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Orthographic structure and deaf spelling errors: Syllables, letter frequency, and speech

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Syllable structure influences hearing students' reading and spelling (e.g., Badecker, 1996; Caramazza & Miceli, 1990; Prinzmetal, Treiman, & Rho, 1986; Rapp, 1992; Treiman & Zukowski, 1988). This may seem unsurprising since hearers closely associate written and spoken words. We analysed a corpus of spelling errors made by deaf students. They would have learned English orthography with an attenuated experience of speech. We found that the majority of their errors were phonologically implausible but orthographically legal. A tendency to replace uncommon letter sequences with common sequences could not account for this pattern, nor could residual influence from speech. Since syllabically defined constraints are required to keep sequences orthographically legal, the deaf data are marked by an influence of syllable structure. Two main conclusions follow: (1) Our results contribute to evidence that abstract constraints, not derived from peripheral speech or hearing mechanisms, govern the organization of linguistic knowledge; and (2) statistical redundancy could not explain the deaf results. It does not offer a general alternative to suprasegmental structure.

Understanding how deaf individuals represent written language is basic to understanding the language capacities of the deaf, but it is also important to our general understanding of human language capacities. Studies often focus on differences between deaf and hearing performance, but similarities can highlight linguistic representations that are abstract enough not to be affected when the modalities that transmit language are altered. We are interested in whether the grammar for legal sequences provided by syllable structure influences deaf representations of the orthography despite deaf students' attenuated and modified experience of speech.

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In addition to the specific question of how deaf students represent orthography, our investigation touches on two very general issues: the status of orthographic representations in the linguistic system and the abstractness of linguistic principles. Theorists disagree about how orthography relates to other linguistic representations. At one extreme, orthography has been considered a relatively uninteresting translation of speech (e.g., Bloomfield, 1933; Mattingly, 1972; Saussure, 1959). At the other, it has been treated as an independent linguistic domain with structure and principles in its own right (e.g., Caramazza & Miceli, 1990; Venezky, 1970). A third possibility is that the principles governing language are abstract enough to encompass both orthographic and phonological representations (Badecker, 1996). If orthography primarily implements a translation of speech, orthographic representations should be altered in the deaf. If, however, orthographic representations are normally organized in a system devoted to written representations alone, or if they are organized by principles that are abstract enough to operate on either phonological or orthographic input, the principles revealed by deaf and hearing errors may be the same.

The point at which orthographic representations are integrated into the general system of linguistic representation is related to the question of whether units like the syllable are abstract or essentially describe mechanisms of perception and/or production. This is the second general issue that our study addresses. Some theorists claim that syllables embody articulatory processes and have linked them closely to spoken speech (see discussion in Haugen, 1956b; Kahn, 1980; Kenstowicz & Kisseberth, 1979). Several specific auditory/acoustic correlates to syllables have been suggested, including the chest pulse (units of muscle activity controlling air from the lungs, Kenstowicz & Kisseberth, 1979), or the opening of the articulators (e.g., for a discussion, see Haugen, 1956b. See also Abercrombie, 1967; Ladefoged, 1971; Pike, 1947; Stetson, 1928; all cited in Kahn, 1980). If syllables are linked to mechanisms of speech, deaf students would be expected to show reduced influence of syllable structure, given their often limited speech production and lack of auditory input.

Other theorists take a different view. Clements (1990) notes that the search for physical dimensions that map directly onto syllables has not been successful. He suggests that the syllable may be an abstract unit necessary for the formal system of linguistic representation/computation, but not linked to perception or production. Its justification will then be based on its predictive and explanatory power, not on physical correlates (see also Goldsmith, 1990). On this view, the syllable embodies a grammar for segments, establishing which phonemes can follow each other to create a legal sequence.

Syllables establish the number of beats in a word and the boundaries between units: These are the two effects of syllabic processes that are most familiar and most frequently measured. In Clements' sense, however, the syllabic grammar also explains the distribution of sequences in an individual language, the distribution of simple and complex syllables in the world's language types, the order in which phonological units are acquired by children (e.g., Ohala, 1999), and errors in nonfluent aphasia (e.g., Romani & Calabrese, 1998).

If syllables are, indeed, abstract, their ability to impose a grammar on orthographic sequences should be relatively unaffected by deafness. Our study asks whether deaf students respect the syllabic grammar and spell using orthographically legal sequences, despite making errors that would not be pronounced like the target word (phonologically implausible errors). We also consider two alternatives to a syllabic grammar that could keep spellings legal: sensitivity to common letter patterns and translation of speech representations.

At this point it is worth defining more clearly what kind of syllabic influence we are evaluating. Intuitively, if errors preserve the number of syllables in a word, despite changing the segments, this is evidence of item-specific or lexical syllable structure. This evidence comes to mind readily because the most familiar role for the syllable, as we have noted, is its role in prosody. This is not, however, the type of evidence we present. We are not investigating whether individual words keep the same number of syllables when they are misspelled.

Determining the number of units in a word and setting boundaries is a by-product of the more general function described above: Syllables specify how consonants and vowels can be combined to make the legal sequences of a language (Clements, 1990; Fudge, 1969; Goldsmith, 1990; Haugen, 1956a, 1956b). This aspect of the syllable's function is not intuitive, partly because we are taught to recognize syllables by counting beats in a word, but also because the legal sequences in one's own language seem to be just those that are pronounceable. In other words, sequences are either legal or illegal by virtue of the mechanics of the vocal tract.

Legality, however, is clearly not a matter of vocal mechanics since sequences that are legal in one language can be illegal in another. For example, if an English speaker were to produce, as the result of aphasia, the sequence /mnæt/ for *mat*, they would not be violating either general constraints on pronounceable sequences, or even general constraints on English sequences. The onset /mn/ is allowable in Russian (Clements, 1990). It is also allowable in English across a syllable boundary (e.g., in *amnesia* or *alumni*). What is illegal about the sequence /mnæt/ is that /mn/ appears in syllable onset, and this is not allowed in English. The sequence /mnæt/, therefore, violates the principles of English syllable structure, not general articulatory constraints. Conversely, if we observe that an English patient does *not* produce speech errors like /mnæt/, this is a substantial observation, which would be explained by assuming that errors must respect English syllables even when they introduce phonemes into responses. If sequences are legal (i.e., syllabically well-formed), they show that the syllabic grammar is operating (in the same way that the production of well-formed sentences is evidence of a functioning syntax).

Syllables impose constraints that are not easily captured by other mechanisms for representing serial order. For example, allowable sequences could be defined according to overlapping sequences of existing bigrams. However, overlapping bigrams would allow sequences like *ltrp*, which are not sequences that can occur either within or across a syllable boundary in English (e.g., *lt* from *bolt*, *tr* from *abstract*, and *rp* from *harp* overlap to make *ltrp*). Our investigation contrasts accounts of deaf spelling errors based on syllables with accounts based on existing letter groups (bigrams or trigrams).

We have switched from talking in terms of phonemes in our initial examples to letters in the preceding paragraph. This is deliberate. As we have noted above, constraints on sequences could apply at a fairly abstract level. If so, syllable structure could impose restrictions on legal sequences of either phonemes or graphemes (letters or groups of letters).

Many constraints on sequences, in fact, are identical in the orthography and the phonology. Orthography, however, imposes additional purely orthotactic constraints. (Double consonants are allowed in codas, e.g., *ss* in *successful* or *ll* in *ball*, but not in onsets. *Sat* cannot be spelled *ssat*.) We do not focus on distinguishing phonological from orthotactic constraints. Orthotactic constraints do not require anything extra from a theoretical point of view. We focus on orthographic syllables. For us, both letter sequences that violate "phonological" constraints and those that violate purely orthotactic constraints will be considered illegal (see Badecker, 1996, for a careful explication of these issues that is compatible with the approach we adopt and for examples of orthotactic constraints defined in terms of syllable structure).

It is also worth pointing out that the sense in which we have described the syllable encompasses a whole class of related units that have been proposed in the literature devoted to reading and spelling. The rules defining syllables say that a syllable is composed of optional onset consonants, an obligatory vowel, and optional coda consonants. Roughly, it is a concatenation of onset (the initial consonants of the syllable, e.g., the *cl* of *class*), vowel, and coda (the final consonants of a syllable, e.g., the *nt* of *sent*), with constraints operating in the onset and coda, but not between the units. Thus, the syllable is implicated whenever effects of onsets, codas, or rhymes (vowel plus coda) are discussed. Syllabic principles also subsume other units like vocalic centre groups (Spoehr & Smith, 1973), or the BOSS (Taft, 1979, 1992).[1]

Many studies of hearing reading or spelling have shown that words are not just linear sequences of letters, but involve larger units (Badecker, 1996; Bruck & Treiman, 1990; Burani & Cafiero, 1991; Caramazza & Miceli, 1990; Goswami, 1986; Katz & Baldasare, 1983; Mewhort & Beal, 1977; Millis, 1986; Prinzmetal, Hoffman, & Vest, 1991; Prinzmetal, Treiman, & Rho, 1986; Rapp, 1992; Spoehr, 1978; Spoehr & Smith, 1973; Treiman, 1992; Treiman & Chafetz, 1987; Treiman & Zukowski, 1988, 1990). This has sometimes been described as evidence of specifically *orthographic* structure. The close connection between orthography and phonology in hearing participants, however, complicates the interpretation of these studies, since the units of spoken language often could have contributed to the results, even when reading or spelling were studied.

Deaf students provide an alternative source of evidence regarding orthographic units. They learn English orthography with altered or undeveloped mechanisms for producing and perceiving speech (Erber, 1983; Harris & McGarr, 1980; Levitt & Stromberg, 1983; Metz, Whitehead, & Mahshie, 1982; Reilly, 1979). If syllabic influences are lacking in the deaf, the hearing results must be underpinned by speech representations. If syllabic influences are present in the deaf, intact speech mechanisms are not required for the development of syllable structure. If deaf results are influenced by syllables, hearing results, by implication, could be based on *strictly* orthographic structure or on representations abstract enough to govern both phonology and orthography.

There are indications that syllables, in some form, influence deaf performance, either from syllable counting (Sterne & Goswami, 2000) or from segmentation tasks (Olson & Nickerson, 2001; Transler, Leybaert, & Gombert, 1999). More directly related to our hypotheses, several studies have found that deaf students are worse at perceiving or remembering illegal nonwords

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[1] The BOSS, for example, is different from conventional syllable structure only in where it sets the boundary between the first and second syllables in a word. The BOSS maximizes the coda of the first syllable (e.g., *ank/le*) whereas conventional syllable structure maximizes the onset of the second syllable (*an/kle*). If the BOSS is only used to locate the initial unit of the word (as Taft uses it), it does not change the principles that we investigate. It cannot be used for *defining* syllables more generally because it allows too much (e.g., *nk* only appears in codas before a word boundary). The proper place for the syllable boundary when there are intervocalic consonants that could be in either onset or coda has been a controversial issue in the literature devoted to English syllabification (see also Hoard, 1971; Kahn, 1980; Selkirk, 1982), but it is not an issue for us. None of the alternatives change the definition of legal onsets, vowels, or codas. From this point of view, onset-maximizing syllables, syllables that attract codas when they are stressed, and BOSS units (to mention three examples) are equivalent.

than legal nonwords in reading, writing, or fingerspelling tasks (Aaron, Keetay, Boyd, Palmatier, & Wacks, 1998; Gibson, Shurcliff, & Yonas, 1970; Hanson, 1982b, 1986). In a previous study of deaf spelling errors, Hanson, Shankweiler, and Fischer (1983) noted that the overwhelming majority of deaf spelling errors did *not* violate orthographic constraints (91.7% of the hearing responses and 96% of the deaf spellings were orthographically legal—although deaf spelling may not always conform to this pattern, see Sutcliffe, Dowker, & Campbell, 1999). Spellings were legal even though many of the errors would not be pronounced like the target (i.e., deaf spellers made mostly phonologically *im*plausible errors; hearing spellers made mostly phonologically plausible errors). All these results are expected if syllabic constraints are operating, but two alternative accounts prevent us from immediately attributing them to syllable structure. One is based on pronounceability and the other on letter frequency.

If deaf participants have sufficient access to speech, speech-based representations could be translated into letters during spelling. Speech representations (e.g., from lipreading) could be incomplete enough to allow phonologically implausible spellings, without allowing illegal errors. This account makes further predictions. Sensitivity to orthographic structure should be correlated with the quality of representations for speech. Hanson (1986), in fact, found a stronger effect of orthographic legality among deaf participants with good speech and argued that sensitivity to orthographic structure was connected to speech skills.

A second alternative is that deaf participants are sensitive to orthographic legality because they are sensitive to letters that appear together frequently in the language. Seidenberg (1987) proposed this type of hypothesis to account for syllable effects in hearing reading, suggesting that syllable boundaries were marked by infrequent bigrams. Aaron et al. (1998) speculated that the conditional probability of one letter following another was responsible for better deaf reproduction of legal versus illegal nonwords. Groups of frequently occurring letters could define "legal" words. Infrequent letter groups would be present in "illegal" words. Although Seidenberg's hypothesis did not, in the end, explain the hearing data (Rapp, 1992; see also Burani & Cafiero, 1991, for evidence in Italian), letter frequency could be more important for deaf students.

Previous studies of the deaf have not been able to explain effects of orthographic regularity using letter frequency (Gibson et al., 1970; Hanson, 1982b, 1986), but a limited range of frequency measures has been considered, and frequency has not been central to these studies. We test a wider variety of measures. Deaf results provide a limiting case for the hypothesis that frequency can mimic structural effects in either the hearing or the deaf, since deaf orthographic representations are based more exclusively on exposure to letter patterns, with limited guidance or interference from speech.

Our study has the following structure. Initially, we characterize the spelling performance of deaf students and hearing controls and ask whether deaf students avoid orthographically illegal spellings more often than would be expected by chance. Next we ask whether patterns of letter frequency can account for the deaf results and provide an alternative to syllable structure. Finally, we look for evidence of spoken language influence in the deaf data. We consider three alternatives and the predictions they make:

1. Patterns in letter frequencies organize orthographic representations, and these patterns mimic structural effects. Deaf spellers may produce mostly orthographically legal spellings, but only because they systematically produce common sequences of letters. Spelling

errors should concentrate on low-frequency sequences, and, crucially, they should increase letter frequency at the location of the error. If deaf students are sensitive to letter frequencies, orthographic representations can, in principle, be organized around statistical regularity. Thus, some hearing results could also be due to patterns in letter frequencies instead of suprasegmental structure.

2. Suprasegmental structure is intimately connected to representations of speech. Speech ultimately underlies the structural effects in hearing reading and spelling. If so, deaf spellers may either show no influence of syllables, or else show influence according to their access to speech. Rates of illegal errors may not be especially low, and they should be inversely correlated with speech skills. If speech is important, phonological variables should also affect deaf spelling (e.g., phoneme–grapheme regularity, stress, syllabic complexity).

3. Specifically orthographic or abstract syllable structure governs deaf representations. Deaf spellers should avoid orthographically illegal spellings, but frequency should not account for the deaf pattern. There should be limited influence of phonological variables. Despite the obvious differences, deaf and hearing spelling should show similar effects because the abstract grammar and primary input (written words) will be the same. Syllable effects should be found in other tasks like reading. If the deaf are influenced by abstract syllables, the same may be true of the hearing.

Method

Participants

Deaf participants. A total of 23 deaf students attending a precollege preparatory course at the Northwest campus of Gallaudet University participated in the experiment. Gallaudet is the most prestigious deaf university in the United States, so it draws the most academically able of the American deaf population. The students at the Northwest campus were college-entry age but were not yet ready for the level of study at the main Gallaudet campus. This means that they were not as advanced as the typical Gallaudet student, but would still be categorized as very able in relation to a sample of the deaf population as a whole. All of our participants had two deaf parents. The greatest number were deaf for hereditary reasons (11), but 1 was deaf from an unspecified infection, 1 because of a high fever, 1 because of rubella, 1 because of meningitis, and 8 had unknown causes. The students were all prelingually deaf with the exception of one student who was later discovered to be slightly older when deafened (3 years).

All students had a hearing loss measured by the better-ear-average of at least –85 dB (M = –100.3 dB, SD = 10.3 dB, min = –85 dB, max = –115 dB; one participant did not have this information recorded). Hearing loss of 80–95 dB is usually considered to be profound deafness (Meadow, 1980; Quigley & Paul, 1984), and –90 dB has been called the point at which the main channel of communication shifts from audition to vision (Conrad, 1979; also Ling, 1976, cited in Quigley & Paul, 1984). The speech awareness threshold for the better ear was at least –70 dB (average for better ear = –88.0 dB, SD = 10.9 dB; 3 participants did not have this information available, and 2 could not be evaluated because they were off the scale). A total of 19 participants used American Sign Language (ASL) for communication at home, and 1 used signs with speech. This information was not available for 3 participants. In the judgement of the Gallaudet teachers, the deaf students were performing at the level of hearing high-school students. Reading test results provided from Gallaudet admissions records indicated that the students were reading at approximately the level of 12-year-old hearing students (Holt, 1993). This estimate is based on reading scores from the Stanford Achievement Test, a test of reading comprehension, which was available for 20 of the students (M = 655, SD = 20). In all but one case, the test was taken in 1990, the same year as the students were tested. The other student was tested in 1987. The 95% confidence interval for this set of reading scores extends from 645 to 663, which corresponds to a range of hearing reading ages between approximately 10 and 13 years old (Holt, 1993). Their chronological ages ranged from 16 to 21 years ($M = 19$, $SD = 1$).

Hearing participants. Spelling errors were collected from 100 hearing participants who were students in grades 10, 11, and 12 (ages approximately 15–18 years old) at Lincoln High School in Lincoln, Nebraska. All were native speakers of English and did not, according to their teachers, have special language problems. Although the deaf students have a slightly lower reading age than the hearing controls, none of the important features of the data can be explained by appealing to this difference in reading ages. We return to this point in the General Discussion.

Procedure

Deaf participants. An ASL interpreter gave the deaf students words to spell on two occasions. There were 179 words in the first list and 162 words in the second list. All 23 deaf students were present for the first session. Of these students, 11 returned for the second session. On each occasion the procedure was the same. First, the intended word was read aloud and signed in isolation, then a sentence containing the word was read and signed, and finally the word was read and signed once again in isolation. Students were instructed to write the intended word in the blank left for it in the written sentence. They had the opportunity to ask questions about any word they were unsure of. Sign language interpreters were instructed not to fingerspell any of the stimulus words.

ASL-to-English translation creates the same ambiguities that arise in any translation between languages, so the stimulus word and/or its morphology were not always precisely specified by the ASL sign. The majority of sentences did elicit the proper word (85%), but other words were sometimes produced (12% morphological variants; 2% other words). If the word the person intended to write was clear from his or her response, these responses were scored. If no target word could be identified, the response was omitted from the analysis. Only 11 of 885 errors in the corpus (1%) come from words that are not either stimulus words or a morphological variant. These have no impact on the overall pattern of results. Since we are interested in the pattern of spelling errors and not morphological errors, we were conservative, and we scored errors in relation to their closest morphological form (e.g., if a deaf student added or subtracted an inflectional ending like “s” or “ed”, these were not counted as spelling errors since their source is ambiguous).

Hearing participants. The procedure was similar for hearing students. The stimulus word was spoken in isolation, spoken in the context of a sentence, and then spoken again in isolation. Students were instructed to write the stimulus word in the blank left for it in the written version of the context sentence.

Stimuli

Deaf participants. Stimulus words were chosen in consultation with the deaf students’ teachers to ensure that the words would have relatively unambiguous signs and would be familiar. We included words with a variety of orthographic structures, but given the need for a sufficient number of items, systematic control of word characteristics (e.g., orthographic structure, frequency, regularity) was not possible. Word frequencies (Kučera & Francis, 1967) covered a wide range (min = 1, max = 847, $M = 82$, $SD = 107$), however, as did the regularity of phoneme-to-grapheme correspondences (min = 0, max = 92, $M = 14$, $SD = 16$). There was little correlation between frequency and regularity ($r^2 = .02$). Word lengths ranged from 4 to 14 letters.

Phoneme-to-grapheme regularity was quantified by taking each English phoneme and calculating the percentage of the time that different graphemes were used to represent it in a large dictionary (20,000 words). We then categorized words that had one or more unusual phoneme–grapheme correspondences as irregular (a correspondence occurring 5% of the time or less was considered unusual; e.g., *doubt* was categorized as irregular because the correspondence between *bt* and /t/ accounts for only 0.1% of the spellings of /t/ in the dictionary). Words with no low-probability phoneme-to-grapheme correspondences were categorized as regular. We counted each word in the dictionary once when tabulating correspondences (rather than counting each according to their frequency), consistent with the majority of the theoretical and empirical work in this area (Baron & Strawson, 1976; Coltheart, 1978; Hanna, Hanna, Hodges, & Rudorf, 1966; Parkin, 1982; Seidenberg, Waters, Barnes, & Tanenhaus, 1984; Venezky, 1970).

Hearing participants. On average, 227 of the words given to the deaf students were given to the 100 hearing students (*SD* = 9, min = 213, max = 234). Time constraints precluded presenting all of the words given to the deaf, and since different classrooms went through the stimulus list at different rates, a small group of words at the end of the hearing list was not written by all students. Word lengths in the hearing stimuli ranged from 4 to 12 letters.

The hearing sample was clearly large enough, both in terms of the number of words spelled and also the number of students tested, to adequately characterize hearing performance. With fewer deaf students available for testing, it was useful to present a larger number of words in order to obtain a sizeable corpus of spelling errors. Nonetheless, in order to ensure that the pattern of spelling errors did not change simply because the hearing did not spell all of the words given to the deaf, we have scored the subset of words spelled by all students. We show that the characteristics of this set match the characteristics of the larger corpus for both the deaf and hearing.

Scoring

Spelling errors were scored according to the type of error made, its position in the word, whether the erroneous spelling could be pronounced in the same way as the stimulus (phonologically plausible vs. implausible errors), and whether the error resulted in an orthographically legal or illegal sequence of letters. The phonological plausibility and orthographic legality of deaf and hearing spelling errors were scored both by computer and by hand. When these methods gave different results, the error was looked at again. Error types included letter substitutions (e.g., *elephant* → *eleplant*), deletions (e.g., *afternoon* → *afteroon*), insertions (e.g., *strict* → *stricit*), transpositions (e.g., *biologist* → *biogolist*), and letter shifts (e.g., *camera* → *carmea*). At least two scorers categorized the error types involved in each error, and conflicts were resolved by reconsidering the error.

Both phonological plausibility and orthographic legality were scored *by individual error* and not by response. For example, in the response *pumpkin* →*pimkin* there are two separate errors. An "i" is substituted for "u", and the second "p" is deleted. The first of these errors is phonologically implausible because *pimpkin* cannot be pronounced like *pumpkin*. The second error is plausible, however, since *pumkin* has the same pronunciation as *pumpkin*. Both of these errors result in orthographically legal sequences.

Phonological plausibility and orthographic legality were determined using explicit and systematic criteria. In order to be considered phonologically plausible, each phoneme–grapheme correspondence from a target–error pair had to have a regular correspondence in our 20,000 word dictionary that would allow the error to be pronounced like the target. Orthographic legality was scored by parsing a response into word-initial consonants or vowels, word-medial onsets, word-medial vowels, word-medial codas, and word-final consonants or vowels. If letters in each of these categories from the spelling error matched existing sequences from the dictionary, the response was scored as legal (unusual spellings from the dictionary, e.g., words like *yclept*, were excluded). The error *camera* → *carmea*, for example, was considered orthographically legal because "c" is an existing word-initial onset, "a" is an existing word-medial vowel, "r" is an existing word-medial coda, "m" is an existing word-medial onset, and "ea" is an existing word-final vowel cluster. The error *scratch →sctrach* was considered illegal because "sctr" is not a possible word-initial onset. If there was ambiguity about which error caused a response to be orthographically illegal, all errors involved were considered illegal. This is conservative in relation to the issues we are investigating.

Results

General characteristics of the spelling errors

The 23 deaf subjects misspelled 885 of the 5899 words they spelled (15%). The individual letter transformations leading from stimulus to response (deletions, substitutions, etc.) were categorized as described above. In some cases, and especially when the response was quite different from the intended word, it was not possible to classify transformations unambiguously. These errors were not included in the analysis of error types. This left a corpus of 706 misspelled words, which contained 857 individual errors (1.2 errors per word). The most clearly unambiguous set of erroneous responses were those that involved a single transformation (e.g., one deletion). Several analyses were run on this subset and are noted as such.

Hearing spellers misspelled 2312 out of the 22,707 words they spelled (10%), and they made 3118 individual errors (1.3 errors per word). Because of the large number of errors, these were not separated into ambiguous and unambiguous categories. A corpus of misspellings with a single unambiguous mistake was used for many analyses, as was the case for the deaf data.

In order to characterize the performance of deaf and hearing spellers using a controlled set of words, we identified the subset of words that were spelled by all participants. These establish the patterns of performance that require explanation in subsequent sections. The pattern of performance on the controlled subset never differed, however, from the pattern in the corpus as a whole.

The corpora of errors from deaf and hearing students look very different on the surface, as even a small set of examples makes clear (Table 1). Tabulating the types of errors that each group makes formalizes these differences (Table 2). Deaf errors were phonologically *implausible* (80%), while hearing errors were plausible (73%). Overall, deaf spellers made a higher proportion of deletions and fewer substitutions. They also rearranged the order of letters more

TABLE 1
Examples of spelling errors made by deaf and hearing students

Target	*Deaf*	*Hearing*
responsible	responbile	responsable
secret	secert	secrete
scissors	sicossics	sciccors
medicine	medince	medican
volunteers	volutter	volenters
substitute	subituse	substatute

TABLE 2
The distribution of error types made by deaf and hearing spellers for the whole spelling corpus and for the subset of words spelled by all participants

	Deaf				*Hearing*			
	All errors		*Common subset*		*All errors*		*Common subset*	
	N	%	*N*	%	*N*	%	*N*	%
				Phonologically implausible errors				
deletions	338	40	208	37	346	11	324	11
adjacent exchanges	128	15	74	13	81	3	70	2
insertions	106	12	71	13	188	6	168	6
substitutions	69	8	47	8	170	5	153	5
letter shifts	45	5	36	6	54	2	51	2
transpositions	20	2	18	3	12	0	12	0
				Phonologically plausible errors				
deletions	50	6	43	8	764	25	672	24
adjacent exchanges	8	1	6	1	98	3	82	3
insertions	39	5	26	5	400	13	376	13
substitutions	39	5	31	5	880	28	827	29
letter shifts	3	0	3	1	69	2	60	2
transpositions	6	1	5	1	42	1	40	1

often (adjacent and nonadjacent transpositions and letter shifts, 25% vs. 11% for hearing spellers). These contrasts provide the first indication that deaf spelling was much less influenced by phonological representations than was hearing spelling. The distribution of error types for the subset of words spelled by all participants and for the full corpus were not different: deaf, $\chi^2(11, N = 1419) = 5.79, p < .89$; hearing, $\chi^2(11, N = 5939) = 1.83, p < 1.0$.

In other analyses, however, deaf and hearing students look similar. There were effects of length and frequency (Table 3). Collapsing over frequency, deaf and hearing groups did not show different effects of length. In a log linear analysis the likelihood ratio χ^2 change for the Deaf/Hearing × Length interaction = 2.1, $p < .15$. Collapsing over length, deaf and hearing

TABLE 3
Percentage of error by deaf and hearing students on words of different lengths and frequencies

		Letter length	
	Frequency	*short*[b]	*long*
Deaf	high[a]	6	14
	low	17	27
Hearing	high[a]	4	10
	low	11	15

[a] > 50 words per million.

[b] < 8 letters long.

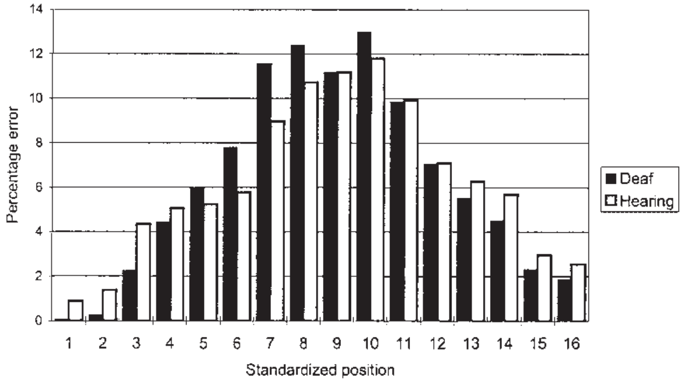

Figure 1. Serial position curve for errors made by deaf and hearing students. Positions have been standardized in relation to the longest word spelled (a morphological variant of *responsible*, *responsibilities*, 16 letters long).

groups did not show different effects of frequency, Deaf/Hearing × Frequency likelihood ratio χ^2 change = 1.6, $p < .21$. There were more errors in the middle of words than at the beginning or the end (Figure 1). The mean error position was not different for deaf and hearing participants: deaf = 9.05, hearing = 9.07; $t = 0.16$, $p < .87$. The similarity of these results probably stems from factors that were not substantially altered by deafness (e.g., frequency of exposure to written words, the increased difficulty of longer items). The serial position curve derived from the common subset of words spelled by all participants did not differ from the curve for the corpus as a whole: deaf, $\chi^2(15, N = 1913) = 8.06$, $p < .92$; hearing, $\chi^2(15, N = 6822) = 2.31$, $p < 1.0$.

This initial pattern of similarities and differences anticipates what is a general trend in our analyses. The error types and examples make it clear that the deaf and hearing corpora are different. Our analyses, however, expose essential similarities. These underlying similarities are exactly what is predicted if there are abstract constraints governing the form that errors can take.

CONSTRAINTS ON SPELLING ERRORS: ORTHOGRAPHICALLY ILLEGAL ERRORS AND SYLLABLE STRUCTURE

Given the large number of phonologically implausible errors in the deaf corpus, it is clear that deaf misspellings are not constrained by a translation of an accurate phonological specification into appropriate graphemes. To the extent that phonological information is present at all, there must be substantial gaps. If a phonological representation does play a role in the error *library* → *libary*, for example, the /r/ must be missing from the phonological form. *Magazine* → *magnize* requires a much larger degree of uncertainty about the phonemes at the end of the word.

A striking characteristic of the deaf students' phonologically implausible errors, however, is that in spite of the latitude allowed by missing phonological information, the errors remain orthographically legal (errors like *sympathy* → *sypathy*, *challenge* → *challengen*, *algebra* → *alegbra*, *umbrella* → *umbrable* are all legal). We concentrate on phonologically implausible errors, because plausible errors inevitably remain legal if they result from translating an accurate phonological form into graphemes. There were 8.1% phonologically implausible and orthographically illegal errors (37/456) in the deaf corpus using only words that all deaf and hearing participants wrote, and there were 6.7% (57/857) illegal errors in the full deaf corpus of deaf errors (examples of illegal errors: *sympathy* → *smpathy*, *challenge* → *chanllege*, *scratch* → *sracth*, *depressed* → *deprressed*). The rate of illegal errors in the full corpus did not differ from the rate in the subset of words written by all participants, $\chi^2(1, N = 1313) = 0.96, p < .33$. We initially ask whether deaf spellings really are as they informally appear—that is, are they constrained to be orthographically legal? Then we examine the source of the constraints.

Our definition of orthographically legal follows from the discussion of legality in the Introduction. Orthographically legal strings are those that can be fully syllabified into existing English onsets, codas, and vowels, without unsyllabified letters. For example, *depressed* → *deprressed* is illegal because the double-*r* cannot be syllabified with either the first syllable (*depr* is not a legal syllable), or the second syllable (*rres* is not a legal syllable).[2] We do not claim to have resolved all potential questions regarding syllabification and orthography, but we adopt a conservative definition of illegal. Patterns must respect both syllable- and word-position constraints to be considered legal, and our guide to allowable patterns is the English lexicon. Accordingly, a spelling like *llamp* would be considered illegal, even if there are rare exceptions like *llama* in the lexicon (e.g., *llama* and *llamas* are the only two words with double consonants at word beginning out of 100,625 entries in the English corpus of the CELEX database; Baayen, Piepenbrock, & van Rijn, 1995). While acknowledging that this leaves some theoretical questions for the future, spellings can be clearly classified using this approach.

Although hearing spellers made fewer phonologically implausible errors, these errors were also overwhelmingly orthographically legal. From the set of words that all participants spelled, only 9.4% (73/774) of implausible errors were orthographically illegal (80/851, 9.4% illegal errors in the entire hearing corpus). This is also an interesting result. These errors, which would normally be categorized as "slips of the pen", also appear to be constrained to be orthographically legal. If both deaf and hearing spellings are governed by the same abstract constraints, however, neither of these results is surprising.

In the remainder of this section we are concerned with analysing whether this small number of orthographically illegal errors really is substantially fewer than that expected by chance given the properties of the stimuli and the general characteristics of the errors. We restrict our analysis to single deletions, multiple deletions and adjacent letter exchanges because the number of errors expected by chance can be calculated for these error types. Examining only deletions and exchanges does not substantially limit the strength of our results, however, since these are the two largest categories of deaf phonologically implausible errors. The method we used to estimate the number of errors expected by chance is similar for all error types. We describe the method in detail only for single deletions. It can easily be extended to multiple deletions and exchanges.

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[2] This definition of syllabification does not require that the orthographic and phonological syllabifications agree. For example, the orthographic syllabification of *illegal* would be *il/le/gal*, while the phonological syllabification is /ɪ/ /liː/ /gəl/. See Badecker (1996) for a detailed treatment of these issues that is compatible with our approach.

Method

To estimate how often random single deletion errors produce illegal sequences, we deleted one letter at a time from the words that had been involved in phonologically implausible deletion errors and categorized the resulting strings as orthographically legal or illegal. We assumed that the probability of a deletion occurring at each letter position was given by the serial position probability of error for the deaf data. The percentage of orthographically illegal errors generated by our simulation was compared to the percentage of illegal single deletion errors in the deaf corpus.

Results

All possible single deletions resulted in 466 illegal strings out of a total of 1867 simulated errors. Adjusting for the serial position probability of error, there were 23% orthographically illegal strings. In the actual corpus, there were six orthographically illegal deletions out of 169 phonologically implausible single deletion errors (3.5% illegal errors). The difference between the observed and predicted number of errors was large and significant: $\chi^2(2, N = 338) = 35.22, p < .001$.

We also analysed errors in which more than one letter was deleted. Our simulation predicted 365/1073 orthographically illegal strings, and, when weighed by the serial position probabilities, this resulted in 31% illegal strings. Out of 72 of the deaf multiple deletion errors, 2 were orthographically illegal (2.8% illegal errors). The observed number of errors was again significantly lower than that predicted by chance: $\chi^2(2, N = 144) = 26.63, p < .001$.

Exchanging all letters in words that lead to exchange errors created 137 simulated illegal strings out of 544. Adjusting for serial position, this produced 23% illegal errors. A total of 10% (9/91) of the exchange errors from the deaf corpus were orthographically illegal, significantly fewer than expected: $\chi^2(2, N = 182) = 8.56, p < .01$.

The results from hearing spellers were similar. Simulated single deletions led to 24% illegal strings after adjusting for serial position (277/1246 illegal strings before adjusting). Only 13 of 149 phonologically implausible single deletions were illegal: 8.7%; $\chi^2(2, N = 298) = 18.6, p < .001$. Simulated multiple deletions predicted 30% illegal errors (289/864 errors before adjusting). Only 2 out of 57 (3.5%) multiple deletions were orthographically illegal: $\chi^2(2, N = 114) = 19.1, p < .001$. A total of 35% illegal adjacent exchange errors would have been expected (107/308 before adjusting). A total of 7 out of 40 adjacent exchange errors were actually illegal: 15%; $\chi^2(2, N = 94) = 8.55, p < .01$.

Discussion

In both the deaf and hearing corpora, phonologically implausible errors were orthographically illegal much less often than predicted by chance. This similarity is important, but it must be interpreted alongside the more general pattern. Overall, deaf and hearing patterns are very different: Implausible errors are only a small part of the hearing corpus, but they constitute the majority of the deaf errors. We have more to say about these similarities and differences in the General Discussion.

We have reported results that were adjusted by the probability of error taken from the serial position curves for each error type. Estimates that were unadjusted were also always significantly different from the observed data (for both deaf and hearing corpora). Looking at our simulated errors, however, this is not surprising. Illegal sequences were generated with relatively equal frequency in all word positions, so that any weighting of some positions at the expense of others will have little effect (i.e., increases in illegal errors in one position are balanced by decreases elsewhere). Thus, the pattern we have reported will not change under a wide variety of assumptions about the positional distribution of errors.

Finding substantially fewer illegal errors than expected is evidence that these errors were systematically avoided. The syllable will limit illegal errors if we assume, along with phonological theories (e.g., Goldsmith, 1990, pp. 123–124) that letters must be syllabified to be produced. In turn, the paucity of illegal errors implies that syllables are part of deaf students' orthographic representations.

As we outlined in the Introduction, however, there are two other ways that spelling errors might remain orthographically legal and not implicate syllables: They could remain legal because deaf spellers use frequently occurring letter sequences when they are uncertain of a spelling, or they could remain legal because errors translate phonological representations that are incomplete enough to allow phonologically implausible errors, but still have enough information to prohibit illegal sequences. In the following sections we consider whether either of these alternatives could explain the deaf pattern.

ORTHOGRAPHICALLY LEGAL ERRORS AND LETTER FREQUENCY

A frequency-based account of deaf spelling has a certain intuitive appeal, and a preference for using frequent letter sequences might hypothetically lead to predominantly orthographically legal spelling errors. Common letter combinations (that are also legal) may be filled in where spellers have some letters in mind but are uncertain of a spelling. Deaf spellers could have more freedom to choose among frequently occurring combinations because incomplete information about phonological forms will allow rearrangements of letters that would be implausible to hearing spellers. Thus, the influence of frequency should be particularly evident in deaf errors. If letter co-occurrence patterns are responsible for the deaf pattern, however, two predictions follow. First, errors should concentrate on the parts of words that are spelled in relatively unusual ways. Second, and more crucially, errors must replace uncommon sequences with more common sequences. The paucity of illegal errors is only explained if letters for the response are selected according to their frequency.

The first of these predictions was fulfilled by the data. For both deaf and hearing spellers, and for both phonologically plausible and implausible errors, misspellings did concentrate on uncommon letter sequences. We omit the details of these analyses because they are not critical to the pattern of results. We used eight different ways of measuring letter frequency (bigrams or trigrams, crossed with type or token frequency crossed with counts by position or overall; by-position counts tabulated separate counts for each position in words of a single length, overall counts tabulated counts without regard to word position or length—see Solso & Juel, 1980, for analogous counts). The 8 measures were applied to three different types of error (deletions, insertions, and substitutions/shifts/transpositions), resulting in 24 measures overall. A total of 13 of 24 measures of phonologically implausible errors showed significantly more errors than expected on uncommon sequences, 9/24 measures gave this result for phonologically plausible errors, and all measures showed some increase over expected numbers of errors.

The hearing results were even more consistent. Phonologically implausible errors concentrated on uncommon sequences in 13 of 24 measures. Phonologically plausible errors concentrated on uncommon sequences in 18 of 24 measures.

It is relatively unsurprising, however, that errors occurred where letter patterns were unusual. Several factors might make these parts of words difficult to spell (poorer memory representations, irregularly spelled sequences, complex phonological sequences). If frequency is to explain the scarcity of orthographically illegal errors, misspellings must also increase the frequency of letter sequences at the point where errors are made. Otherwise, frequency will only have explained where errors occur and not the form that errors take.

DO ERRORS INCREASE LETTER FREQUENCY?

Method

In order to check whether errors increased letter frequency, we compared the frequency of bigrams and trigrams at the position of a spelling error to the frequencies of the correct letters in the target. We present the method by example using deletion errors and bigrams. Analyses for trigrams and other error types were computed in an analogous fashion.

Deletion errors required us to compare two bigrams from the stimulus to the one bigram remaining after the error. Initially, a frequency margin was set to enable us to categorize bigrams that were of roughly equal frequency versus those that were unequal. All bigrams from words involved in deletion errors were collected and the standard deviation of their frequencies was calculated. An arbitrary criterion of 1/8 of this standard deviation was used as a margin when counting increases and decreases in frequency. For example, the deletion error *deteCTIve* → *deteCIve* required us to compare the bigrams *ct* and *ti*, from the stimulus, to the bigram *ci*, from the response. If the bigram created by the error (*ci*) was more frequent than the first bigram in the stimulus (*ct*) by an amount more than the margin, an increase was counted. If it was less frequent by an amount less than the margin, a decrease was counted. Bigrams that differed by less than plus or minus the margin were counted as *no change*. The process was repeated, comparing the second bigram from the stimulus (*ti*) to the bigram from the response (*ci*). Phonologically plausible errors and phonologically implausible errors were analysed separately.

Results

Both deaf and hearing participants showed some tendency to increase local letter frequency when they made phonologically plausible errors. For deaf participants, 10 of 24 measures showed a significant increase in frequency, and 1 showed a decrease. For hearing participants, 10 of 24 showed a significant frequency increase; 9 measures showed a significant decrease. Phonologically plausible errors, however, were uncommon in the deaf corpus, and they are the errors guided by the sound of the target. The role of frequency in these errors depends on whether the spelling chosen was especially frequent among the set of spellings that would be pronounced like the target. This is not our focus here.

In contrast, and more importantly, phonologically implausible errors always significantly decreased or did not change letter frequency. A total of 13 of 24 measures decreased in the deaf data (typical results are shown in Table 4). No measures increased. A total of 14 of 24 measures decreased in the hearing data, and none increased (Table 5). Considering phonologically plausible and implausible errors separately, deaf and hearing patterns were similar. As we noted

TABLE 4
Number of phonologically implausible errors made by deaf students that increased, did not change, or decreased local letter frequency

		Bigrams		*Trigrams*	
	Letter frequency	*By position*	*Overall*	*By position*	*Overall*
Deletions	Margin	11	195	3	45
	Increased	82.5	83.5	55.5	78.3
	No change	100.5	33.5	114.3	147.5
	Decreased	149.0	209.0	211.0	246.0
	Sign test	$p < .001$ decrease	$p < .001$ decrease	$p < .001$ decrease	$p < .001$ decrease
Insertions	Margin	7	199	2	41
	Increased	31.5	34.0	22.16	33.0
	No change	15.0	7.3	40.6	26.2
	Decreased	25.5	28.3	28.7	29.7
	Sign test	$p < .51$ —	$p < .55$ —	$p < .44$ —	$p < .77$ —
Substitutions/shifts/transpositions	Margin	10	202	4	48
	Increased	198	235	96	176
	No change	158	74	359	222
	Decreased	173	220	162	219
	Sign test	$p < .21$ —	$p < .51$ —	$p < .001$ decrease	$p < .03$ decrease

TABLE 5
Number of phonologically implausible errors made by hearing students that increased, did not change, or decreased local letter frequency

		Bigrams		*Trigrams*	
	Letter frequency	*By position*	*Overall*	*By position*	*Overall*
Deletions	Margin	9	190	3	48
	Increased	80.0	80.5	43.0	88.3
	No change	72.5	38.5	231.0	149.0
	Decreased	145.5	161.0	146.0	163.8
	Sign test	$p < .001$ decrease	$p < .001$ decrease	$p < .001$ decrease	$p < .001$ decrease
Insertions	Margin	12	180	2	36
	Increased	41.5	52.0	39.0	56.5
	No change	37.5	9.0	53.5	38.5
	Decreased	39.0	56.0	69.0	66.0
	Sign test	$p < .87$ —	$p < .77$ —	$p < .005$ decrease	$p < .44$ —
Substitutions/shifts/transpositions	Margin	10	188	4	38
	Increased	120	149	96	137
	No change	117	76	359	149
	Decreased	142	154	162	173
	Sign test	$p < .19$ —	$p < .82$ —	$p < .001$ decrease	$p < .05$ decrease

previously, however, the overall pattern was different. Hearing spellers made primarily phonologically plausible errors, which may have been influenced by frequency. Deaf students made primarily implausible errors, which were not influenced by frequency.

Discussion

In sum, there was evidence that frequency played a role in determining where errors occurred. The spellings that were chosen at points of uncertainty, however, were not determined by letter frequency. Frequency, therefore, could not account for the scarcity of deaf orthographically illegal errors.

Our first alternative to syllabic constraints cannot explain the deaf spelling pattern. We now turn to our second alternative. As we noted previously, the paucity of orthographically illegal errors could result from a representation of spoken language that is substantially different from the hearing representation, but still limits the types of error that deaf spellers can make. If phonological information is important, however, the influence of phonological variables should be measurable in the deaf data.

THE ROLE OF PHONOLOGY: EFFECTS OF PHONOLOGICAL VARIABLES

In this section, we evaluate the role of speech-based representations in the deaf spelling pattern. There are two ways in which speech may be important for the hypotheses we are considering. The first and most fundamental of these we have mentioned above: Errors could remain legal because they translate phonological representations. In other words, representations derived from speech could constrain deaf errors rather than syllables. Alternatively, syllables may be necessary to explain the deaf pattern, but they, in turn, may require speech. When we talk about the influence of speech-based representations in this section, we mean all forms of information about spoken language including representations derived from lip-reading, residual hearing, or speech production. "Speech-based" contrasts with information about words that comes from written language.

To put our results in context, we briefly review studies that investigate what deaf students know about spoken language. Evaluating the impact of speech is not straightforward either theoretically or empirically. Theoretically, representations of spoken language exist on several levels from relatively peripheral motor programmes to central phonological representations. As is apparent in the discussion that follows, the role of peripheral representations will be easiest to judge. However, at the levels that are divorced from the mechanics of producing or perceiving speech, language representations could be influenced by a combination of sources—residual speech, lipreading, or writing—making it difficult to separate the contributions of spoken and written input.

Empirically, the intelligibility of speech may not provide a clear index of more abstract phonological knowledge. Distinctions that are present at more abstract levels may not be evident because they cannot be implemented, or they may be signalled, but by means that hearing listeners do not understand (McGarr & Harris, 1983; Reilly, 1979; Stein, 1980, all cited in Metz et al., 1982). Deaf students, however, clearly do have problems using articulatory mechanisms appropriately. This is initial evidence against the hypothesis that syllables, if important, are based on articulatory mechanisms for speech.

Studies of perception also present problems. Much of deaf information about speech is based on lipreading. Lip-reading has often been studied in idealized situations, with a clearly articulating, well-lit speaker who is producing simple syllables or single words. This can overestimate access to sound distinctions. Erber (1974, 1983) suggests that there are only 9–16 visibly distinguishable sound units in conversational speech. In addition, the context in which segments appear will be influential. For example, segments that are relatively easy to lip-read in simple syllables may be harder to perceive in clusters, yet clusters are important because they set the level of syllabic complexity allowed by the language. Lip-reading will, no doubt, provide some information about speech. We try to determine whether this, along with other sources, is enough to put meaningful constraints on written words.

Several indirect measures have previously been used to gauge deaf phonological knowledge. The visual similarity of items in a list, their sign similarity, but also their phonological similarity, have all been found to influence short-term memory tasks (Campbell & Wright, 1989; Conrad, 1972, 1979; Conrad & Rush, 1965; Hanson, 1982a, 1990; Hanson, Liberman, & Shankweiler, 1984; Locke & Locke, 1971; Siedlecki, Votaw, & Bonvillian, 1990). Leybaert and Alegria (1995) found phonological effects in a stroop task using pseudowords. Rhyme judgements suggest that sometimes enough phonological information is present to support better than chance performance but much of the time results depend on whether words look similar (Campbell & Wright, 1988; Hanson & Fowler, 1987; Hanson & McGarr, 1989; Sterne & Goswami, 2000; Waters & Doehring, 1990).

The varied and sometimes contradictory nature of these results is probably due, in part, to differences in the deaf participants who have been studied; in part it is almost certainly due to emphasis. Some researchers highlight any influence of phonological variables in the deaf; others note that deaf patterns are rarely, if ever, like hearing patterns. Clearly deafness, even profound deafness, does not banish all knowledge of sound-based distinctions. Some deaf participants, particularly amongst those who are good readers and speakers, appear to use information that has a basis in articulation, lip-reading, or more abstract phonology. On the other hand, few, if any, deaf individuals show evidence of the detailed phonological representations that are available to the hearing.

With these issues in mind, we consider two kinds of evidence related to spoken language. The first is the correlation between speech abilities and the rate of orthographically illegal errors. If spellings depend rather directly on speech-based representations, those students with the most accurate speech should produce the fewest orthographically illegal errors.

As we have indicated, however, abstract representations could keep spelling errors orthographically legal, even if production itself is poor. Missing phonological distinctions or systematic distortions could produce phonologically implausible errors without allowing them to be illegal. Lip-reading, for example, will not distinguish voiced/unvoiced phonemes. The error *bin* → *pin* is consistent with lip-read speech, and no syllables would be required to explain this kind of phonologically implausible but legal error. To gauge the contribution of speech-based representations without depending on speech itself, we consider several indirect measures of phonological influence.

One indirect measure of phonology that we examine involves stress. Stress exists in the phonology, but not in the orthography. Stressed syllables may be easier for deaf students to perceive (e.g., in lip-reading), and if these syllables are written more accurately than unstressed syllables, a strictly phonological dimension is influencing errors. Hearing students should have no trouble perceiving both stressed and unstressed syllables, so a contrast between deaf and hearing results is predicted.

We also examine syllabic complexity. Consonants in clusters may mask each other, leading deaf students to delete the consonant that is least evident in lipreading when they spell. These deletions would result in systematically legal spellings. Hearing students, in contrast, should have no trouble perceiving complex onsets and/or codas in speech. If speech is important, we expect the deaf, but not the hearing, to make errors on consonant clusters. If abstract syllables are important, deaf and hearing error patterns should not differ. We focus on consonant deletions in our analyses of stress and complexity. The kinds of deletions that deaf speech perception should lead to are clear for consonants—it is clear how the predicted errors will result in legal syllables—and a phonologically motivated pattern of consonant deletions contrasts with what is expected from hearers.

Following previous studies, we use the influence of phoneme-to-grapheme correspondences as a final indirect measure of phonology. Speech is essential to establish correspondences between sounds and letters. With no speech representation, for example, there is no evidence that a word like *colonel* has an unusual spelling. If it were pronounced /kɔlənəl/ the spelling would be regular. Conversely, a spelling that regularizes *colonel* (e.g., "kernel") differs from the correct spelling at exactly the points where the phoneme-to-grapheme mappings are unusual. Some previous studies have found that deaf participants treat words with regular phoneme–grapheme correspondences differently from words with irregular correspondences (Hanson et al., 1983; Leybaert, 1993; Leybaert & Alegria, 1995; Sutcliffe et al., 1999), while other studies have not found this (Chen, 1976; Corcoran, 1966; Dodd, 1980; Gates & Chase, 1926; Locke, 1978; Merrills, Underwood, & Wood, 1994; Waters & Doehring, 1990). Representations of speech that are complete enough to support robust regularity effects might also be complete enough to prohibit illegal errors. Less complete representations will not only produce weaker regularity effects, they will also be unable to keep errors legal.

CORRELATIONS WITH SPEECH MEASURES

To gauge the relationship between speech skills and spelling constraints we computed correlations between speech or hearing abilities and the tendency to avoid illegal errors.

Method

Measures of speech understanding and speech intelligibility were taken from audiology records provided by Gallaudet. These ratings provide a gross measure of which students have better facility with the surface form of the language, and in previous studies the same ratings have been correlated with other linguistic measures (e.g., Hanson, 1986). Speech understanding was rated by an audiologist who answered two questions: "Rate the student's ability to understand the conversation of his hearing friends and relatives when they use speech alone (no signs or gestures)" and "Rate the student's ability to understand the conversation of the general public when only speech is used (no signs or gestures)". Answers were given on a 5-point scale: (1) very well, (2) well, (3) fair, (4) poor, and (5) not at all (a good understanding of speech corresponds to low ratings). Speech intelligibility measures were based on the same 5-point scale, but used two different questions: "How well do the student's hearing friends and relatives understand his speech?" and "How well does the general public understand the student's speech?" Ratings were available for 20 of the students we tested. The highest rating from among the two questions was used, in order to reflect the contrasts the student was able to represent, even if a familiar context (friends and relatives) was necessary for the contrasts to be understandable.

Results and discussion

The correlation between the proportion of orthographically legal errors and speech intelligibility ratings was low and nonsignificant ($r^2 = 0.3\%$; $p < .8$), as was the correlation with speech understanding ($r^2 = 5.0\%$; $p < .3$). There was no indication that facility with speech was related to the spelling constraints we have observed. These results have two consequences. First, when put alongside the documented difficulty that deaf students have mastering articulation, our results make it very unlikely that peripheral mechanisms for speech could be the basis for syllable structure in the deaf. Second, they give no hint that translation from speech is involved in avoiding orthographically illegal errors. Our result is at odds with that of Hanson (1986), who found a correlation between speech skills and the ability to report letters from briefly presented legal and illegal letter strings. Even her poor speakers, however, were influenced by the legality of the strings, so these results may be less contradictory than they seem. As a caveat to our results, limited ranges in both dimensions restricted the scope for correlations. Speech ratings rarely used the endpoints of the scale, and the proportion of orthographically legal errors varied from .82 to 1.00. The limited range of the illegal proportion, however, also indicates how consistent the pattern of spelling errors was.

STRESS AND SYLLABIC COMPLEXITY

As we argued above, facility with speech may not be a particularly good index of phonological knowledge. We have also, therefore, looked at indirect measures of phonological influence. Here we compare rates of error on stressed versus unstressed syllables, and on simple versus complex syllables.

Method

Consonant deletions were compared in syllables that were stressed and unstressed, and simple and complex. Syllables were categorized as simple or complex according to their onsets and codas. If a target had a single consonant in onset or coda it was considered simple (simple syllable types included: CV,V,VC,CVC). If either the onset or coda had more than a single consonant, the target was considered complex. Deletions were expected in complex onsets or codas.

The number of deletions in each syllable type was compared to the number of opportunities for deletions in the stimuli. When counting the number of opportunities, we weighted letters according to their word position using the overall serial position curve for errors. Deaf and hearing overall deletion rates were different (deaf, 1%; hearing, 0.7%). As a result, deletion rates for individual syllable types cannot be compared directly. To facilitate comparison, we report results as a proportion of the overall deletion rate. Values above 1 indicate that a larger than average number of deletions were made (e.g., if hearing spellers delete complex onsets 1.4% of the time, this is twice the overall deletion rate of 0.7% and is reported as 2). Values lower than 1 indicate that a smaller than average number of deletions were made. Log-linear analyses of raw counts were used to evaluate statistical significance.

Results

Deaf consonant deletion errors were affected by complexity but not stress (Figure 2). The rate of error on simple syllables was lower than the rate of error on complex syllables (complexity, proportion of the average deletion rate, simple 0.90, complex 1.33, likelihood ratio χ^2 change = 15.3, $p < .001$). There were no other significant effects (stress, stressed 0.87, unstressed 1.09, likelihood ratio χ^2 change = 0.8, $p < .38$; Complexity × Stress, likelihood ratio χ^2 change = 0.04, $p < .84$). Hearing results also showed a main effect of complexity, but no main effect of stress or interaction (complexity, simple 0.83, complex 1.61, likelihood ratio χ^2 change = 20.8, $p < .001$; stress, stressed 0.92, unstressed 1.06, likelihood ratio χ^2 change = 1.1, $p < .29$; Complexity × Stress, likelihood ratio χ^2 change = 2.6, $p < .11$).

We also looked at where deletions occurred. We compared deletions of interior consonants (those closest to the vowel, e.g., the "r" in *brass* and the "n" in *sent*) to deletions of exterior

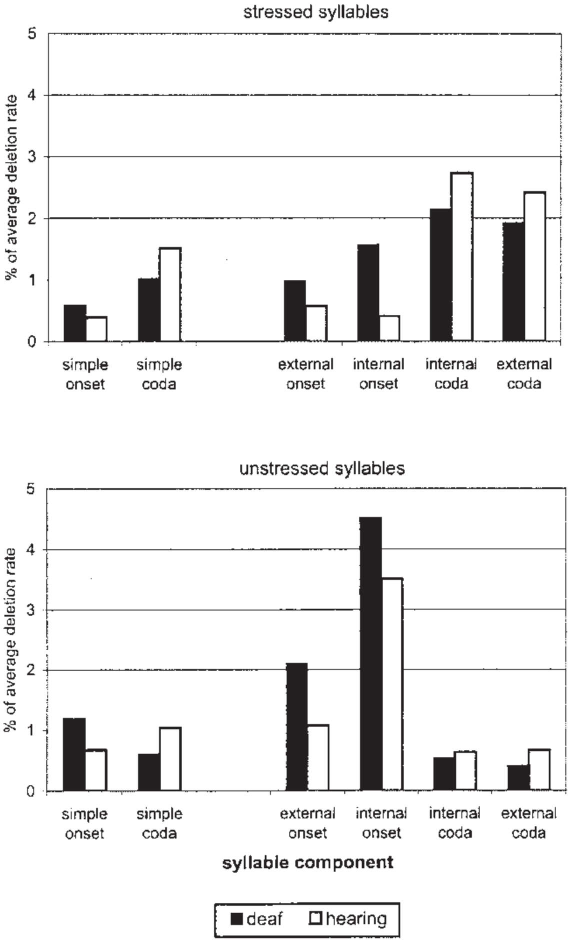

Figure 2. Deletion rates for consonants in different syllabic positions of stressed and unstressed syllables. Rates are expressed as a proportion of the average deletion rate.

consonants (e.g., the "b" in *brass* and the "t" in *sent*). In onset, deaf spellers deleted more interior than exterior consonants (proportion of the average deletion rate, 2.58 vs. 1.43, likelihood ratio χ^2 change = 5.2, $p < .02$) There was no main effect of stress or interaction (stressed 1.66, unstressed 2.09, likelihood ratio χ^2 change = 1.8, $p < .18$; Cluster Position × Stress, likelihood ratio χ^2 change = 2.2, $p < .14$). Hearing spellers show a more complex pattern in which syllabic position interacts with stress (likelihood ratio χ^2 change = 18.3, $p < .001$). In stressed syllables, internal and external consonants do not differ: external 0.52, internal 0.26, $\chi^2(1, N = 5574) = 2.3$, $p < .13$. In unstressed syllables there is a large difference in the expected direction: external 0.45, internal 1.93, $\chi^2(1, N = 5665) = 32.3$, $p < .001$.

In coda, deaf spellers deleted external and internal coda consonants at the same rate, and codas were unaffected by stress (syllable position, exterior 1.00, interior 1.22, likelihood ratio χ^2 change = 0.3, $p < .55$; stress, stressed 1.34, unstressed 0.75, likelihood ratio χ^2 change = 2.0, $p < .16$; Syllable Position × Stress, likelihood ratio χ^2 change = 0.07, $p < .79$). Hearing spellers deleted codas more often in stressed than in unstressed syllables (1.66 vs. 1.02, likelihood ratio χ^2 change = 4.55, $p < .03$), but there was no effect of internal/external position and no interaction (syllable position, external 1.33, internal 1.50, likelihood ratio χ^2 change = 0.3, $p < .59$; Syllable Position × Stress, likelihood ratio χ^2 change = 0.2, $p < .62$. The coda results are based on relatively few errors from a relatively small number of words, so they need to be interpreted with caution.

Discussion

Deaf and hearing spellers showed similar effects of stress and complexity. Complexity influenced both deaf and hearing spellers, but stress influenced neither. This does not support a speech-based account of the spelling pattern, which predicts a difference between deaf and hearing spellers.

Deaf students systematically deleted interior consonants in onset clusters. Interior consonants could be harder to lipread, and taken alone, the deaf pattern might suggest that visibility underlies legal and implausible errors. Hearing results, however, do not support this interpretation. Hearing students cannot be said to delete interior consonants because they are less perceptible, yet hearing students also made more errors on interior consonants in unstressed syllables (the tendency to delete interior consonants in onset did not differ between deaf and hearing participants, likelihood ratio χ^2 change for the interaction = 0.001, $p < .97$). Other hearing results from the literature support this interpretation. Studies of French and English children learning to spell have reported that interior consonants were deleted in onset more often than exterior consonants (Sprenger-Charolles & Siegel, 1997; Treiman, 1991). In the English study, perceptibility could not have been the source of the problem since the children correctly repeated the words before spelling them (Treiman, 1991). Given the hearing result, perceptibility is not required to account for the deaf pattern. As with other results we have reported, in fact, the influence of stress and complexity are remarkably similar in the deaf and hearing data given the differences in how these students perceive speech. This is not predicted if deaf spelling is underpinned by speech, but it is consistent with a pattern driven by properties of abstract representations.

PHONEME-TO-GRAPHEME REGULARITY

Another indirect measure of phonological influence is sensitivity to the regularity of phoneme-to-grapheme mappings (Burden & Campbell, 1994; Chen, 1976; Corcoran, 1966; Dodd, 1980; Gates & Chase, 1926; Hanson, Shankweiler, & Fischer, 1983; Leybaert, 1993; Leybaert & Alegria, 1995; Locke, 1978; Merrills, Underwood, & Wood, 1994; Sutcliffe et al., 1999; Waters & Doehring, 1990). Words with irregular phoneme-to-grapheme mappings are difficult to spell correctly, but not because the letter sequences are difficult (e.g., the *i* in *pint* is not part of an unusual letter pattern). Nor are they phonologically difficult (the /aɪ/ from /paɪnt/ is not part of an unusual phonological pattern). What makes these spellings difficult is the mismatch between spelling and sound (*i* rarely spells /aɪ/), and this requires a phonological representation. In fact, whether a mismatch between spelling and sound is evident depends on how complete the phonological representations are.

For example, *yacht* is an unusual spelling because *ch* usually spells /ʧ/ but the coda of *yacht* is pronounced /t/, not /ʧt/. If you can see the tongue move to the alveolar ridge at the end of *yacht* you have some phonological information about the word, but not enough to know that *yacht* is irregular, since this gesture is consistent with both /ʧt/ and /t/. To know that *yacht* is irregular you need to know that there is no affricate in the coda. Sensitivity to phoneme–grapheme regularity provides a rough index to the completeness of phonological representations. As phonological representations become more complete, sensitivity to the regularity of phoneme-to-grapheme mappings will increase.

As phonological representations become more complete, they not only support stronger phoneme–grapheme regularity effects, but they are also more able to keep spellings legal. For example, if the only information about the coda of *halt* is that the tongue goes to the alveolar ridge, this does not prevent illegal spellings. Spellings consistent with an alveolar place of articulation include the illegal *tl* as well as the legal *lt*. In other words, the strength of phoneme–grapheme regularity effects and speech-based constraints on illegal sequences should increase together. Conversely, weak phoneme–grapheme regularity effects will indicate that phonological representations are not complete enough to translate only into legal letter sequences.

When we divided our corpus and looked at the words with the most regular and the least regular spellings, deaf spellers showed no tendency to make more errors on words that had irregular phoneme-to-grapheme mappings. There were 225 errors on the third of the stimuli that were *least* regular, and 259 errors on the third of the stimuli that were *most* regular: $\chi^2(1, N = 484) = 2.2$, $p > .05$. The frequency of the regular and irregular targets did not differ (average frequency of irregular words involved in errors = 53.73, $SD = 226.27$; average frequency of regular words involved in errors = 43.76, $SD = 164.44$; $t = 0.0356$, $p > .05$). There was no reason to believe that an effect of regularity was obscured by an influence of frequency.

Hearing students, instead, were strongly influenced by phoneme-to-grapheme regularity. There were 807 errors on the *least* regular words, and 572 errors on the *most* regular words: $\chi^2(1, N = 1379) = 39.7$, $p < .01$. The regular words that were involved in errors were slightly less frequent, on average, than the irregular words (average frequency of 49 vs. 59), so frequency could not have produced the difference between regular and irregular words.

If speech representations influence spellings, we can make a more specific prediction: errors should occur at the places where phoneme-to-grapheme mappings are unusual, not just anywhere in words with unusual mappings. For example, errors should occur on the *cht* of *yacht*, but not on the *y* if the error results from unusual phoneme–grapheme correspondences. Examining the locations with unusual phoneme–grapheme mappings could provide a more sensitive measure of phonological influence.

We have already shown that letter frequency influences where errors occur. To measure the influence of phoneme–grapheme regularity, then, frequency and regularity must be examined together. If frequency is the more important variable, there should be more errors on low-frequency sequences than on high-frequency sequences, regardless of their regularity. If regularity is important, more errors will be found on irregular, compared to regular sequences, regardless of their frequency.

We expect to find effects of phoneme–grapheme regularity when we analyse phonologically plausible errors since, by definition, these errors are influenced by speech. What is crucial is the evidence from implausible errors. If speech representations constrain these errors (and this is why they are legal), we should find regularity effects comparable to those found for the plausible errors when we analyse implausible errors. The alternative, that the deaf implausible errors are constrained by abstract syllables, predicts a different outcome. Phonologically plausible and implausible errors should behave differently, but deaf and hearing patterns should be similar *within* each class of error. Crucially, neither the deaf nor the hearing should show robust regularity effects when we analyse implausible errors. This will strengthen our findings suggesting, so far, that speech is not responsible for keeping these errors legal.

Method

Spellings with single unambiguous errors were used for this analysis. We analysed deletions, shifts, substitutions, and transpositions. Each error location was categorized as involving either a high- or a low-frequency letter sequence and involving either a regular or an irregular phoneme-to-grapheme correspondence. Regularity was categorized by calculating the mean phoneme-to-grapheme conversion probability for all mappings in the corpus (68%, *SD* = 34; see the description of the spelling stimuli for the method used to calculate regularity). An arbitrary cut-off of one standard deviation below the mean was used to separate relatively unusual phoneme-to-grapheme correspondences (those with a probability of 34% or less) from more common mappings.

We measured frequency using the type frequency of trigrams that was specific to word position in words of a single length. There had consistently been more errors, across error types, where this measure was low. The lowest frequency locations in each word were identified in the same way as in our previous analysis of letter frequency: The minimum trigram in each word was marked, and an arbitrary margin of 1/8 of the standard deviation of all trigrams in words and errors was used to mark other locations that were not the minimum, but were still relatively low frequency. We counted the number of errors in each frequency by regularity category and compared this to the opportunities for error. Opportunities for error were adjusted by the serial position probability of error. The influence of frequency and regularity was assessed using log-linear analysis.

Results

Results are presented in Figure 3. Where regularity dominates the pattern, the bars on the right side of the graph are large compared to those on the left. Where frequency dominates, black bars are large compared to white bars. Phonologically plausible errors were dominated

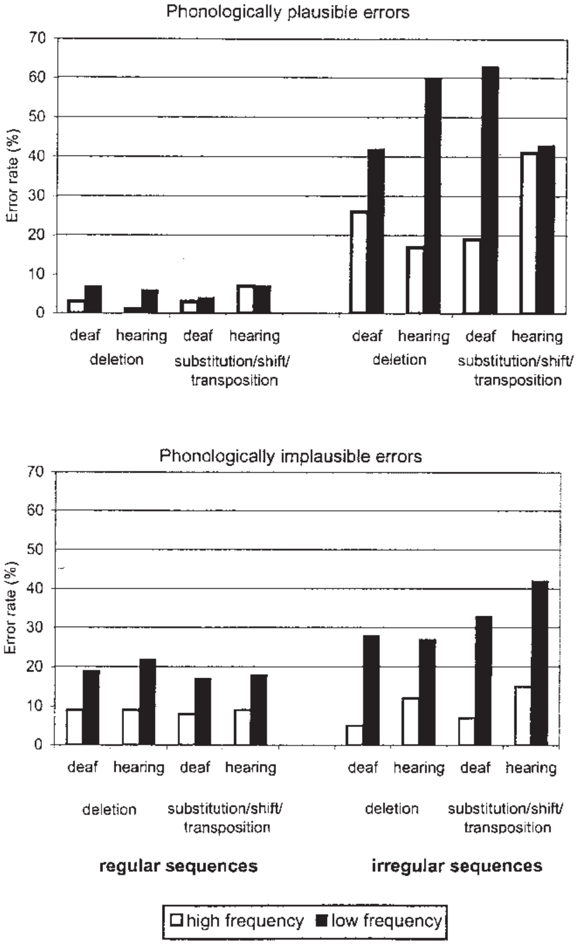

Figure 3. Error rates on locations of high/low letter frequency and high/low phoneme-to-grapheme regularity.

by phoneme–grapheme regularity. The deaf and hearing both made relatively modest numbers of errors on regular sequences regardless of their frequency. Irregular sequences were much more error-prone. Hearing shifts, substitutions, and transpositions were affected only by regularity. Hearing deletions showed effects of both frequency and regularity. There were no interactions. Deletions: frequency, likelihood ratio χ^2 change = 329.5, $p < .001$; regularity, likelihood ratio χ^2 change = 779.6, $p < .001$; Frequency × Regularity, likelihood ratio χ^2 change = 2.4, $p < .12$. Substitutions, shifts, and transpositions: regularity, likelihood ratio χ^2 change = 516.1, $p < .001$; frequency, likelihood ratio χ^2 change = 0.3, $p < .57$; Frequency × Regularity, likelihood ratio χ^2 change = 0.04, $p < .85$. The number of deaf phonologically plausible errors is relatively small, so our conclusions should be somewhat cautious; however, regularity effects were very much in evidence. Frequency plays a smaller, but still significant role. Deletions: regularity, likelihood ratio χ^2 change = 42.1, $p < .001$; frequency, likelihood ratio χ^2 change = 7.0, $p < .008$. Substitutions, shifts, and transpositions: regularity, likelihood ratio χ^2 change = 53.7, $p < .001$; frequency, likelihood ratio χ^2 change = 11.8, $p < .001$.

Frequency was the dominant influence on phonologically implausible errors in both the deaf and the hearing. In contrast to the pattern for plausible errors, implausible errors concentrated on low-frequency letter sequences regardless of their regularity (black bars in Figure 3). There were some interactions with regularity, but regularity is clearly modifying a stronger influence of frequency, whereas plausible errors showed the opposite pattern. For example, deaf deletions showed an interaction with regularity (likelihood ratio χ^2 change = 5.2, $p < .02$). Irregular sequences lead to more errors than regular sequences when both were low frequency, but fewer errors when regular and irregular sequences were high frequency. Collapsing over regularity gave a strong frequency effect (likelihood ratio χ^2 change = 31.3, $p < .001$), but collapsing over frequency did not give a regularity effect (likelihood ratio χ^2 change = 0.1, $p < .75$). The big increase in substitution, shift, and transposition errors also occurs between high- and low-frequency sequences (likelihood ratio χ^2 change = 35.2, $p < .001$). There was an interaction with regularity (likelihood ratio χ^2 change = 4.5, $p < .03$). Regularity affected low- but not high-frequency sequences: regularity effect for high-frequency sequences; $\chi^2(1, N = 515) = 0.01$, $p < .9$; regularity effect for low-frequency sequences, $\chi^2(1, N = 476) = 13.9$, $p < .001$.

Hearing implausible errors, like the deaf errors, were dominated by frequency. Deletions were only influenced by frequency. Substitutions, shifts, and transpositions showed effects of both factors. There were no interactions. Deletions: frequency, likelihood ratio χ^2 change = 39.3, $p < .001$; regularity, likelihood ratio χ^2 change = 2.5, $p < .11$; Frequency × Regularity, likelihood ratio χ^2 change = 0.11, $p < .74$. Shifts, substitutions, and transpositions: frequency, likelihood ratio χ^2 change = 24.3, $p < .001$; regularity, likelihood ratio χ^2 change = 20.4, $p < .001$; Frequency × Regularity, likelihood ratio χ^2 change = 2.0, $p < .16$.

Discussion

The pattern of regularity effects we found does not support speech as a robust source of constraint on deaf spelling errors. Deaf students showed no overall tendency to make more errors on irregular words. Even when we looked in more detail at the locations where errors occurred, implausible errors showed little influence of speech. This was clear in the comparison between plausible and implausible errors. Plausible errors, by definition, are driven by the relationship between spelling and sound. These errors showed large regularity effects. Even in the small number of phonologically plausible errors that deaf students made, the influence of regularity was clear. Plausible errors set the benchmark for comparison with implausible errors. Implausible errors, however, showed a contrasting pattern. Letter frequency was most important, and any effects of regularity were much weaker.

As in previous analyses, the pattern in the deaf and hearing is strikingly similar. However, separating plausible and implausible errors masks the major difference between groups. Hearing students make mostly phonologically plausible errors, and these are controlled by mapping between sounds and letters, but deaf students make mostly phonologically implausible errors, and these are not controlled by speech. What is interesting, instead, is that hearing implausible errors are like the deaf errors. Perhaps it is unsurprising that "slips of the pen" are not controlled by speech. More surprisingly, however, these errors also remain orthographically legal. Hearing spellings, in other words, provide additional evidence that abstract syllables organize orthographic representations.

GENERAL DISCUSSION

We have investigated deaf students' spelling to see how limited experience with the sound system of English affects their orthographic representations. We found a striking lack of orthographically illegal sequences in their errors. In particular, there were fewer illegal errors than would have been predicted by the number and types of errors made, and the positions where they occurred. Syllables provide the grammar that keeps sequences legal. The spelling errors show that syllabic principles are part of the system responsible for orthographic representations.

Finding evidence of syllables in spelling predicts that other orthographic tasks will also be sensitive to syllable structure. This is exactly what we found in a reading experiment (Olson & Nickerson, 2001). The same students were asked to judge the colour of letters in briefly presented words. They were influenced by syllable boundaries, but not by letter frequency. Consistent with the spelling pattern, there was no correlation between the strength of the syllable effects and the students' speech skills. These results provide support for the syllabic account from different materials, a different task, and another orthographic domain.

Sensitivity to common letter patterns failed to explain deaf data from either spelling or reading. If frequency normally shapes the orthographic system, as has sometimes been suggested (e.g., Seidenberg, 1987; Seidenberg & McClelland, 1989), this should be especially evident in the deaf, since they can choose letter patterns with less regard for how they are pronounced. Letter frequency played a role in where deaf spelling errors occurred, but frequency could not explain why misspellings remained orthographically legal. Frequency also failed to explain the reading data. The failure of a frequency account here, taken with the lack of support for it in the hearing data (e.g., Rapp, 1992), suggests that frequency does not substitute for abstract structure under any circumstances.

We also examined direct and indirect measures of influence derived from spoken language (lip-reading, residual hearing, or residual speech). If deaf spellings could translate incomplete representations of speech, systematic gaps might allow phonologically implausible errors without giving scope for illegal errors. Correlations with speech abilities, analyses of stress, syllabic complexity, and phoneme-to-grapheme regularity all failed to clearly support an account based on speech. In addition, deaf students did not all make the same spelling errors. For example, *detective* was spelled *dectentive*, *dectictive, decetive, dective, delivatine, detecive, detervice, decetives*. Clearly, the spelling of the second and third syllables is not guided by an impoverished phonological form that nonetheless substantially restricts the spellings that are consistent with it. If the sections of words that are spelled very differently remain orthographically legal, it cannot be because of phonological information. Finally, mechanisms of speech production are an unlikely source of linguistic structure since it is well established that they are difficult for profoundly deaf students to master. Taken together, these results make it unlikely that the constraints we have observed in spelling originated in physical mechanisms devoted to speech.

We do not claim that these students have no knowledge of phonological distinctions, just that it is not commensurate to explain the paucity of illegal spellings. In addition, if it turned out that some abstract phonological distinctions play a role in the kind of pattern we have reported, this would not fundamentally change our conclusions. What is surprising is that with limited experience of peripheral productive and receptive mechanisms devoted to speech, deaf students still organize written material in terms of syllables.

Our results do not imply whether hearers have one set of principles that governs both written and spoken language or two sets that independently govern orthographic and phonological representations. Deciding this issue is beyond the scope of the current paper. What is clear, however, is that syllabic structure can be relatively independent of the peripheral systems devoted to speech. Assuming that deafness does not create whole systems of linguistic representation that do not exist in the mind of hearers, it follows that the structure governing hearing orthographic representations could be relatively independent of peripheral phonological systems as well (see also Badecker, 1996; Caramazza & Miceli, 1990; Prinzmetal et al., 1986, 1991; Rapp, 1992).

The hypothesis that abstract syllables govern both deaf and hearing spellings predicts similarity between the error patterns despite the obvious differences in their superficial characteristics. This is what we found. Spelling patterns were similar when analysed at a suitable level of abstraction. Although we have concentrated on the comparison between deaf and hearing data, the fact that hearing phonologically implausible errors remained orthographically legal is a substantive result from this point of view.

We noted in the Method section that the reading age of our hearing controls was slightly higher than that of the deaf students. Since both populations showed similar patterns in our analyses, however, nothing in our results or conclusions hinges on the difference in reading age. It is unlikely that hearing controls with slightly lower reading ages would produce vastly different numbers of illegal errors or implausible errors, or show much weaker regularity effects. More important, it is unclear how any hypothesis connected to the reading age of the hearing controls could change the conclusions we derive from the deaf data.

An alternative source of spelling structure suggested by Hanson et al. (1983) was finger-spelling. There is "coarticulation" in finger-spelling, such that some patterns will feel awkward on the hand. However, finger-spelling, by itself, can explain the results only if irregular patterns are awkward because they involve *motorically* difficult movements, rather than linguistically illegal ones. Nothing obvious in the manual alphabet would make illegal sequences motorically more difficult. Both finger-spelled and printed words provide information about how letters are distributed in the English vocabulary. A contribution from fingerspelling would not change the interpretation we propose. Fingerspelling tasks, in fact, could provide an interesting additional source of evidence regarding the abstractness of syllabic principles.

Our study is based on the errors made by a particular group of deaf students. The heterogeneity of the deaf population prevents us from expecting the same pattern to characterize all deaf spellers. Students with a stronger oral background, for example, may make more errors derived from speech. Students with less experience of the written language may make larger numbers of illegal errors. Gallaudet students, however, are ideal for testing the hypothesis we have advanced. They have good language skills, are less oriented toward the speaking world, and constitute a sample from the upper end of the academic spectrum. In other words, they have good orthographic knowledge, but without the experience of speech that someone committed to oral communication may have. As such, they demonstrate how linguistic knowledge *can* be organized despite an altered experience of the spoken modality. Within this sample there was not a great deal of variability in the extent to which individuals were constrained by orthographic regularity. These results do not, however, indicate that linguistic knowledge *must* always be organized in this way. The generality of the pattern, and how and where it appears in the deaf population as a whole, in fact, would reveal the conditions required to support suprasegmental structure and would be a theoretically useful contribution to data on the acquisition or triggering of linguistic representations.

This brings us to the question of how syllable structure could be acquired. This question is not only a question for the deaf, however, because we could equally ask how language-specific syllable structure is acquired in general and then ask whether the task is any different for the deaf. Acquiring the right syllable inventory would obviously be different for the deaf and hearing if syllables could only be structured through the experience of speech. Vowels might be identified because they do not obstruct the vocal tract. They would provide the syllabic nuclei. Consonants make some kind of obstruction and are systematically arranged around the vowels. The alternating opening and closing of the articulators associated with vowels and consonants might provide a rough guide to syllable units. However, while this outline has intuitive appeal, the details of the relationship between syllable structure and sound are not this simple, and the account leaves important gaps. Diphthongs, glides, triphthongs (e.g., Anderson, 1974, p. 255), hiatuses, and syllabic consonants make it clear that distinguishing vowels from nonvowels in speech is not the same as syllable structure. Each vowel does not form a syllabic nucleus, and sometimes there is no vowel at all in the nucleus. More important, making no distinctions among consonants fails to account for the systematic way in which consonants appear internally and externally in clusters. Separating vowels from consonants based on how they are produced is clearly not enough. A more systematic account that results in the rules of combination must be provided.

A second approach assumes that some universal principles governing syllables are innate. Language-specific structure is set using distributional properties of the input. The innate principles include the requirement that segments be assigned a fixed position on a continuum between obstruents and vowels (i.e., given a sonority value). The continuum defines the syllable. Segments must increase in sonority before the nucleus and decrease after. The continuum also defines a metric of syllabic complexity. More complex syllables have larger numbers of segments leading to their peak or larger numbers following it. Each language picks a level of complexity that it allows. Universals stipulate that if clusters of a particular level are allowed (e.g., CCCV) then all simpler clusters will also be allowed (e.g., CCV, CV). Acquisition involves assigning segments to the sonority scale (if necessary) and setting the level of complexity allowed by the language environment (for further discussion, see Clements, 1990). In spoken language, there are several ways that a segment's sonority can be determined. Sonority can be defined by relationships among phonological features (Clements, 1990). It may also have a phonetic basis. Given the universal principles, however, the distribution of segments in the vocabulary also gives information about the position of segments along the sonority continuum.

If this is roughly the correct outline, much of the acquisition machinery may not be seriously affected by deafness. Once the relationships among segments have been established, choosing a level of complexity is the same whether the input is sounds or letters. The question boils down to whether establishing relationships among segments (among more or less sonorous sounds in the hearing, or among letters in the deaf) requires acoustic or articulatory information, or whether these relationships can be derived from distributional properties of the vocabulary (in the hearing articulatory/acoustic properties and distributional information could converge; in the deaf distributional properties would be the only source).

We outline how a universal scale of complexity and the distributional properties of the vocabulary could be sufficient to derive the segmental relationships that are important for the syllabic grammar, even among units that have no sound content like letters. In this context, interestingly, frequency may play a role. According to the complexity hierarchy, simple syllables should be more common than complex syllables. In fact, 65% of the three letter words in the CELEX English corpus (Baayen et al., 1995) are CVC syllables. The most frequent letters appearing in position 2 of three-letter words provide the syllabic nuclei (of course, vowel letters could also be acquired or reinforced by explicit reading instruction). With syllabic nuclei available, word-initial and word-final consonants and consonant clusters can be identified. The universal profile of the syllable tells the learner that the interior consonants of clusters are more sonorous (ordered closer to vowels) than the exterior consonants. Noting which consonants appear internally and externally in clusters defines the classes of consonants that participate in the rules for legal onsets or codas (e.g., liquids appear inside obstruents in onset but not vice versa). Grapheme clusters that correspond to a single sound behave differently (e.g., *ch*), but they can be identified because they appear in both onset and coda, without reversing their order as sonority demands (e.g., *blub* and *bulb* vs. *chop* and *poach*). Allowable word-internal onsets and codas are a subset of word-initial onsets and word-final codas. Certainly there are many details of this process to be filled in. However, this brief sketch shows that the kind of syllable structure we hypothesize can be acquired by the deaf, that the process of using distributional information would be largely the same for letters and phonemes, and that deaf acquisition may have certain important characteristics in common with hearing acquisition (even if some sources of information are absent).

This does not mean that deaf and hearing acquisition will proceed at the same pace or succeed to the same extent. Deaf students will almost certainly be behind their hearing counterparts just on the basis of their exposure to English and the age at which this occurs. Hearing students will have complete representations of spoken and written language and their relationships, and deaf students will not. There may, however, be more subtle and theoretically interesting differences. Given the very able population we have studied, our results speak to what is possible, not what is inevitable. We have already noted that understanding the differences between deaf and hearing acquisition of orthographic structure will contribute to our understanding of the more general conditions under which structured representations develop.

In sum, these results show that our deaf students' spelling is governed by a syllabic grammar that is not derived from the mechanisms of speech perception or production. This grammar is a property of linguistic representation and not an artifact of statistical patterns in the orthographic environment. It probably reflects the form that representations are obliged to take at the abstract level where segments are organized into words. Orthographic information by itself or in combination with limited abstract phonological information is sufficient for syllabic principles to apply at this level.

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