rime shared phonology with many other real words; for example, *hake* has the same rime as in *rake, lake, fake, make,* and *cake* (see also Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995). There is also evidence that adults process pseudohomophones like real words (Lukatela & Turvey, 1994a, 1994b; Van Orden, 1987). We would like to argue that it is the wordlike nature of pseudohomophones that allows them to display rapid interactive convergence of orthographic and phonological information. Taken together, these results suggest that wordlike nonwords are processed more like real words than other nonwords and may explain why the pseudohomophone priming effects were so robust for the older and skilled readers.

Finally, we would like to discuss whether orthographic and pseudohomophone priming effects depended on target frequency or prime–target orthographic similarity. Experiment 1 showed that the pseudohomophone priming effect was independent of target word frequency. Because reliable priming effects were not limited to a certain frequency, this suggests that phonology influences the recognition of all words regardless of their specific word-level characteristics. This is in contrast to some models of visual word recognition that argue that phonological assembly can influence the recognition of only certain types of words (Coltheart, 1978; Paap & Noel, 1991). There was also reliable orthographic priming for both high- and low-frequency words, but high-frequency words benefited more from orthographic priming than did low-frequency words. This can be accounted for by a model of word recognition that assumes that high-frequency targets are driven more strongly by orthographic input due to increased frequency of exposure (Morton, 1969; Plaut et al., 1996). Stronger input for high-frequency words means that less priming information is needed to produce correct identification. Low-frequency targets are not driven strongly by orthographic input, so more priming information is needed to produce correct identification. We are not claiming that high-frequency words receive a larger relative benefit from priming than low-frequency words, but just that high-frequency words are driven more strongly by input, and therefore, additional priming information is more likely to produce correct identification in the brief-exposure paradigm. Indeed, computational models and experimental data of RTs in the lexical decision paradigm show that low-frequency targets receive a larger relative benefit from priming compared with high-frequency targets (Borowsky & Besner, 1993; Plaut, 1995).

Experiment 1 also showed that the magnitude of priming depended on the orthographic and phonemic overlap between the prime and target. High-similarity pairs benefited more from orthographic priming simply because there was more consistent priming information than in low-similarity pairs. In contrast, low-similarity pairs benefited more from pseudohomophone priming than did high-similarity pairs because less orthographic overlap meant there was "more room" for phonological priming. We are not implying that orthographic primes have an initial effect and that pseudohomophone primes have a later effect. Rather, orthographic and phonological priming result from the interactive convergence of letter and sound information (Van Orden & Goldinger, 1994; Van Orden et al. 1990). Pseudohomophone priming is larger for low-orthographic-similarity pairs because the orthographic primes provide less consistent information.

The orthographic similarity effect on orthographic priming was modulated by naming ability only at the short presentation durations in Experiment 1. This experiment showed that orthographic priming for high-similarity pairs increased with naming ability more than orthographic priming for low-similarity pairs. Only good readers were able to more effectively use priming information with increasing prime–target similarity at a very short presentation duration. As we see in Experiment 2, the longer duration allowed all children to use the orthographic priming information regardless of prime–target similarity.

Experiment 2

Experiment 1 showed that, in contrast to younger and poor readers, older and good readers were able to effectively activate pseudohomophone priming information even at a very short exposure duration. It could be the case that the differences between good and poor readers reside largely in the speed with which the good readers can activate their representations, which could in turn be affected by variation in the underlying quality of these representations. If the activation of phonological and orthographic constituents occurs more slowly for poor readers, then a longer exposure duration might be expected to reduce the priming difference between good and poor readers. To test this hypothesis, in Experiment 2 we increased the presentation duration of the prime and target to 60 ms, a duration that should allow both good and poor readers to effectively activate orthographic and phonological information in a prime–target pair. With a longer duration, naming accuracy should explain little, if any, variance in the magnitude of the orthographic and pseudohomophone priming.

We were also interested in knowing whether younger and poor readers would benefit more from orthographic and pseudohomophone priming at a 60-ms duration in Experiment 2 than at a 30-ms duration in Experiment 1. Poor readers should show larger differences in orthographic and pseudohomophone priming across the two experiments than good readers. Additional time should be of marginal additional value to good readers whose phonological and orthographic processes are effective enough to have been activated at 30 ms. This predicted effect is also relevant for the issue of strategic control over phonological processes. If only poor readers show a significant difference in orthographic and pseudohomophone priming between long and short durations, this would argue against the claim that priming effects in the brief-presentation identification paradigm are due to strategic control (Brysbaert & Praet, 1992). If orthographic and pseudohomophone priming effects are due to strategic control, one would expect these effects to increase with a longer duration for good and poor readers. Certainly, one would not expect that only skilled readers would fail to use strategic processes at the longer duration.

Method

Participants

Twenty-three third graders (mean age = 8.9 years, *SD* = 0.5 years) and 22 fifth graders (mean age = 10.6 years, *SD* = 0.6 years) participated in the study. These students were from two different private schools in the Pittsburgh, Pennsylvania metropolitan area. Different grade levels were used in Experiment 2 than in Experiment 1 because only the third- and fifth-grade levels were allowed to participate in the study at these particular schools.

Procedure, Materials, and Design

The procedure, materials, and design were the same as for Experiment 1. However, for the experimental task, the prime and target were presented for 60 ms each instead of 30 ms each.

Results

Individual-Difference Independent Variables

The analysis strategy for Experiment 2 uses the same definitions and procedures as that developed for Experiment 1 (see Experiment 1, *Results* section).

Table 5 displays the correlations between the individual naming measures and age (all *ps* $< .001$, unless otherwise noted). Accuracy scores on the three naming tasks, $r(45) = .84$, as well as RTs on the three naming tasks, $r(45) = .71$, were highly intercorrelated, so accuracy or RTs for the word identification, nonword, and exception word measures were averaged separately into two mean naming measures (naming accuracy and naming RT). Naming accuracy was negatively correlated with naming RT, and this was relatively uniform for all individual naming measures, $r(45) = -.55$. Finally, there were modest correlations of age with the individual naming measures, $r(45) = .47$.

Table 6 presents the means and standard deviations for the individual naming measures and the combined naming measures for the younger and older students in Experiment 2. There were clear grade differences in accuracy and RT on all measures. However, groupings that were based on accuracy or RT resulted in

Table 5
Correlation Coefficients Between Individual Naming Tasks (Accuracy and RT) and Age for Experiment 2

Variable	1 %	1 RT	2 %	2 RT	3 %	3 RT	4
1. Word identification							
%	—						
RT	−.49*	—					
2. Exception words							
%	.91*	−.50*	—				
RT	−.52*	.77*	−.60*	—			
3. Nonwords							
%	.77*	−.48*	.83*	−.59*	—		
RT	−.55*	.67*	−.61*	.70*	−.59*	—	
4. Age	.46*	−.39	.53*	−.33	.27	−.38	—

Note. RT = reaction time.
* $p < .001$.

larger mean differences and smaller standard deviations between good and poor readers than groupings that were based on age.

Age Analyses

Table 7 presents the means and standard deviations (raw scores) for the high- and low-orthographic-similarity prime–target pairs and for the high- and low-frequency targets in the pseudohomophone, orthographic, and control priming conditions for the younger and older children.

Table 6
Means (and Standard Deviations) of Accuracy (%) and RT (in Milliseconds) for the Individual and Combined Naming Tasks for the Younger and Older Children in Experiment 2

Variable	Younger (n = 44)	Older (n = 24)
Word identification		
%	57.6 (10.8)	67.9 (9.9)
RT	711 (217)	567 (110)
Exception words		
%	46.3 (17.1)	64.4 (15.6)
RT	874 (381)	627 (207)
Nonwords		
%	58.3 (19.8)	67.6 (18.3)
RT	952 (485)	676 (222)
Total		
%	54.0 (15.2)	66.6 (13.6)
RT	839 (326)	636 (168)
Age		
M	8.8	10.9
SD	(0.3)	(0.5)

Note. Younger < 9.75 years old; older > 9.75 years old. RT = reaction time.

Pseudohomophone priming. In contrast to Experiment 1 and as predicted, older children (d = 10%) did not benefit significantly more from pseudohomophone priming than younger children (d = 7%), $F(1, 180) = 1.20$, $p = .27$. As in Experiment 1, low-orthographic-similarity pairs (d = 13%) benefited more from pseudohomophone priming than high-similarity pairs (d = 4%), $F(1, 180) = 8.23$, $p < .01$. All other main effects and interactions were not significant (Fs < 1.8, ps $> .17$).

Orthographic priming. As in Experiment 1, older children (d = 32%) exhibited more orthographic priming than did younger children (d = 25%), $F(1, 180) = 4.98$, $p < .05$; low-orthographic-similarity pairs (d = 20%) benefited less from orthographic priming than did high-similarity pairs (d = 37%), $F(1, 180) = 33.74$, $p < .001$; high-frequency items (d = 32%) benefited more from orthographic priming than did low-frequency items (d = 23%), $F(1, 180) = 7.05$, $p < .01$. Although there was greater priming for high-frequency targets, both high- and low-frequency targets benefited from orthographic primes. However, the main effect of frequency was qualified by a significant interaction between frequency and orthographic similarity, $F(1, 180) = 4.96$, $p < .05$. There was a difference in the magnitude of orthographic priming between high- and low-frequency items for high-orthographic-similarity pairs (d = 15%) but not for low-similarity pairs (d = 1%). There was also a significant interaction between age and orthographic similarity, $F(1, 180) = 5.34$, $p < .05$. The difference in magnitude of orthographic priming between the high- and low-orthographic-similarity pairs was larger for older children (d = 20%) than for younger children (d = 14%). All other interactions were not significant (Fs < 1.2, ps $> .26$).

The priming difference scores for orthographic and pseudohomophone priming, collapsed across frequency and orthographic similarity, were then plotted as a function of age. There was a trend for a linear relationship between age and orthographic priming, $r(45) = .25$, $p = .09$. However, there was no relationship between age and pseudohomophone priming, $r(45) = .19$, $p = .19$. As predicted, these correlations are smaller than the correlations between age and priming for the shorter prime–target durations in Experiment 1.

Table 7
Experiment 2: Means (and Standard Deviations) for Accuracy in the Pseudohomophone (Pseudo), Orthographic (Ortho), and Control Priming Conditions for High- and Low-Orthographic-Similarity Prime–Target Pairs (OS) and for High- and Low-Frequency Targets (FQ)

	Older			Younger		
OS/FQ	Pseudo	Ortho	Control	Pseudo	Ortho	Control
High						
High	71.3	68.9	18.1	60.1	54.7	16.8
	(21.2)	(18.5)	(15.2)	(21.5)	(22.5)	(13.8)
Low	61.6	52.0	20.1	36.5	38.8	12.5
	(22.2)	(21.0)	(24.1)	(21.7)	(21.3)	(15.9)
M	66.3	59.7	19.1	48.0	46.6	14.2
	(20.4)	(16.1)	(17.7)	(18.3)	(19.9)	(11.6)
Low						
High	56.5	41.9	21.6	47.8	35.4	17.1
	(17.7)	(19.8)	(21.4)	(21.2)	(15.2)	(15.0)
Low	52.4	37.1	17.5	40.9	29.4	13.3
	(21.5)	(25.0)	(22.7)	(21.6)	(19.4)	(13.0)
M	56.3	41.1	20.4	45.8	34.4	16.0
	(16.3)	(19.4)	(21.0)	(18.1)	(17.5)	(11.9)
M	61.5	51.4	19.6	47.3	40.1	14.8
	(17.3)	(17.1)	(18.0)	(16.9)	(15.9)	(11.0)

Note. Older > 9.75 years old; younger < 9.75 years old. However, age was treated as a continuous regressor variable in the analyses of covariance presented in the text.

Naming Accuracy Analyses

Table 8 presents the means and standard deviations (raw scores) for the high- and low-orthographic-similarity prime–target pairs and for the high- and low-frequency targets in the pseudohomophone, orthographic, and control priming conditions for the high- and low-naming-accuracy children.

Pseudohomophone priming. The naming-accuracy analyses produced the same results as the age analyses reported earlier.

Table 8
Experiment 2: Means (and Standard Deviations) for Accuracy in the Pseudohomophone (Pseudo), Orthographic (Ortho), and Control Priming Conditions for High- and Low-Orthographic-Similarity Prime–Target Pairs (OS) and for High- and Low-Frequency Targets (FQ)

	High naming			Low naming		
OS/FQ	Pseudo	Ortho	Control	Pseudo	Ortho	Control
High						
High	77.2	69.7	20.7	52.2	53.0	13.4
	(15.4)	(17.0)	(16.3)	(21.0)	(23.2)	(10.5)
Low	62.4	56.4	23.2	34.3	32.8	8.3
	(20.2)	(15.2)	(23.6)	(22.2)	(22.3)	(13.0)
M	69.6	62.6	21.8	43.0	42.4	10.6
	(15.6)	(13.0)	(17.7)	(18.3)	(19.5)	(8.0)
Low						
High	59.4	45.3	26.0	43.7	30.9	11.5
	(18.2)	(19.6)	(21.3)	(18.3)	(11.7)	(10.4)
Low	57.0	43.2	19.0	34.6	21.3	11.1
	(18.8)	(29.6)	(22.2)	(19.8)	(17.7)	(12.3)
M	59.8	45.9	24.3	40.8	28.1	11.0
	(14.8)	(20.2)	(20.4)	(15.6)	(10.1)	(8.2)
M	64.9	54.7	23.1	42.3	35.5	10.3
	(13.3)	(15.5)	(17.7)	(16.1)	(13.3)	(6.6)

Note. High naming > 63% accuracy on combined word-naming measure; low naming < 63% accuracy on combined word-naming measure. However, naming accuracy was treated as a continuous regressor variable in the analyses of covariance presented in the text.

High-naming-accuracy children did not benefit significantly from pseudohomophone priming (d = 10%) compared with low-naming-accuracy children (d = 7%), $F(1, 180) = 0.86$, $p = .35$, and low-orthographic-similarity pairs (d = 13%) benefited more from pseudohomophone priming than did high-similarity pairs (d = 3.8%), $F(1, 180) = 8.11$, $p < .01$. All other main effects and interactions were not significant (Fs < 1).

Orthographic priming. The naming-accuracy analyses also produced similar results to the age analyses reported earlier. High-naming-accuracy children exhibited more orthographic priming (d = 32%) than did low-naming-accuracy children (d = 25%), $F(1, 180) = 13.43$, $p < .001$. Low-orthographic-similarity pairs (d = 19%) benefited less from orthographic priming than did high-similarity pairs (d = 36%), $F(1, 180) = 34.59$, $p < .001$. High-frequency items (d = 32%) benefited more from orthographic priming than did low-frequency items (d = 24%), $F(1, 180) = 7.23$, $p < .001$. The main effect of frequency was qualified by a significant interaction between frequency and orthographic similarity, $F(1, 180) = 5.09$, $p < .05$. There was a difference in the magnitude of orthographic priming between high- and low-frequency items for high-orthographic-similarity pairs (d = 16%) but not for low-similarity pairs (d = 3%). All other main effects and interactions were not significant (Fs < 1.5, ps > .22).

The priming difference scores for orthographic and pseudohomophone priming, collapsed across frequency and orthographic similarity, were then plotted as a function of naming accuracy. There was a weak linear relationship between naming accuracy and orthographic priming, $r(45) = .40$, $p < .01$. However, there was no relationship between naming accuracy and pseudohomophone priming, $r(45) = .16$, $p = .27$. As predicted, these correlations are smaller than the correlations between naming accuracy and priming for the shorter prime–target durations in Experiment 1.

In sum, the naming-accuracy analyses produced exactly the same results as the age analyses in Experiment 2, except that for the age analyses there was a significant interaction between age and orthographic similarity for orthographic priming.

Unique Variance Explained by Age and Naming Accuracy

Hierarchical regressions were not calculated with naming accuracy and age as predictors of pseudohomophone priming, because age and naming accuracy did not explain a significant amount of variance in pseudohomophone priming in the ANCOVAs. For orthographic priming, age was not a significant predictor, $t(180) = 0.66$, $p = .51$, when entered on the second step after naming accuracy. However, naming accuracy was a significant predictor of orthographic priming, $t(180) = 2.66$, $p < .01$, $R^2 = .38$, when entered on the second step after age. Age contributed only redundant predictive power in explaining the magnitude of orthographic priming at the long presentation durations in Experiment 2.

Statistical Comparison of Experiments 1 and 2

To directly compare priming at short and long durations, we combined the data sets from Experiments 1 and 2. This was appropriate because Experiments 1 and 2 only differed in the exposure duration of prime and target. The cross-experiment comparisons were calculated with naming accuracy because the age of participants differed slightly between the experiments and because age and naming accuracy were redundant in accounting for variance in orthographic and pseudohomophone priming. The fact that mean naming accuracy was nearly identical across experiments for both good and poor readers also makes this a reasonable procedure. These comparisons are as follows: for good readers, $M = 72.9$, $SD = 8.3$ in Experiment 1 and $M = 72.3$, $SD = 6.4$ in Experiment 2; for poor readers, $M = 46.6$, $SD = 12.6$ in Experiment 1 and $M = 46.3$, $SD = 10.6$ in Experiment 2. Furthermore, cross-experiment analysis of variance showed no interaction of the between-experiments variable of stimulus duration and naming accuracy, $F(1, 110) = 0.01$, $p = .94$.

The durations of both prime and target were increased by 30 ms from Experiment 1 to Experiment 2; therefore, we cannot claim that priming differences between the two experiments are due specifically to the increased duration of the prime or target. We interpret differences in priming between the two experiments as reflecting facilitation or inhibition due to orthographic and phonological overlap between the prime and target. Because we were only interested in ability differences in priming, the data sets were collapsed across all item characteristics (i.e., orthographic similarity and frequency). First, we computed a 2 (duration: 30 ms, 60 ms) × 2 (naming accuracy: high, low) analysis of variance for raw scores in the control condition. The significant main effect for duration, $F(1, 110) = 33.73$, $p < .001$, suggests that there is more inhibition in the control condition at the long durations than at the short durations (d = 4.1). This analysis also yielded a nonsignificant interaction between duration and naming accuracy, $F(1, 110) = 0.66$, $p < .41$. The lack of an interaction suggests that any naming-accuracy differences in orthographic and pseudohomophone priming at long versus short durations cannot be attributed to differences in the control condition.

We then computed an ANCOVA with duration as a dichotomous independent variable (30 ms, 60 ms) and with naming accuracy as a continuous independent variable. For pseudohomophone priming, there was a significant main effect for naming accuracy, $F(1, 110) = 8.87$, $p < .01$, and a significant interaction between duration and naming accuracy, $F(1, 110) = 2.52$, $p = .05$. This interaction results from pseudohomophone priming increasing from short to long durations for low-naming-accuracy children, whereas priming did not increase for high-naming-accuracy children. Tables 4 and 8 display the mean percentage correct identification rates for high- and low-naming-accuracy children in the three different conditions for Experiment 1 (30 ms) and Experiment 2 (60 ms). For orthographic priming, there were significant main effects for naming accuracy, $F(1, 110) = 20.10$, $p < .01$, and duration, $F(1, 110) = 16.01$, $p < .05$. There were larger priming effects for high-naming-accuracy children and for longer durations.

Discussion

Experiment 2, with a long stimulus presentation duration, produced three results that replicate those of Experiment 1 with a short duration. First, older and good readers benefited more from orthographic priming than younger and poor readers. Second, high-frequency targets exhibited larger orthographic priming effects than low-frequency targets. Third, high-orthographic-similarity pairs benefited more from orthographic priming than low-similarity pairs, whereas low-similarity pairs benefited more from pseudohomophone priming than high-similarity pairs. (See Experiment 1 for a discussion of these findings.)

The most important finding of Experiment 2 was that age or naming accuracy did not explain variance in pseudohomophone priming. We suggest that, at the 30-ms duration in Experiment 1, younger and poor readers were less able to effectively activate the overlapping phoneme information in the prime–target pair, so they showed little pseudohomophone priming. This resulted in age and ability differences in pseudohomophone priming at the short duration. However, at the 60-ms duration in Experiment 2, younger and poor readers were more able to derive enough information to benefit from prime–target overlap, so they showed more pseudohomophone priming. This resulted in no significant age or naming-accuracy differences in pseudohomophone priming.

A statistical comparison between Experiments 1 and 2 revealed that only low-naming-accuracy children exhibited more pseudohomophone priming at the long compared with the short prime–target duration. The interaction between presentation duration and naming accuracy helps us to evaluate the possibility that the brief-exposure word identification paradigm might be influenced by strategic control processes (Brysbaert & Praet, 1992). If the phonological mediation of target identification were under strategic control, one would expect that good readers should exhibit a larger priming difference between long and short durations than poor readers. Good readers should show more benefit from the additional time available in Experiment 2, because their efficient lower level feature extraction processes and higher level word recognition processes (Eden et al., 1995) should increase the probability of activating letter or word information in the prime–target pair. They could then use this more precise information to guide a strategic lexical activation process. For example, given a pseudohomophone prime, such as *abbuv,* and target word, such as *above,* a good reader could use the overlapping letters in the prime–target pair (i.e., *ab v*) to guide a strategic search through the lexicon in an attempt to activate the correct lexical representation *above.* This proposed strategic effect should also extend to orthographic primes. Given an orthographic prime, such as *abliv,* a good reader could use the overlapping phonological and orthographic cues to guide a strategic search. This strategic search can be successful because there are a limited number of four- and five-letter words with the letters *a, b,* and *v.* In the control condition, there are no overlapping cues in the prime and target, so the imprecise letter information should rarely allow an effective strategic search. Good readers may be in a position to make particularly efficient use of the more precise information they glean from the orthographic and pseudohomophone priming conditions, because their lexicon is better organized to permit strategic activation through retrieval cues. The better feature extraction and word recognition processes of the better readers also predict that they should show a particular strategic advantage in identification accuracy over poor readers at longer stimulus durations. However, the strategic hypothesis prediction was not supported by the present experiments. Instead, it was only the less-skilled readers who showed an increase in orthographic and pseudohomophone priming from short to long durations. This pattern of results, which cannot be attributed to floor or ceiling effects, given the identification rates of 25% to 45% for poor readers and 55% to 65% for good readers, is not readily explained by the strategic hypothesis.

A study of adults by Xu and Perfetti (1996) also suggests that strategic control plays a minimal role in brief-presentation identification paradigms. In a series of backward priming studies in which the target was always presented for 30 ms, Xu and Perfetti found that the proportion of pseudohomophone primes did not influence the magnitude of phonological priming at baseline identification rates of less than 40% as determined by a control condition. Identification rates were manipulated by adjusting the exposure duration of the backward primes. The low baseline identification rates in our experiments (<30%) suggest that strategic processing was not a factor.

General Discussion

The results of our experiments contribute to a growing body of research that concludes phonology plays a central role in skilled visual word recognition (e.g., Lukatela & Turvey, 1994a, 1994b; Van Orden, 1987) and in reading acquisition (e.g., Share, 1995; Wagner et al., 1994, 1997). However, the present experiments provide evidence relating to an important missing link between the adult research and the developmental studies. Adult research has focused attention on the use of brief-presentation paradigms as a way of supporting the claim that phonological processes are quick, automatic, and general (e.g., Perfetti & Bell, 1991). Because developmental research has either not collected RTs or has used stimulus presentation durations of 500 ms or longer, it has been difficult to evaluate the degree to which the findings in the adult literature might generalize to claims about the development of reading. The present experiments bridge that gap by showing that becoming a skilled reader involves the development of fast and automatic orthographic and phonological processes. We argue that younger and poor readers have less efficient orthographic and phonological processes that may result from the imprecise and sparse nature of their representations.

Our experiments show that orthographic and pseudohomophone priming occurred in good readers even when the prime and target were presented briefly enough (30 ms and 60 ms) to prevent complete processing. The fact that priming occurred with very brief exposures suggests that phonological activation occurred at a prelexical level. In the control condition, in which the prime and target shared no common letters, identification rates were less than 30%, but these rates rose by 13% to 40% in the orthographic and pseudohomophone priming conditions for all durations and ability groups. The low rate of identification in the control condition suggests that, on average, exposure durations were below the "threshold" of identification. The effects of the orthographic and pseudohomophone primes can be interpreted as the consistent information in the prime–target pair raising the activation level of the target word enough to produce correct identification. We also found reliable orthographic and pseudohomophone priming effects for high- and low-frequency targets. Under the conditions of these experiments, the phonological effects require an account that assumes that phonological processes are early and general, rather than slow and constrained, in skilled readers (Coltheart, 1978; Paap & Noel, 1991). The rapid and general phonological activation in skilled visual word recognition may result from the interactive convergence of orthographic and phonological information as captured in parallel distributed processing models (Plaut et al., 1996; Van Orden & Goldinger, 1994).

Of particular interest was our finding that naming accuracy explained variance in the magnitude of pseudohomophone priming only at short durations and not at long durations. Short presentation durations place greater demands on the rapid, effective use of orthographic and phonological information in order to produce correct identification. Poor readers, who are less effective at activating orthographic and phonological information, showed significantly smaller priming effects at shorter durations compared with good readers. At longer durations, however, poor readers had more time to activate information, and therefore, their identification accuracy was closer to that of good readers. Stated differently, our experiments revealed that poor readers showed greater orthographic and pseudohomophone effects at long durations than at short durations, but that good readers did not differ in these effects between the two durations (see Tables 4 and 8). As discussed earlier, these findings are not consistent with a strategic hypothesis.

The interaction between naming accuracy and duration in the magnitude of priming can be understood within a parallel distributed processing framework (Booth & Plaut, 1998; Plaut, 1995; Plaut et al., 1996). In this framework, differences in the strength of orthographic input are modulated by the asymptomatic nature of a sigmoid function that relates a system's input to its output or activation level (see Figure 1). Certain combinations of variables produce stronger orthographic input to a system, and this stronger input results in larger priming effects in the brief-presentation identification paradigm. First, orthographic input strongly drives word representations in high-naming-accuracy conditions because of frequent exposure to words or a greater amount of training, whereas orthographic input weakly drives word representations in low-naming-accuracy conditions because of limited exposure to words or little training. The system is driven more strongly in high-naming-accuracy conditions because the precision and redundancy of connections allow for rapid interactive convergence of orthographic and phonological forms. Second, a long presentation duration allows more time for the orthographic input to strongly

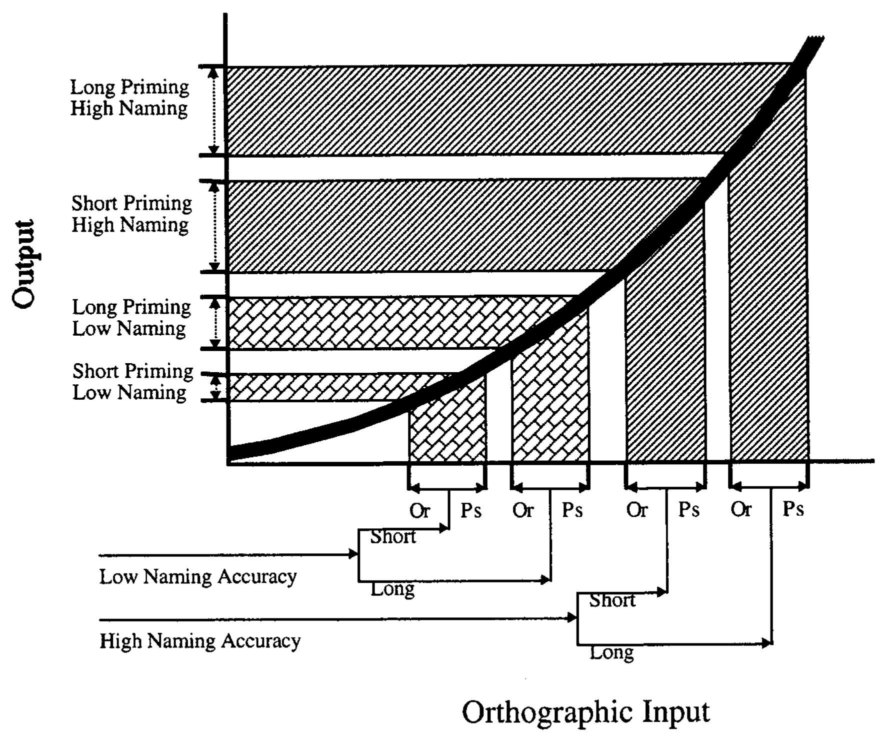

Figure 1. A depiction of how nonlinearities in a sigmoid activation function can give rise to greater priming in the identification paradigm, that is the difference in performance for pseudohomophone (Ps) versus orthographic (Or) primes, for a long duration versus a short duration (long and short, respectively) for low-naming-accuracy children (diagonal bricks) but approximately equal priming for long and short durations for high-naming-accuracy children (diagonal hashing). The combination of arrows at the bottom depicts the separate contributions of naming accuracy, duration, and priming condition, which are summed together to form the orthographic input (indicated by small vertical lines on the *x* axis) to which the sigmoid function is applied to determine the output activation (amount of priming). Note that the relative magnitudes of these contributions are assumed to be greater for high- compared with low-naming-accuracy children, for long compared with short durations, and for pseudohomophone compared with orthographic primes. Note in particular that an identical contribution from priming context has the same effect at long and short durations for high-ability children but has a larger priming effect for a long duration compared with a short duration for low-ability children. Only the bottom third (lower tail) of the sigmoid function is shown because we assume that orthographic input weakly drives output activation in the brief-presentation identification paradigm.

drive word representations, whereas a short duration only allows orthographic input to weakly drive word representations. Third, pseudohomophone primes activate more "features" consistent with the target, whereas orthographic primes activate fewer "features" consistent with the target. These three characteristics of the model can explain the larger phonological priming effects (pseudohomophone minus orthographic) found in the present experiments for high-naming-accuracy children and for long presentation durations. This model can also account for the finding in our experiments that the phonological priming differences between short and long durations were larger for low- than for high-naming-accuracy children. In the model, the word representations at low-naming-accuracy conditions are weakly driven by orthographic input, so activation levels fall near the lower tail of the sigmoid function. This means that any additional orthographic input, for example, with longer durations, will substantially increase the magnitude of phonological priming. By contrast, the word representations at high-naming-accuracy conditions fall closer to the linear region of the activation function. This means that differences that are due to priming context are approximately equal for the short and long durations.

The results of our experiments also address complex issues about the development of reading skill. They implicate a role for both orthographic and phonological knowledge in acquisition of reading skill by children. The fact that skill in word identification, as measured by naming accuracy, was strongly associated with both orthographic and pseudohomophone priming is consistent with the assumption that children acquire word representations that include sublexical orthographic and phonological knowledge of increasing functionality (Ehri, 1992). This knowledge, demonstrated in priming effects, must be established through word reading experience. One possibility for how this works is through what Share (1995) referred to as a "self-teaching device," in which phonological recoding from letters to sounds functions to establish orthographic representations and hence an autonomous orthographic lexicon. Thus, not only do phonological processes have a causal role on later word decoding ability (Wagner et al., 1994; Wagner et al., 1997), but they may also serve to increase the representational properties of words as they are actually read. A child's knowledge of the sound structure of language can be used in the process of learning to read.

Our finding that there are age-related and skilled-related increases in the magnitude of orthographic and phonological priming is also important in light of the well-established finding that there are age-related decreases in the use of semantic information when reading (Booth & Plaut, 1998; Schwantes, 1981; Simpson & Lorsbach, 1983; West & Stanovich, 1978). It appears that "top-down" semantic information influences reading less as children develop, whereas "bottom-up" orthographic and phonological information influence reading more as children develop. In a quasiregular orthography, such as English, the relationship between orthography and phonology is relatively inconsistent, so one would expect more reliance on semantics than on phonology in the initial stages of learning to read. Children are able to compensate for their inefficient decoding ability by bringing to bear semantic knowledge about the world. As children learn the statistical regularities between phonology and orthography, they rely more on the interactive convergence of orthographic and phonological representations when reading. These developmental differences provide constraints on models of visual word recognition because reading acquisition does not just involve age-related increases in all component skills. Rather, some effects such as semantic priming appear to decrease with age, whereas other effects such as orthographic and phonological priming appear to increase with age.

Conclusion

Our experiments suggest that children make quick, automatic, and general use of both orthographic and phonological information to identify written words. We found reliable orthographic and phonological priming even at a very brief presentation duration that prohibits complete processing of the prime or target. This suggests that phonological information is activated early in the visual word recognition process and that this activation occurs in tandem with orthographic activation. We argue that skilled reading involves the rapid interactive convergence of orthographic and phonological information. The orthographic and phonological priming effects also appear to be automatic because the extremely short presentation duration of the prime and target prevented the strategic use of context. Finally, the orthographic and phonological priming effects were general across word types. Both high- and low-frequency target words benefited from orthographic and phonological priming.

The most important finding of our study is that older and good readers use orthographic and phonological information sooner and more effectively compared with younger and poor readers. Indeed, naming accuracy explained 38% of the variance in the magnitude of orthographic priming and 16% of the variance in the magnitude of phonological priming at the short prime–target duration. The ability differences in these priming processes suggest that rapid access to precise and redundant orthographic and phonological representations may play a pivotal role in the acquisition of reading proficiency.

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Appendix

List of the Four- and Five-Letter Target Words and Their Pseudohomophone (Pseudo) Primes, Orthographic (Ortho) Primes, and Control Primes

Target	Pseudo	Ortho	Control	Target	Pseudo	Ortho	Control
			Four letters				
bake	BAIK	BAWK	RUND	leaf	LEEF	LELF	THUP
blue	BLOO	BLAR	FROT	lure	LOOR	LEIR	TOND
boat	BOTE	BOTS	CIRE	made	MAYD	MARD	COLK
code	KOAD	TOID	SNAL	near	NERE	NERI	GOST
cold	KOLD	DOLD	HESS	need	NEAD	NELD	YARK
come	KUMM	SIMS	RALT	noon	NUNE	NANS	SINT
crow	CROE	CRON	SHEG	owns	OANS	OINS	CRIM
dead	DEDD	DEND	LOMB	paid	PADE	PADO	MERT
deaf	DEFF	DELF	BROT	poke	POAK	POSK	RAST
doll	DAWL	DIRL	JUCK	raid	RADE	RADS	KETS
done	DUNN	DINT	HIRM	rake	RAIK	RASK	MILT
door	DORE	DORT	NALL	rate	RAYT	RALT	FOOM
fame	FAIM	FALM	CRON	reef	REAF	RELF	MOOL
fate	FAYT	FAWT	ROUL	roll	ROAL	RORL	CAFT
gain	GAYN	GARN	BOLF	rule	ROOL	RAWL	HOXA
germ	JURM	LORM	KUHN	side	SYDE	SODE	BROT
glue	GLOO	GLIS	BROM	soon	SUNE	SINA	BARP
head	HEDD	HEWD	ROPS	tomb	TYME	TAMS	USAN
hole	HOAL	HOIL	IRBY	toys	TOIZ	TORD	PAIF
home	HOAM	HOIM	TRIN	wait	WATE	WATS	PRES
hope	HOAP	HOIP	SPAG	wake	WAIK	WASK	RIRM
kite	KYTE	KUTE	MANG	zone	ZOAN	ZOIN	PRAL
			Five letters				
above	ABBUV	ABLIV	RISCH	knock	NAUCK	NEECK	FAIST
alone	ALOAN	ALORN	CRIZZ	least	LEEST	LERST	JORPH
arrow	ARROE	ARROG	PLEEP	noise	NOIZZ	NOIST	KLUDD
blaze	BLAYZ	BLARZ	FRICK	onion	UNYIN	ANAIN	AJARM
blood	BLUDD	BLIRD	THAIN	paste	PAIST	PALST	NOOCK
booth	BUTHE	BITHY	SEAFF	pause	PAWZE	PAPLE	JIROT
bowls	BOLZE	BOLTA	PARTH	phase	FAIZE	BACLE	WILOR
brain	BRANE	BRANT	FLEST	quack	KWACK	SPACK	TROST
canoe	KANOO	TANOP	LURSH	queen	KWENE	DRENE	LAIRD
carry	KARIE	DAROO	TULEZ	quote	KWOTE	PLOTE	BARSH
cello	CHELO	CRELO	SPAIL	raise	RAYZE	RAOLE	KNOLP
claim	KLAME	FLAMB	ROUNT	ready	REDDI	ROIDA	HOISH
clown	KLOUN	FLOIN	SHERM	rifle	RYFUL	RAFOL	THOAN
creep	KREAP	WRELP	OLAIN	sauce	SAWSE	SARLE	PLOWY
cycle	SYKLE	AYOLE	NOATH	scale	SCAYL	SCARL	DROIM
dairy	DERRY	DOORY	KOETH	scoop	SCUPE	SCAPT	WHURT
dense	DENCE	DENPE	KRATT	score	SCOAR	SCOIR	HAIGH
diver	DYVER	DEVER	JOFOP	screw	SKROO	STRAD	QUINT
early	URLEE	ARLEY	OSTIL	sewer	SUWAR	SOWOR	MONOD
elbow	ELBOE	ELBOP	ASPIL	shame	SHAIM	SHARM	QUOCK
elite	ELEET	ELEST	SQURK	shoot	SHUTE	SHETS	DRUFF
fence	FENTS	FENAD	GAROT	skirt	SCURT	SPART	WOACH
fight	PHITE	GHITS	DOPLE	stalk	STAWK	STANK	BANGE
final	FYNUL	FONOL	GOESP	tears	TEERZ	TEYRO	COUDO
flame	FLAYM	FLASM	WRINN	theme	THEAM	THELM	SWOAB
float	FLOTE	FLOTS	PRIMP	tooth	TUTHE	TATHO	FRAIM
flood	FLUDD	FLIRD	USILT	train	TRANE	TRANK	GLOUM
floor	FLORE	FLORP	EKAUP	troop	TRUPE	TRAPU	MALSH
frail	FRALE	FRALO	INJON	vault	VAWLT	VADLT	KWOPE
ghost	GOAST	GOIST	YIEND	verse	VURCE	VORTE	DAPNY
girls	GURLZ	GERLD	SCODD	visit	VIZIT	VILIT	LOPOR
graze	GRAYZ	GRATZ	STULP	waist	WEYST	WOOST	VOUGH
green	GREAN	GREIN	SPOAT	whose	HOOZE	HOUTE	MAIFF
hound	HOWND	HOIND	JIBLI	women	WIMIN	WAMUN	SHIDD
ideal	IDEEL	IDEOL	FOOSH	worry	WURRI	WERRA	FAUGH
issue	ISCHU	ISTOU	AROCT	worse	WURSE	WARSE	POICK
knees	NEEZE	NEELD	CRAYL	xerox	ZEROX	TEROX	SHAYT

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