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Influence of consonantal context on the reading of vowels: Evidence from children

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Abstract

When college students pronounce nonwords, their vowel pronunciations may be affected not only by the consonant that follows the vowel, the coda, but also by the preceding consonant, the onset. We presented the nonwords used by Treiman and colleagues in their 2003 study to a total of 94 first graders, third graders, fifth graders, and high school students to determine when these context influences emerge. According to some theories of reading development, early decoding is characterized by context-free links from graphemes to phonemes. However, we found that even children reading at the first-grade level (6-year-olds) were influenced to some extent by a vowel's context. The effect of context on vowel pronunciation increased in strength up to around the fifth-grade reading level (8- and 9-year-olds), and sensitivity to coda-to-vowel associations emerged no earlier than did sensitivity to onset-to-vowel associations. A connectionist model of reading reproduced this general pattern of increasing context effects as a function of training.

Keywords: Vowels; Word reading; Decoding; Context; Connectionist; Models; Spelling-to-sound translation

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Introduction

Alphabetic writing is a visual representation of language, and the written forms of words bear a systematic relation to the pronunciations of words. Children need to learn about these relations so that they can remember the pronunciations of words they have been taught and, importantly, so that they can decipher new words. Children who can do these things need not rely on adults to tell them how to pronounce words. They can teach themselves to read to some extent (e.g., Share, 1985), and their phonological decoding skills can serve as a basis for comprehension. Because of the importance of phonological decoding in reading development, many researchers have examined the knowledge and skills that are involved in spelling-to-sound translation.

According to some researchers (e.g., Frith, 1985), early reading is characterized by whole-word memorization. During this logographic period, children cannot convert spellings to sounds in any systematic way. Other researchers claim that children with good knowledge of letter–sound correspondences and good phonological awareness can decode phonologically from early on in the development of reading (e.g., Stuart & Coltheart, 1988). Regardless of whether or not children pass through a full-blown logographic phase, it is important to investigate how children link spellings and sounds when they do begin to decode.

In one view, decoding ability develops in a sequence of stages. At first, children use simple context-free correspondences between graphemes and phonemes. Thus, a child who has not seen the word *wan* would pronounce it as /wæn/ on the basis of links between *w* and /w/, *a* and /æ/, and *n* and /n/.[1] According to Marsh, Friedman, Welch, and Desberg (1981), children in the first and second grades typically use context-free grapheme–phoneme associations of this kind. Because of limits in their reading vocabulary and cognitive skills, these young children are not able to use rules that specify how the pronunciation of a letter is affected by its context. For example, young children do not yet know that *a* is generally pronounced as /ɑ/ after *w* and *u* (e.g., *wand*, *squash*) but as /æ/ in most other environments (e.g., *hand*, *splash*). The use of context in the assignment of phonemes represents a qualitatively new strategy, one that emerges at some point after the second grade and before the fifth grade, according to Marsh and colleagues. Frith (1985) also stressed the importance of single graphemes and single phonemes in young children's word reading. It is not until children enter a more advanced stage of reading development, according to Frith, that they begin to use larger units such as *wa* when translating between spellings and sounds.

An opposing view holds that large units are important from the beginning of reading development. According to this view, young children often use sequences that are larger than single graphemes and single phonemes when they link printed and spoken words, although they may use smaller units as well (e.g., Goswami,

[1] Phonemic symbols are those of the International Phonetic Association. (1999). Symbols requiring special attention are the following: /æ/ ***a**pple*, /ɑ/ *w**a**nd*, /aɪ/ ***ai**sle*, /e/ *V**e**gas*, /ɛ/ ***e**dit*, /o/ ***o**bey*, /ɔ/ *p**aw***, /ʊ/ *b**oo**k*, /u/ *s**oo**n*, and /ʌ/ *b**u**t*.

1993; Goswami & Bryant, 1990). For example, a young child who is taught to pronounce *bug* links the initial *b* to the onset /b/ in the spoken word. The child may also connect the two-letter group *ug* to the rime /ʌg/. (The onset of a spoken syllable is its initial consonant or consonant cluster, whereas the rime consists of the vowel and any following consonants. For a discussion, see Treiman & Kessler, 1995.) Children who represent the spelling-to-sound relations in this way can decipher other words ending in *ug* such as *rug* and *glug*. However, knowledge of *bug* does not help in pronouncing words such as *cup* and *bud*, which do not share the entire *ug* unit. According to the large-unit view, then, young children might not learn the pronunciations of vowel graphemes such as *u* as independent units. Beginning readers often code the vowel as part of a larger unit, one that corresponds to the syllable's rime.

Debates between small-unit and large-unit theories have often centered on the clue word task. In this task, children are presented with a word such as *bug*, are told its pronunciation, and then are asked to use this clue to help them pronounce other items such as *rug*, *bud*, and *cup* (e.g., Goswami, 1986, 1993). In Goswami's studies using the clue word task, children tend to derive more benefit from shared rimes than from other shared units. For example, children who have been taught to pronounce *bug* show more transfer to words such as *rug* than to words such as *bud* and *cup*. However, other researchers have not always found a shared rime advantage (e.g., Bowey, Vaughan, & Hansen, 1998). Questions about the interpretation of results from the clue word task have also arisen. When more transfer occurs for rimes than for other units, the difference may reflect, in part, children's tendency to guess a pronunciation for a novel word that rhymes with the pronunciation of the clue word (e.g., Roberts & McDougall, 2003). The ecological validity of the clue word task has been questioned as well (e.g., Savage, 1997). In real life, children who are trying to decipher an unknown word do not generally have a similar known word in front of them as they do in the clue word task.

To move beyond the often heated debate between small-unit and large-unit theories of reading development, we must consider exactly what it might mean for readers to use large units. A strong interpretation of the rime-based large-unit view is that children who pronounce *nook* as /nʊk/ in the clue word task, by analogy with the clue *book*, have used a link between the entire spelling pattern *ook* and the entire rime /ʊk/. Even if these children can read words such as *soon* and *room*, this knowledge does not influence their performance on *book* and *nook* because the children treat rime letter patterns and rime sound patterns as wholes. However, the results of studies using the clue word task and other tasks may alternatively be explained in terms of small units. According to this view, readers use associations at the level of single graphemes and single phonemes, but these associations are sensitive to the graphemes' positions and to the surrounding elements. Readers learn, through exposure to words such as *book*, *cook*, *room*, and *soon*, that *oo* is often pronounced as /ʊ/ when it is followed by *k* but that it is typically pronounced as /u/ when it is followed by letters such as *m* and *n*. Much of the evidence that has accrued to support the large-unit view is equally consistent with the idea that readers use grapheme–phoneme links that consider context. The question that we address in the current study is whether readers of various levels of skill use context-free or context-sensitive associations when assigning pronunciations to vowel graphemes. This question is better defined than the question of whether readers use small or large units, and it may prove to be easier to answer.

To examine whether readers use context in the assignment of phonemes to graphemes, we ask how they pronounce nonwords such as *pook*. These nonwords are of interest because, in real English words, the pronunciation of *oo*, like that of certain other vowel graphemes, varies systematically with the identity of the following consonant (Kessler & Treiman, 2001). Before most consonants, *oo* is pronounced as /u/. This pronunciation occurs in words such as *room*, *monsoon*, and *toot*. A different pronunciation, /ʊ/, is more common before /k/, as in *book*, *cook*, and *hook*. Just a few words, such as *spook*, have the /u/ pronunciation of *oo* before /k/. Given the patterns that characterize English words, how do readers pronounce nonwords such as *poom* and *pook*? If people use the most common pronunciation in all circumstances, they should produce /u/ regardless of the final consonant. This is the pattern of results we would expect if readers rely on context-free associations between graphemes and phonemes when translating from print to sound. However, if readers use associations between graphemes and phonemes that are sensitive to context, we would expect to find some context-conditioned /ʊ/ pronunciations for nonwords such as *pook* but very few such pronunciations for nonwords such as *poom*.

Treiman, Kessler, and Bick (2003) used the logic just described in a study with college students. Based on the analysis of Kessler and Treiman (2001), they identified six instances in which the English pronunciation of a vowel is systematically associated with the following consonant. One example of such a coda-to-vowel association involves *oo* before *k*. Two cases in which the pronunciation of a vowel is conditioned by the onset were also selected. For example, *w* tends to condition the /ɑ/ pronunciation of *a*, as in *wan* and *swamp*, whereas /æ/ is more likely after other onsets. Onset-to-vowel associations are less common than coda-to-vowel associations in English, explaining why the study included six cases of the former type but only two of the latter type. The experimental context for each case was the one in which the critical pronunciation occurs most often in real English words—final /k/ for *oo*. There was also a control context in which the vowel is generally pronounced in the typical manner—before final consonants such as /m/ and /n/ in the case of *oo*. Treiman and colleagues (2003) designed one set of nonwords with the vowel in the experimental context and a matched set of nonwords with the vowel in the control context. For example, *oo* appears in the experimental context in nonwords such as *pook* and *prook*, whereas it appears in the control context in nonwords such as *poom* and *proon*. If readers use context-sensitive associations between vowel graphemes and vowel phonemes, they should produce more of the context-conditioned vowel pronunciations for the experimental nonwords than for the control nonwords. This result was found for *oo* and all of the other vowels that were examined.

A notable result of Treiman and colleagues (2003) is that reliable context effects emerged for the onset-to-vowel cases as well as the coda-to-vowel cases. Although onsets do not often affect the pronunciations of vowels in English, skilled readers were sensitive to those onset-to-vowel associations that exist in the language. For example, participants modified their pronunciation of *a* in nonwords as a function of whether the preceding letter was *w* or *n*. The results suggest that college students have learned about associations that cross the onset–rime boundary as well as associations that occur within the rime.

Another important finding of Treiman and colleagues (2003) is that college students were not as highly influenced by context in their pronunciation of nonwords as one might expect given the strength of the contextual effects in real English words. This was true for both onset-to-vowel and coda-to-vowel associations. For example, in the monosyllabic English words that end with *ook*, the vowel is pronounced as /ʊ/ 94% of the time in the word list of Kessler and Treiman (2001). Words such as *book*, *cook*, and *look* are much more numerous than words such as *spook*. The adults in Experiment 1 of Treiman and colleagues (2003) used /ʊ/ 70% of the time for nonwords that ended in *ook*, substantially less than the 94% one would expect if their pronunciations mirrored the statistics of *ook* in English words. The findings suggest that adults' pronunciations of vowels in nonwords are driven by both generalizations (knowledge about the most common pronunciation of a vowel across all contexts) and specifics (knowledge about how vowels are pronounced in particular contexts).

In the current Study 1, we investigated the extent to which children at various levels of reading skill consider the consonants before and after a vowel grapheme when assigning a pronunciation to that grapheme. One question addressed when children begin to show the pattern that Treiman and colleagues (2003) found in adults—the use of both preceding and following consonants to help choose among alternative pronunciations of vowels. According to the view of sequentially developing strategies proposed by Marsh and colleagues (1981), children should begin to do this at some point after the second grade and before around the fifth grade. Prior to this point, children's pronunciations of vowel graphemes should be unaffected by the vowels' contexts. Other theories that stress the importance of small and contextually independent units during the beginning phases of reading development, including those of Frith (1985) and Ehri (1998), lead to similar expectations. Large-unit theories, such as the theory of Goswami (1993; see also Goswami & Bryant, 1990), predict different results. According to these theories, even beginning readers' pronunciations of vowel graphemes should be influenced by the coda.

A second question addressed by Study 1 is whether children show an earlier or greater sensitivity to coda-to-vowel associations than to onset-to-vowel associations. Such a difference would be expected if rimes play a central role in the development of decoding skills, as in current large-unit theories (e.g., Goswami, 1993; Goswami & Bryant, 1990). An influence such as that of *k* on the pronunciation of *oo* occurs within the rime. Children should learn and use such associations more readily than they do associations such as that between *w* and a following *a* if their ability to identify rimes as isolable units prepares them to use corresponding units in dealing with printed words.

Yet a third question arises if we find that children at a particular point in reading development are pulled away from the typical pronunciation of a vowel grapheme by the identity of the onset, the coda, or both. If so, we can ask about the magnitude of the context effects. Do children, like adults, show smaller influences of context than one would expect given the real words to which they have been exposed?

Table 1
Proportions of critical pronunciations of vowels by various groups of readers in previous studies using nonwords similar to experimental nonwords of current study

Study	Grade level	*n*	Age (years; months)	Reading grade equivalent or reading age (years; months)	Proportion critical pronunciations
Bowey and Underwood (1996, Experiment 1)	Mid 2	36	7;1	—	.23
	Mid 4	36	9;1	—	.54
	Mid 6	36	11;3	—	.46
Bowey and Underwood (1996, Experiment 2)	End 2	41	7;5	<Grade 2	.36
	End 2	38	7;5	~Grade 3	.42
	End 2	41	7;6	~Grade 3.5	.62
	End 2	43	7;6	~Grade 5	.62
Brown and Deavers (1999, Experiment 1)	1–4	~30	—	8;8	.44
	1–4	~30	—	11;6	.54
	University	15	—	—	.58
Coltheart and Leahy (1992)	Mid 1	26	6;7	—	.21
	End 1	26	6;10	—	.19
	End 2	26	8;1	—	.28
	End 3	26	8;11	—	.35
	University	26	—	—	.36
Coltheart and Leahy (1996, Experiment 1)	1	23	6;11	—	.43
	3	23	8;11	—	.56
	University	23	—	—	.48
Laxon, Masterson, & Coltheart (1991, Experiment 1)	2–4	40	~7;11	8;0	.27
	2–4	36	~8;8	10;6	.30

Note. A dash (—) indicates that the information was not available in the research report.

Preliminary evidence relevant to these questions comes from studies in which participants at different levels of reading ability were asked to pronounce nonwords in which the codas signal atypical pronunciations of the vowels. The nonwords used in these studies were similar to the experimental nonwords designed by Treiman and colleagues (2003) to assess readers' use of coda-to-vowel associations. Table 1 provides information about the relevant prior studies. Note that clue words were not shown to the participants in any of these studies. From the information provided in the original reports, we calculated or estimated the proportion of pronunciations of the rime that used the critical or context-conditioned vowel pronunciation relative to the total number of critical pronunciations and typical pronunciations. For example, when participants pronounced a nonword ending in *ook* in a reasonable way (e.g., as either /ʊk/ or /uk/), how often did they use /ʊk/? We refer to this measure as the proportion of critical vowel pronunciations.[2] The results in Table 1 show that the proportion of critical vowel pronunciations increases with reading skill up to

[2] In the studies reported in Table 1, the pronunciation of the entire rime was scored as critical or typical. Not enough information was provided in the reports to calculate the pronunciation of the vowel itself. Given the relatively low ambiguity in the pronunciation of most consonant graphemes, however, it is likely that the results for vowels are quite similar to the results for rimes.

some point around the third- to sixth-grade level. After this point, any further increases are negligible. These findings suggest that children's pronunciations of vowel graphemes are increasingly influenced by context up through the later years of elementary school.

Although the previous results provide some information about how following consonants affect children's spelling-to-sound translation for vowels, several important questions remain. One limit of the previous studies is that they did not systematically sample control items that had the same vowel graphemes as the experimental nonwords but in different contexts. If a study includes a nonword such as *pook*, it is useful to include a control nonword such as *poom* so that one can compare the proportions of /ʊ/ pronunciations for the two items. Because the previous studies lacked such control words, we cannot determine whether younger and less skilled readers, in particular, were truly influenced by context. A second limit of the previous studies is that they focused exclusively on rimes. The researchers asked whether children's pronunciations of vowel graphemes are affected by the following consonants, but they did not ask whether children's pronunciations of vowel graphemes are also affected by the preceding consonants. Thus, we do not know whether children's sensitivity to onset-to-vowel associations follows a similar or different developmental course compared with their sensitivity to coda-to-vowel associations. A third limit of the previous studies is that they did not provide information on how often the critical pronunciations of the vowels appear in various contexts in children's written vocabularies. Without such information, we cannot compare the strength of the context effects in child readers with the strength of the effects in the written words to which children have been exposed. We cannot determine whether children, like adults, show smaller context effects than would be expected given the context effects in the vocabulary.

Study 1 was designed to overcome the limitations of the previous studies. We presented the experimental and control nonwords that were designed by Treiman and colleagues (2003) to children and adolescents of a wide range of reading levels. The participants were tested individually using procedures that were similar to those of the previous study involving individual testing with college students (Treiman et al., 2003, Experiment 1). The children also took a standardized reading test involving real words, the reading subtest of the Wide Range Achievement Test 3 (WRAT-3) (Wilkinson, 1993). Thus, we could examine children's use of context in nonword reading in relation to their reading skill. Because the nonwords were designed to assess influences of both the onset and the coda on vowel pronunciation, we could compare the development of sensitivity to coda-to-vowel associations with that to onset-to-vowel associations. In addition, we examined the spelling-to-sound relations for the graphemes of interest in words that appear in written materials targeted at children of various grade levels. These analyses can help to show whether any observed changes in context use as a function of reading skill reflect changes in the types of words that children experience or changes in the children themselves. In Study 2, which is introduced in more detail later, we went on to ask whether a prominent computational model of reading could reproduce the patterns in the behavioral data of Study 1.

Study 1

Method

Participants

The participants were 34 first graders (mean age 6 years 11 months), 20 third graders (mean age 9 years 2 months), 20 fifth graders (mean age 11 years 0 months), and 20 high school students (mean age ~ 17 years 3 months [exact ages were missing for several high school students]). All participants were native speakers of English who reported no speech, hearing, or reading disorders. Of the 34 first graders, 14 were tested during the first half of the school year and the remaining 20 were tested near the end of the school year. All third graders and fifth graders were tested near the end of the school year. The high school students were tested during the summer. The participants had generally been taught to read by mixed approaches that included some phonics instruction. The elementary school students who were tested tended to perform above the levels expected for their grades on the WRAT-3. The high school students performed on average at expected levels. At all grade levels, however, the range of reading ability was wide. Given this, for purposes of analysis, we divided the participants into five groups based on their performances on the reading subtest of the WRAT-3. The groups were not identical in size due to some tied scores. Table 2 provides information about the five groups, which hereafter are referred to by their mean levels on the WRAT-3 reading subtest.

Materials

We used the experimental and control nonwords developed by Treiman and colleagues (2003) to examine readers' sensitivity to two cases of onset-to-vowel conditioning and six cases of coda-to-vowel conditioning. Table 3 provides information about the onset-to-vowel cases that we examined, and Table 4 provides information about the coda-to-vowel associations. The experimental and control nonwords were designed in pairs, with generally 10 pairs of experimental and control stimuli for each case. The list included 20 filler nonwords, adding variety to the stimuli. Appendix A lists all of the stimuli. Three different quasi-random sequences were prepared for

Table 2
Reading groups used in analyses

Mean grade level on reading subtest of WRAT-3	*n*	Median age (years;months)	Median grade in school
1	18	6;4	1
3	21	7;8	1
5	18	8;7	3
8	19	10;10	5
High school	18	17;1	Finished 11

Table 3
Information regarding tested onset-to-vowel associations

	Case 1: *a* (followed by consonant other than *r* or velar)	Case 2: *ar*
Preceding context for experimental nonwords	*u* or *w*	*u* or *w*
Preceding context for control nonwords	other letter	other letter
Critical vowel pronunciation	/ɑ/	/ɔ/
Sample experimental nonword	*squant*	*quarm*
Sample control nonword	*spant*	*narm*
Number of experimental–control pairs analyzed	9[a]	10

[a] One additional pair was erroneously included in the stimulus list but was not analyzed.

Table 4
Information regarding tested coda-to-vowel associations

	Case 1: *a*	Case 2: *a*	Case 3: *ea*	Case 4: *i*	Case 5: *o*	Case 6: *oo*
Following context for experimental nonwords	*nge*	*ld* or *lt*	*d*	*nd* or *ld*	*ld* or *lt*	*k*
Following context for control nonwords	*nce*	*nd* or *nt*	*b*, *l*, *m*, *n*, or *p*	*nt* or *lt*	*nd* or *nt*	*m*, *n*, or *p*
Critical vowel pronunciation	/e/	/ɔ/	/ɛ/	/aɪ/	/o/	/ʊ/
Sample experimental nonword	*blange*	*yald*	*clead*	*ild*	*solt*	*blook*
Sample control nonword	*blance*	*yand*	*cleam*	*ilt*	*sont*	*bloon*
Number of experimental–control pairs analyzed	10	10	10	10	10	10

purposes of presentation. In each sequence, the experimental items, control items, and fillers were randomly intermixed with the constraint that no more than two consecutive items involved the same case.

Procedure

The participants were tested individually. They were assigned to one of the three sequences according to the order in which they were tested. For the elementary school children, the first session began with the reading subtest of the WRAT-3. The number of subsequent sessions differed depending on the participants' academic levels. For the first graders who were tested during the first half of the school year, 30 items from the nonword reading test were given after the WRAT-3 during the first session. Three more sessions followed with 50 nonwords per session. For the first graders who were tested near the end of the school year, 50 items from the nonword reading test were given during the first session and 65 were given during each of the second and third sessions. The third and fifth graders were given 60 items during the first session and were given the remaining items during a second session. For the high school students, the entire nonword reading test was given during the same session as the WRAT-3. A rest break was provided halfway through the nonword reading test for these students.

The participants were told that they would be asked to pronounce a series of "made up words." They were asked to pretend that these were ordinary, everyday words of English and to pronounce each one the way in which they thought it would be read it if were a real word. The participants were told that there were no right or wrong responses in this task. These instructions were similar to those used by Treiman and colleagues (2003) in individual testing of adults. The participants' pronunciations were scored online by a phonetically trained experimenter and were also tape-recorded. The pronunciation of each experimental and control nonword was coded as containing the critical context-conditioned pronunciation of the vowel, the typical pronunciation of the vowel, or some other pronunciation (hereafter called an unusual pronunciation). To check reliability, a second individual coded the results for five participants at each grade level using the tapes. Agreement between the two coders was 89% for the first and third graders, 92% for the fifth graders, and 95% for the high school students. Data analyses were based on the decisions of the original coder, who was present when the children were tested and so was in the best position to interpret the pronunciations.

Results and discussion

Fig. 1 shows the proportions of responses with unusual vowels for the children in each reading ability group. The results are pooled across all of the onset-to-vowel and coda-to-vowel cases. For purposes of comparison, the results for the college

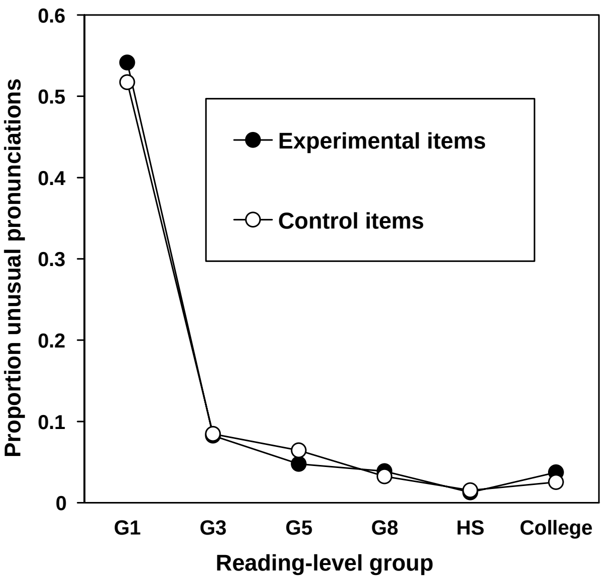

Fig. 1. Mean proportions of pronunciations with unusual vowel pronunciations as a function of reading level group and item type in Study 1. G1, Grade 1; G3, Grade 3; G5, Grade 5, G8, Grade 8; HS, high school.

students tested by Treiman and colleagues (2003, Experiment 1) are also displayed. Analyses of variance (ANOVAs) using the factors of item type (experimental vs. control) and reading ability group were carried out on the child data. Here and elsewhere, statistical analyses were carried out across participants (F_1) and across items (F_2) unless otherwise noted. Only results that reached the .05 level in both types of analyses are reported as significant. The ANOVAs on unusual pronunciations showed only a main effect of reading ability, $F_1(4,89) = 82.11$, $F_2(4,213) = 584.37$, $p < .001$, for both. The children with the lowest levels of reading skill produced many responses with unusual vowel pronunciations. Such responses became less common as reading skill increased. There were no significant differences as a function of item type in the analyses of unusual responses.

We now turn to the key question: When children pronounced the vowel in a reasonable way, did they use the critical pronunciation or the typical pronunciation? Fig. 2 depicts, for experimental and control items, the proportions of critical vowel pronunciations relative to the total number of critical pronunciations and typical pronunciations. Results are shown for children at the five levels of reading ability and for the college students tested by Treiman and colleagues (2003). ANOVAs using the factors of item type (experimental vs. control) and reading group, carried out on the child data, showed a main effect of item type, $F_1(1,89) = 786.50$, $F_2(1,78) = 346.29$, $p < .001$, for both. This main effect was qualified by an interaction with reader group, $F_1(4,189) = 20.54$, $F_2(4,312) = 51.12$, $p < .001$, for both. The proportion of critical pronunciations was significantly higher for the experimental nonwords than for the control nonwords for each of the five reading groups.

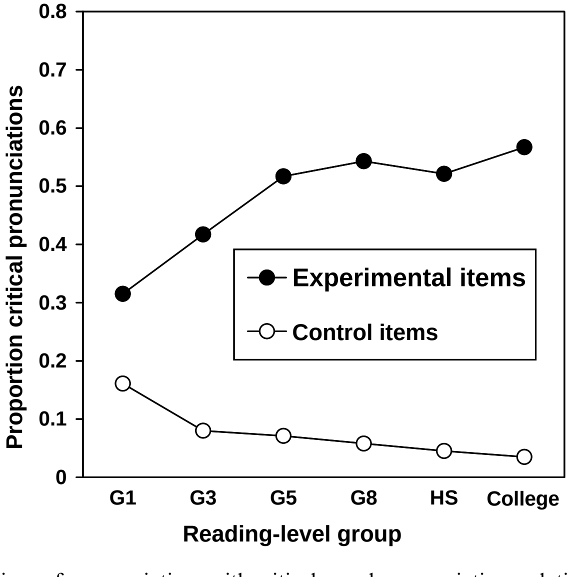

Fig. 2. Mean proportions of pronunciations with critical vowel pronunciations relative to total number of pronunciations with either critical vowels or typical vowels as a function of reading level group and item type in Study 1.

However, the size of the difference increased from the first-grade reading level group to the fifth-grade reading level group. After this point, the difference score did not change reliably. These results indicate that children make increasing use of consonantal context in the pronunciations of vowels up through the final years of elementary school. Additional analyses showed that the difference score correlated more highly with a child's performance on the reading subtest of the WRAT-3 than with his or her grade in school ($r = .64$ vs. .50, $p < .01$, for the difference between the correlation coefficients). This result supports our decision to analyze the data in terms of reading scores rather than in terms of school grade. Because certain spelling patterns were repeated over the course of the experiment, we examined the pronunciations that the children produced for the first experimental item and the first control item of each type that was presented in each session. The results were quite similar to those shown in Fig. 2.

The results in Fig. 2 are pooled over all of the onset-to-vowel and coda-to-vowel cases that we examined. The data were analyzed in more detail by performing one-tailed *t* tests with a *p* level of .05 to compare the proportions of critical pronunciations for experimental and control items for each case and each group of children. For the group of children who performed on average at a first-grade reading level, significant differences emerged both by participants and by items for onset-to-vowel Case 1 and for coda-to-vowel Cases 5 and 6. Thus, the significant overall difference between experimental and control items that was found for this group reflects reliable differences on some types of items but not on others. We scrutinized the item data for this group of children in an attempt to determine why statistically significant effects appeared with some vowels but not with others. One factor that seemed to be influential was the presence of a familiar embedded real word that would support the critical vowel pronunciation such as *look* in *blook*. Embedded words that were likely to be known to the least-skilled group, defined as words that appear in the preprimer through second-grade levels of Harris and Jacobson (1972), occurred in half of the experimental items in coda-to-vowel Cases 5 and 6 but rarely occurred elsewhere. An items analysis for this group of children using the factors of embedding (common embedded word vs. no common embedded word) and item type (experimental vs. control) produced an interaction between embedding and item type, $F_2(1,77) = 13.61$, $p < .001$, as well as main effects of both embedding, $F_2(1,77) = 18.08$, $p < .001$, and item type, $F_2(1,77) = 53.14$, $p < .001$. The difference between experimental and control nonwords in the proportion of critical pronunciations was larger when an embedded word was present than when it was not. Importantly, however, the difference was significant even when no familiar embedded word was present. Thus, the presence of embedded words does not fully explain the observed differences between experimental and control stimuli for children who performed at a first-grade level. For the remaining groups, *t* tests showed significant differences between experimental and control nonwords in the proportion of critical spellings for both onset-to-vowel cases and all six coda-to-vowel cases. The only exception was coda-to-vowel Case 3 for the high school readers, where the proportion of critical pronunciations was not significantly higher for experimental items than that for control items. Overall, the results of these analyses provide no evidence that sensitivity to coda-to-vowel associations emerges earlier than sensitivity to onset-to-vowel associations.

The least skilled group, which performed on average at a first-grade reading level, included children who scored at the kindergarten, first-grade, and second-grade reading levels. For those five children who read at the kindergarten level, the proportions of critical pronunciations did not differ significantly for experimental nonwords and control nonwords. For these children, 65% of all vowel pronunciations were unusual, pointing to the children's low level of skill in translating vowel graphemes into reasonable phonemes. The eight first-grade level readers showed reliable differences between experimental and control items for both onset-to-vowel associations taken together and coda-to-vowel associations taken together. The results of these subgroup analyses must be interpreted with caution given the small numbers of children involved. However, they support the suggestion that the children reading at the first-grade level already show contextual influences on vowel pronunciation. The results also support the earlier suggestion that sensitivity to coda-to-vowel associations and sensitivity to onset-to-vowel associations emerge at around the same time.

The increase in context use as a function of reading ability that we observed has several possible explanations. One possibility is that the spelling–sound relations in the words of children's reading vocabularies change as a function of reading experience. For example, suppose that the proportion of words ending in *ead* (coda-to-vowel Case 3) that have the context-conditioned pronunciation of the vowel (/ɛ/) was relatively low in reading materials designed for first graders but was higher in reading materials designed for older children. If this were true for *ea* and the other vowels in our experiment, it could account for the increase in critical pronunciations with reading skill.

To test whether the observed developmental differences can be explained in this way, we examined how often the vowel was pronounced in the critical fashion in the experimental and control contexts in English words. The counts of pronunciation frequency in monosyllabic words for children sum across the words in the Kessler and Treiman (2001) list, each word weighted by the logarithm of 2 plus its frequency of occurrence in either the K/1 list, the Grade 3 list, or the Grade 5 list of Zeno, Ivenz, Millard, and Duvvuri (1995). For adults, the figures are based on the full Kessler and Treiman (2001) word list, which contains monosyllables that are familiar to college students. We also examined the pronunciation of each vowel in the experimental and control contexts in a larger sample of American English words that includes polysyllables as well as monosyllables (Carnegie Mellon University, 1998). Here, the first vowels of words and their environs were considered for the onset-to-vowel cases; the vowel had to be stressed and in an orthographically closed syllable. For the coda-to-vowel cases, we considered the last vowels of words that had stresses on the final syllables. As Table 5 shows, the proportions of words with the critical pronunciations in the experimental context are very similar across grade levels, both in the monosyllabic counts and in the counts using the larger sample. These results indicate that the observed increase in use of consonantal context as a function of reading level does not reflect systematic changes in the spelling-to-sound relationships in the words to which readers are exposed.

Table 5
Summed frequencies and proportions of words with critical vowel pronunciations in experimental and control contexts in reading materials at various levels

Context	Measure	Grade 1	Grade 3	Grade 5	Adults
Experimental	Summed frequency of words with critical vowel pronunciations	218 (356)	238 (396)	241 (422)	483 (1472)
	Summed frequency of words with structural contexts	248 (392)	266 (425)	271 (456)	545 (1608)
	Proportion of words with structural contexts that have critical vowel pronunciations	.88 (.91)	.89 (.93)	.89 (.93)	.89 (.92)
Control	Summed frequency of words with critical vowel pronunciations	3 (16)	1 (21)	3 (19)	11 (154)
	Summed frequency of words with structural contexts	817 (2126)	831 (2311)	848 (2538)	1976 (11516)
	Proportion of words with structural contexts that have critical vowel pronunciations	.00 (.01)	.00 (.01)	.00 (.01)	.01 (.01)

Note. Values for monosyllabic words are the first values listed, and values for larger sets of words that include polysyllables are in parentheses.

In Study 2, we examined the degree to which a connectionist model could explain the pattern of results observed in Study 1. According to current connectionist models, the pronunciations of both real words and nonwords involve the spread of activation along connections between units. The weights on these connections change with training as the model picks up the links between spellings and sounds that are embodied in the words on which it is trained. Such models have fared relatively well in explaining various aspects of skilled reading and dyslexia (e.g., Harm & Seidenberg, 1999, 2004; Plaut, McClelland, Seidenberg, & Patterson, 1996). However, the ability of connectionist models to account for data on normal reading development has not been evaluated comprehensively (but see Hutzler, Ziegler, Perry, Wimmer, & Zorzi, 2004). In Study 2, we tested a version of the model developed by Harm and Seidenberg (1999, 2004). The results of Study 1 show that effects of consonantal context on vowel pronunciation become stronger, up to a certain point, as reading skill increases. This occurs even though, according to our analyses, the context effects do not become stronger in the vocabulary to which children are exposed. In Study 2, we asked whether a connectionist model that was trained on a fixed set of words showed, as do children, an increase in the size of context effects with training.

Study 2

Method

Materials

The model was trained with a set of 3102 monosyllabic words familiar to college students. Spellings and pronunciations were those standard in the use of the participants in Study 1. Each word was assigned its general frequency as reported by Zeno and colleagues (1995).

Model architecture

The input layer was divided into nine groups corresponding to nine possible positions in a word's spelling. The groups contained 1 unit for each distinct letter that can occur at the corresponding position, giving a total of 111 input units for our word list. Each input unit was connected to 100 hidden units that were fully connected to the output units. These output units were divided into 10 groups corresponding to 10 possible positions in a word's pronunciation. Each group contained 1 unit for each of 25 binary phonological features, and these features were connected in both directions to one another and to each of 20 cleanup units. These cleanup units were intended to help the model learn phonological restrictions on what features can coexist within a phoneme and what phonemes can coexist within a syllable.

Training

Each training trial began with the selection of a word from the word list. Its spelling was encoded in the input layer by fully activating the unit in each group that represents the letter actually found in the corresponding position. For example, the first vowel letter in the word was encoded in position 5, and any second vowel letter was encoded in position 6. Coda consonants were encoded beginning in position 7. Onset consonants were aligned next to the vowel; that is, the consonant nearest the vowel was encoded in position 4. The activations were allowed to propagate through the model until the cleanup units had a chance to operate for 10 cycles. At this point, the output units represented the network's conjecture as to the pronunciation. This was compared with the correct pronunciation, and the network was trained to correct a fraction of the difference using a variant of the continuous recurrent back-propagation algorithm.

The probability that a word would be chosen for a given training trial was proportional to the square root of its frequency in Zeno and colleagues (1995), subject to a ceiling: All words with a frequency greater than 10,000 were treated as having a frequency of 10,000. Because of the stochastic nature of this selection process, it is possible for the model to produce different results each time it is trained on the same word list. These differences were smoothed by running the model 15 times and averaging the results (Zevin & Seidenberg, in press).

Testing

In a testing trial, we gave the network the same nonwords that were presented to the children in Study 1. We observed the output on the phonological layer after the cleanup units operated for 10 cycles. Each group of output units was interpreted as a set of phonetic features and was read off as the phoneme whose phonetic features matched that set most closely. Pronunciations were then scored in the same manner as were pronunciations from children. Testing was carried out every 10,000 trials after the first 100,000 trials to characterize the developmental trajectory of different pronunciation types. (A more detailed description of the model, as well as additional analyses and data files, can be obtained from the Web site http://artsci.wustl.edu/~rtreiman/InflCContxtOnPronV.)

Results and discussion

Fig. 3 shows the proportions of responses with unusual vowels across testing points. The results are pooled across all of the onset-to-vowel and coda-to-vowel cases. The proportions of unusual responses decreased throughout training, just as the proportions of unusual responses decreased across groups in Study 1. However, unusual responses declined more rapidly and reached lower levels for the control items than for the experimental items, a result that was not found in the child data. ANOVAs on the proportions of unusual responses using the factors of item type (experimental vs. control) and time (10,000 trial epochs of training vs. age in

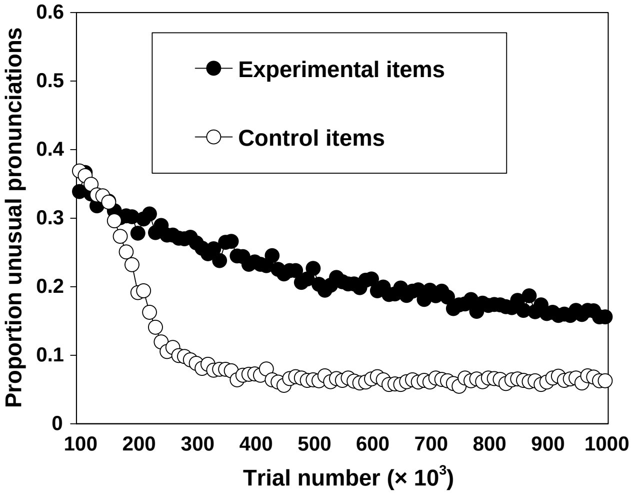

Fig. 3. Mean proportions of pronunciations with unusual vowel pronunciations as a function of trial in Study 2.

children) supported these statements. There was a main effect of time, $F_1(90, 1260) = 107.55$, $F_2(90, 14040) = 29.21$, $p < .001$, for both; a main effect of condition, $F_1(1, 14) = 273.90$, $F_2(1, 156) = 12.65$, $p < .001$, for both; and an interaction, $F_1(90, 1260) = 19.05$, $F_2(90, 14040) = 4.20$, $p < .001$, for both.

Of primary interest here are the results pertaining to the proportions of critical responses. These are shown in Fig. 4. In their general pattern, the findings reproduce those of Study 1. That is, the influence of context increases as a function of training,

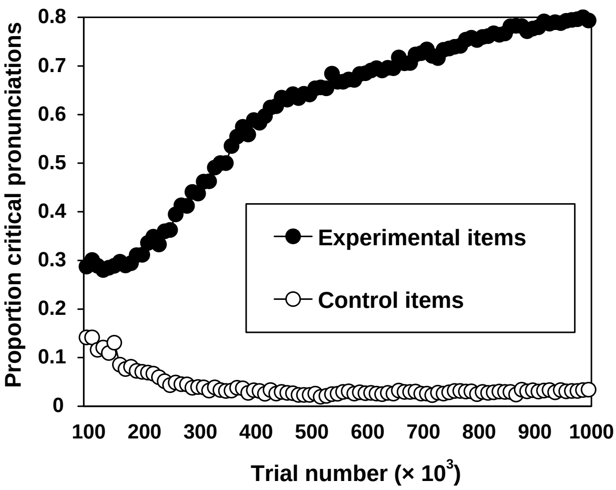

Fig. 4. Mean proportions of pronunciations with critical vowel pronunciations relative to total number of pronunciations with either critical vowels or typical vowels as a function of trial and item type in Study 2.

such that the more highly trained models show a larger difference between experimental and control items than do the less trained models. However, the proportions of critical responses to experimental items reached higher levels for the model than they did for the most skilled human readers. ANOVAs on the proportions of critical pronunciations support these interpretations. The analyses were carried out by participants only because early in training there were a large number of items for which every run of the model produced an unusual pronunciation, and dropping these items from items analyses could have produced some misleading results. There was an interaction between time and condition, $F_1(90, 1260) = 303.83$, $p < .001$, as well as main effects of condition, $F_1(1, 14) = 3570.26$, $p < .001$, and time, $F_1(90, 1260) = 145.53$. For the model, as for the children, effects of context did not generally emerge earlier for the coda-to-vowel cases than for the onset-to-vowel cases.

The most important result, for current purposes, is that the model showed an increasing sensitivity to contextual influences on vowel pronunciation as a function of experience. This occurred even though the set of words to which the model was exposed did not change systematically across the training trials and even though the learning approach adopted by the model did not change. These results suggest that changes in human behavior as a function of reading experience, as observed in Study 1 and previous research, do not necessarily reflect qualitative changes in reading strategies. Several influential theorists have postulated such changes (e.g., Frith, 1985; Marsh et al., 1981), but this does not appear to be necessary to explain the data. Humans, like the model, may attend to context all along. However, context-conditioned patterns are more complex than simpler patterns and take longer to learn. The simulation results further support the idea, borne out also by the vocabulary statistics presented earlier, that increasing use of contextual patterns with reading experience does not reflect major shifts in vocabulary as children get older. The model was trained with the same vocabulary all along, and it too showed increased use of context with training.

The performance of the connectionist model deviated in some ways from that of humans. Several of these differences were noted previously by Treiman and colleagues (2003) when they compared the performance of adults on the current experimental and control nonwords with the performance of several connectionist and nonconnectionist models. One difference between the simulation results and the human results concerns unusual pronunciations. As Treiman and colleagues discussed, even highly trained models make certain errors that humans rarely make. For example, current connectionist models code consonants in codas differently from consonants in onsets and, as a result, tend to have difficulty with letters that appear relatively rarely in one of these positions. Also, the connectionist model examined here, like the models examined by Treiman and colleagues, tended to make more use of context than did human readers. That is, the proportion of critical responses to experimental items was higher for the model than it was for even the most advanced readers. As Treiman and colleagues discussed, humans may sometimes operate at a context-free grapheme–phoneme level even when that level is not the best predictor of an item's pronunciation. Connectionist models, in contrast, appear to show a greater sensitivity to the vocabulary statistics. These models might perform more similarly to humans if they received explicit training on correspondences between spelling and sounds at the subword level. Harm, McCandliss, and Seidenberg (2003) explored the effects of such phonics exercises on the performance of computational models, and this may be a fruitful direction for future research.

General discussion

The English writing system is difficult to learn. Many letters and letter groups have more than one possible pronunciation, and this is especially true for vowels (e.g., Kessler & Treiman, 2001; Venezky, 1970). How do learners cope with this variability when they translate printed letter strings into pronunciations? If children learned only the most common pronunciation of each vowel grapheme, they would err when the vowel pronunciation deviates from the norm, as it often does. If children learned a list of alternative pronunciations but had no principled way of choosing among them, they would also make many mistakes. Fortunately for learners of English, the context in which a vowel spelling occurs can aid in the choice among the alternative pronunciations. The consonant that follows the vowel, the coda, is often helpful. In other cases, the preceding consonant, or onset, helps to disambiguate vowel pronunciation. Skilled readers use both codas and onsets as aids in vowel pronunciation (Treiman et al., 2003). In the current work, we asked when children begin to do so and how we might explain the changes that occur in context use as a function of reading experience.

Our results suggest that learners of English begin to use context-sensitive associations between vowel graphemes and vowel phonemes quite early in the development of reading skill. We found statistically significant context effects as early as the first-grade reading level. These results speak against the view that children go through a lengthy period during which they rely solely on context-free associations between graphemes and phonemes. The theory of Marsh and colleagues (1981), which states that children begin to use context at some point after the second grade, is not supported by our results. If there is a period in the development of reading during which children are not affected by context in the assignment of pronunciations to spellings, as the theories of Frith (1985) and Ehri (1998) hold, that period must be shorter than is usually believed. In our study, it was only children reading at the kindergarten level—children who could identify most letters and a few common words—who were not influenced by the context in which a vowel occurs. Our results further show that context effects become stronger as reading ability increases, reaching a plateau at around the fifth-grade reading level. A similar increase, with a similar time course, has been found in previous studies (Table 1). Because our study included appropriate control words, we are able to go beyond the earlier results by showing that true context effects occur in beginning readers, even though these effects are smaller than the effects seen in more advanced readers.

Previous work on context effects in reading, including the studies summarized in Table 1, has examined effects that occur within the rime. A strong interpretation of a rime-based large-unit view is that children treat letter sequences corresponding to rimes as indivisible units. However, this interpretation is not plausible given the current results. Because a vowel's pronunciation may be affected by both the onset and the coda, and because children are sensitive to both types of associations, any large units would need to overlap. No single way of parsing written words would always yield the most useful units. Moreover, if children were insensitive to the internal structure of a letter group such as *ook*, exposure to *oo* in words such as *food* and *toot* should not influence children's pronunciation of *oo* in items such as *pook*. However, our results suggest that such influences do exist.

Another possible interpretation of rime effects is that children are exclusively or predominantly sensitive to contexts that occur within rimes. According to this view, children come to the task of learning to read prepared to use spelling patterns that correspond to rimes. Thus, they can pick up coda-to-vowel associations relatively easily. Onset-to-vowel associations should be more difficult to learn, according to this view, because the onset–vowel sequence is harder to isolate and treat as a unit than is the rime. However, we found that even children performing at a first-grade reading level could use those onset-to-vowel associations that exist in English. As in some other recent studies (e.g., Bernstein & Treiman, 2004), we did not find that sensitivity to coda-to-vowel associations emerges earlier than sensitivity to onset-to-vowel associations. If rimes play a favored role in the reading of English, this is probably because codas have more influence on vowel pronunciations than do onsets across the English vocabulary as a whole (Kessler & Treiman, 2001; Treiman, Mullennix, Bijeljac-Babic, & Richmond-Welty, 1995). When onset-to-vowel associations exist in the language, however, they are not particularly difficult to learn.

Our results fit with the idea that even young readers generally code words in terms of individual graphemes and individual phonemes—small units. Children's use of small units is shown by the fact that they make generalizations that reflect the behavior of vowel graphemes such as *oo* across a variety of contexts. Children are not limited to large units such as *ook*. Effects that have been interpreted to reflect large units arise, in our view, because links between graphemes and phonemes often take the surrounding context into account.

Although children reading at the first-grade level and beyond were influenced to some extent by the surrounding consonants in their pronunciations of vowels, these influences were not as large as one might expect given the words to which children are exposed. For example, nearly all of the words ending in *ook* that appear in first-grade reading materials are pronounced with /ʊk/; *spook* and *kook* are rarely found in printed materials targeted at this grade level. However, children reading at the first-grade level were actually more likely to pronounce *ook* with /u/ than with /ʊ/. Several factors may help to explain this outcome. First, even though the critical pronunciations dominate in certain contexts, they are in the minority overall. As Table 5 shows, many more English words have the vowels in the control contexts, where the critical pronunciations are rare, than in the experimental contexts. Of course, English also includes a number of words in which the vowels occur in contexts other than the experimental and control contexts as defined here (e.g., *oo* occurs without a following consonant in words such as *boo*) and in which the vowels are not pronounced in the critical manner. The minority status of the critical pronunciations likely pushes children toward pronunciations with the typical vowels. Also contributing to this outcome may be the fact that the typical pronunciations are taught in phonics instruction. Children are taught, for example, that "short *a*" is pronounced as /æ/; they are rarely explicitly taught how its pronunciation may change if the preceding letter is *w* or *u*. Moreover, use of context requires that children consider a letter they have already decoded (in the case of onset-to-vowel associations) or a letter they have yet to fully process (in the case of coda-to-vowel associations) when they are pronouncing the current letter. Given the many factors that would seem to conspire against use of consonantal context in the pronunciations of vowels, it is remarkable that even children reading at the first-grade level use context to some extent. The relatively slow development of this process, extending up through the fifth-grade reading level according to the results of Study 1, likely reflects the fact that context-sensitive associations between graphemes and phonemes are more complex than context-free rules. Even when a context-sensitive rule permits a high degree of predictability, its complexity makes it harder to learn and use than a rule that does not take context into account.

The simulation results of Study 2 add to the picture by showing that changes in use of context in vowel pronunciation do not necessarily reflect changes in the vocabulary to which learners are exposed. The vocabulary on which the model was trained did not change, and yet the model, like the children, showed an increasing use of context as a function of training. The simulation results further show that it is not necessary to postulate qualitative changes in reading strategies with development, as researchers such as Marsh and colleagues (1981) have done, to explain increases in context use. The model's learning algorithm did not change, and yet its use of context did. This outcome probably reflects the fact that patterns that take context into account are intrinsically more complex than patterns that do not.

Our results suggest that the processes that young children use to decode words are similar, in many respects, to the processes that adults use. By the first grade, children have begun to adjust their pronunciations of vowels depending on the surrounding letters in those cases where such adjustments are necessary. Children already treat English as not limited to simple context-free associations between letters and sounds. To at least some degree, they vary their pronunciations of vowels as a function of both the preceding and following contexts. Although children's ability to make such adjustments increases during the course of elementary school, the rudiments of the process are in place quite early.

In the United States and other countries, children are generally taught about the most frequent pronunciation of each consonant and vowel grapheme. In some cases, phonics instruction also offers children common alternative pronunciations for certain graphemes. Usually, however, children are not explicitly taught how the pronunciation of a letter or letter group may systematically change as a function of its context. Although children pick up some of this variability on their own, as our results show, it takes a number of years for their performance on context-conditioned vowels to reach adult levels. With appropriate teaching, children could likely master these skills before the fifth grade, speeding up the process of learning to read and preparing them to read to learn.

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Appendix A

In the following pairs of items used to test onset-to-vowel associations, each pair is presented in the order of experimental/control:

Case 1: *squant/spant*, *quab/clab*, *wabs/trabs*, *twamp/glamp*, *wadge/tadge*, *squamp/namp*, *quatch/flatch*, *quap/blap*, *guat/trat*
Case 2: *warge/carge*, *wark/tark*, *warse/sharse*, *warx/garx*, *quarb/darb*, *quarge/garge, quarm/narm*, *quarn/starn*, *swarb/tarb*, *swark/vark*

In the following pairs of items used to test coda-to-vowel associations, each pair is presented in the order of experimental/control:

Case 1: *blange/blance, brange/brance*, *crange/crance*, *drange/drance*, *shange/shance*, *quange/quance*, *sange/sance*, *spange/spance*, *slange/slance*, *snange/snance*
Case 2: *yald/yand*, *dald/dant*, *frald/frand*, *fralt/frant*, *talt/tant*, *nald/nand*, *nalt/nant*, *pralt/prant*, *shald/shand*, *tald/tand*
Case 3: *clead/cleam*, *chead/cheal*, *swead/swean*, *glead/gleap*, *pread/preal*, *quead/queam*, *splead/spleab*, *squead/squean*, *stread/streal*, *yead/yeab*
Case 4: *ild/ilt*, *brild/brilt*, *chind/chint*, *crind/crint*, *drind/drint*, *smind/smint*, *shrind/shrint*, *slind/slint*, *snild/snilt*, *swild/swilt*
Case 5: *brold/brond*, *chold/chond*, *crold/crond*, *golt/gont*, *jold/jond*, *nolt/nont*, *polt/pont*, *prold/prond*, *rolt/ront*, *solt/sont*
Case 6: *blook/bloon*, *grook/groon*, *clook/cloom*, *drook/droon*, *glook/gloon*, *prook/proom*, *pook/poom*, *plook/ploon*, *slook/sloom*, *trook/troon*

Filler items:
bluth, *bripe*, *feg*, *gletch*, *yud*, *korf*, *mobe*, *poin*, *splem*, *reet*, *shig*, *sabe*, *sneff*, *telp*, *troke*, *vay*, *zung*, *glish*, *thruff*, *sploich*

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