A Treatment Sequence for Phonological Alexia/Agraphia

Pélagie M. Beeson
Kindle Rising
Esther S. Kim
University of Arizona, Tucson

Steven Z. Rapcsak
University of Arizona, Tucson, and Southern Arizona VA Health Care System, Tucson

Purpose: Damage to left perisylvian cortex often results in impaired phonological processing abilities with written language profiles consistent with phonological alexia and phonological agraphia. The purpose of this article was to examine a behavioral treatment sequence for such individuals intended to strengthen phonological processing and links between phonology and orthography, as well as train a means to maximize use of residual orthographic and phonological knowledge for spelling.
Method: Two women with persistent impairments of written language and phonological processing following damage to left perisylvian cortical regions participated in this study. Both exhibited characteristic features of phonological alexia and agraphia in that reading and spelling performance for real words was better preserved than nonwords (lexicality effect). A 2-stage treatment protocol was administered to strengthen sublexical skills (phonological treatment) and to train interactive use of lexical and sublexical information to maximize spelling performance (interactive treatment).
Results: Both participants improved phonological processing abilities and reading/spelling via the sublexical route. They also improved spelling of real words and were able to detect and correct most residual errors using an electronic spelling aid.
Conclusions: Behavioral treatment served to strengthen phonological skills supporting reading and spelling, and provided a functional compensatory strategy to overcome residual weaknesses.

KEY WORDS: aphasia, dyslexia, dysgraphia, rehabilitation, stroke

Phonological alexia and phonological agraphia are impairments of written language processing characterized by disproportionate difficulty in reading and spelling nonwords relative to real words (Beauvois & Dérouesné, 1979; Coltheart, 1996; Roeltgen, Sevush, & Heilman, 1983; Shallice, 1981). There is compelling evidence to suggest that the underlying cause of these two syndromes is a common impairment of phonological processing ability that is not specific to written language (Crisp & Lambon Ralph, 2006; Fiez, Tranel, Seager-Frerichs, & Damasio, 2006; Patterson & Marcel, 1992; Rapcsak et al., 2009). The phonological impairment is evident on tasks that require segmentation and manipulation of sounds without reference to orthography, as well as those that require grapheme–phoneme conversion for reading (Crisp & Lambon Ralph, 2006; Fiez et al., 2006; Patterson & Marcel, 1992; Rapcsak et al., 2009) and phoneme–grapheme conversion for spelling (Rapcsak et al., 2009). These impairments are associated with damage to left perisylvian cortical regions and are common following left-middle cerebral artery stroke (Fiez et al., 2006; Henry, Beeson, Stark, & Rapcsak, 2007; Rapcsak et al., 2009).

Although the lexicality effect (i.e., better real-word than nonword performance) is the hallmark feature of phonological alexia and agraphia, performance on real words is typically impaired as well. A review of individual case reports and group studies indicates that most individuals with phonological alexia have at least a mild impairment in reading real words (Berndt, Haendiges, Mitchum, & Wayland, 1996; Crisp & Lambon Ralph, 2006; Fiez et al., 2006; Rapcsak et al., 2009). For example, the average real-word reading accuracy calculated from the data reported in two recent group studies of phonological alexia was 89% (Fiez et al., 2006; $n = 11$) and 61% (Crisp & Lambon Ralph, 2006; $n = 12$). Similarly, real-word spelling performance is typically impaired in individuals with phonological agraphia, and to a greater extent than real-word reading. A direct comparison of reading and spelling in phonological alexia/agraphia was provided in a recent study by Rapcsak and colleagues (2009), who examined a large group of individuals with left perisylvian damage ($n = 31$). In the context of significant impairment to nonword reading and spelling, the overall accuracy for spelling real words was 48% compared with 73% for reading the same words. Taken together, these findings are consistent with the clinical observation that most individuals with aphasia due to left-middle cerebral artery stroke have a functional deficit in written language processing, with spelling typically more impaired than reading.

With regard to rehabilitation, several researchers have demonstrated that phonological processing abilities for reading and spelling can be improved to some extent with behavioral treatment. A number of single-participant and small-group studies focused on retraining individual sound–letter (or letter–sound) correspondences with positive results (e.g., Cardell & Chenery, 1999; Carlomagno, Iavarone, & Colombo, 1994; Carlomagno & Parlato, 1989; Greenwald, 2004; Hillis & Caramazza, 1994; Hillis Trupe, 1986; Luzzatti, Colombo, Frustaci, & Vitolo, 2000). Such training often involves the use of "key words" associated with individual phonemes in the language that serve to cue the production of sounds and letters for more difficult words. Although the self-cuing approach can be somewhat laborious, its value has been documented in a number of individuals and across several languages (see, e.g., Carlomagno & Parlato, 1989, for Italian; de Partz, 1986, for French; Hillis Trupe, 1986, for English). Other treatment studies have also included training of sublexical skills, such as phonological awareness, segmentation, manipulation, and blending of sounds, in words or nonwords to improve reading (Friedman & Nitzberg Lott, 2002; Kendall, Conway, Rosenbek, & Gonzalez-Rothi, 2003; Yampolsky & Waters, 2002) or spelling (Cardell & Chenery, 1999; Carlomagno, Pandolfi, Labruna, Colombo, & Razzano, 2001; Conway et al., 1998; Luzzatti et al., 2000; Schechter, Bar-Israel, Ben-Nun, & Bergman, 1985). Overall, these studies have demonstrated positive outcomes of phonological treatment for written language impairments; however, residual difficulties are reported in nearly all cases.

One reason that improved phonological ability fails to fully resolve reading and spelling errors is the fact that most languages do not have completely transparent phonology–orthography relations, and English is certainly among the less transparent (Venezky, 1999). Therefore, improved sublexical reading and spelling skills will not yield successful processing of all written words; accurate performance requires input from lexical orthography. As conceptualized in a dual-route model of written language processing, lexical and sublexical systems interact in a manner that can either reinforce or compete for activation of the appropriate target (Houghton & Zorzi, 2003).[1] Evidence of interaction and integration of lexical and sublexical information is provided in several carefully described cases of acquired agraphia (Folk, Rapp, & Goldrick, 2002; Hillis & Caramazza, 1991, 1995; Rapp, Epstein, & Tainturier, 2002). Rapp and colleagues demonstrated that error responses from their patient (L.A.T.) combined output from both lexical and sublexical spelling routes (Rapp et al., 2002). For example, L.A.T.'s spelling of *bouquet* as *bouket* combined a sublexical (phonological) spelling approach (*k* for *qu*) with the inclusion of a low-frequency phoneme–grapheme mapping (*et* for /e/) derived from the lexical word form. An earlier case (J.J.) reported by Hillis and Caramazza (1991, 1995) demonstrated interaction of lexical and sublexical spelling knowledge that served to decrease semantic errors on a writing-to-dictation task compared with written or spoken naming of picture stimuli. It appeared that J.J. combined output from sublexical information (i.e., sound–letter correspondences) that served to block semantic errors resulting from degraded orthographic representations. In another case (R.C.M.; Hillis, Rapp, & Caramazza, 1999), there was evidence that the interaction of lexical and sublexical information enhanced performance over the course of recovery, in that semantic spelling errors declined as sublexical skills improved. Such cases prompt consideration of the rehabilitation potential of behavioral treatments that facilitate the use of interactive processing as a means to resolve spelling errors.

In a previous study, we investigated a spelling treatment designed to promote interactive use of residual lexical and sublexical abilities in two individuals with acquired spelling impairment (Beeson, Rewega, Vail, & Rapcsak, 2000). Prior to the initiation of interactive treatment, the participants demonstrated the ability to generate phonologically plausible spellings for many of the words that they could not spell. Training included focused

[1] An alternate model of language processing based on connectionist architecture does not posit distinct lexical/sublexical processing routes, but acknowledges frequency-dependent phonological-to-orthographic translations across various units, ranging in size from single phonemes and graphemes to whole words (see Plaut McClelland, Seidenberg, & Patterson, 1996). Therefore, the potential for lexical and sublexical interactions exists in these models as well.

attention on self-detection and correction of spelling errors. They were trained to use an electronic spelling device to assist in self-directed attempts to resolve spelling difficulties in a problem-solving manner. Both participants improved their spelling abilities when using the device, but also improved spelling of untrained words without the device. Some of the spelling attempts provided evidence of interactive use of lexical and sublexical information in a manner similar to L.A.T. (Rapp et al., 2002) in that they contained phonologically plausible segments combined with low-frequency phoneme–grapheme mappings that were correct for the target word (e.g., *perpose* for *purpose*). Improvements following treatment appeared to reflect an increase in the detection and self-correction of such errors, suggesting a therapeutic effect of the relatively explicit training to use information from both lexical and sublexical processing to resolve spelling errors.

In the present study, we explored the application of interactive treatment as a complement to phonological treatment in two individuals with phonological alexia/agraphia. Specifically, the purpose of the current study was to examine the therapeutic effects of a two-stage treatment: phonological treatment followed by interactive treatment. The treatment sequence was intended to strengthen phonological processing abilities and the links between sounds and letters, and then promote interactive use of sublexical and residual lexical knowledge to resolve spelling errors. We predicted that this approach would result in generalized improvement of spelling for untrained words and provide a strategic means of compensation for residual spelling difficulties.

Method

Participants

Two individuals with aphasia due to left-middle cerebral artery stroke participated in this study. Participant 1 was a 76-year-old, right-handed woman with 12 years of education who was 9 years poststroke. She was retired from a career as a gift shop owner at the time of the stroke. Her spoken language profile was consistent with conduction aphasia of moderate severity on the Western Aphasia Battery (WAB; Kertesz, 1982; WAB aphasia quotient [AQ] = 76), and her performance on the Boston Naming Test (Kaplan, Goodglass, & Weintraub, 2001) revealed a significant naming impairment (31/60 correct; 2nd percentile for age according to Ivnik, Malec, Smith, Tangalos, & Petersen, 1996, normative data). Participant 1 also exhibited mild apraxia of speech that resulted in minor articulatory errors that did not significantly affect intelligibility. Participant 2 was a 43-year-old, right-handed woman with 14 years of education who was 5½ years poststroke. She had been working as a bank teller at the time of the stroke. She exhibited mild impairment of spoken language characterized by word retrieval difficulty, with a WAB AQ of 96.4 and a score of 46/60 on the Boston Naming Test (3rd–5th percentile according to Ivnik et al., 1996, normative data for closest age group, 56–62 years). Auditory digit span was markedly impaired for both participants on the Wechsler Memory Scale—Revised (Wechsler, 1987). Participant 1 was able to repeat only two-digit sequences (<2nd percentile for age), and Participant 2 was limited to three- to four-digit sequences (<3rd percentile for age). Both participants demonstrated well-preserved nonverbal cognitive function as confirmed by age- and education-appropriate performance on the Raven's Coloured Progressive Matrices (Raven, Court, & Raven, 1990).

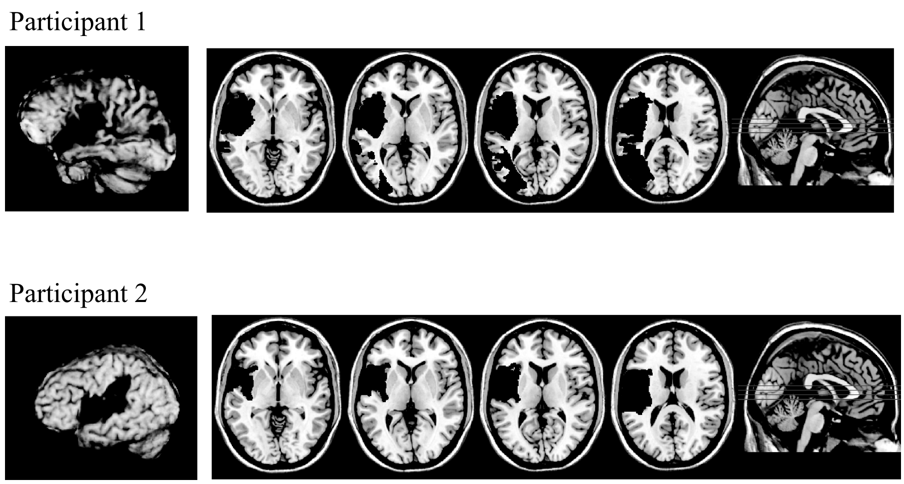
Both individuals had received previous individual and group therapy that focused primarily on spoken language abilities. Their progress had been followed for several years prior to this study in the context of clinical and research activities within the Aphasia Research Project and the Aphasia Clinic at the University of Arizona. Participant 1 showed improvement in spoken language abilities over the course of the 9 years after her stroke, improving her AQ more than 20 points. Participant 2's mild aphasia had improved by 3 to 4 points on her AQ over 4 years. Neither participant had received treatment specifically directed toward reading or spelling. Participant 1 was motivated to improve her overall language performance and also wanted to improve her spelling so that she could more easily compose written letters and e-mail messages to friends and family. Participant 2 was enrolled in community college coursework with the intention of ultimately returning to work. She was highly motivated to improve her spelling, as this residual deficit interfered with her ability to be successful in school. A pretreatment questionnaire confirmed that both participants reported average or better reading and spelling abilities prior to their strokes.

High-resolution MRI brain scans were obtained for both participants. As shown in Figure 1, there was evidence of extensive damage to left perisylvian regions in both individuals, including critical areas implicated in phonological processing: Broca's area, supramarginal gyrus, and Wernicke's area. Participant 1's overall lesion size was larger than Participant 2, and she had more extensive damage to anterior perisylvian cortex.

Pretreatment Assessment

Prior to a comprehensive language evaluation, audiologic testing (pure-tone air-conduction thresholds) confirmed normal hearing in both participants. Pretreatment language assessment included a number of standardized measures and research tasks administered to characterize performance in the following areas: semantics,

Figure 1. Surface rendering of participants' left-hemisphere lesion and depiction of the lesion on standard axial slices.



phonological ability, phonology–orthography relations, visual–orthographic processing, allographic, and graphomotor ability. Rather than relying on a single measure to estimate the integrity of these complex cognitive and perceptual/motor skills, composite scores were calculated for each of the relevant domains by averaging the percentage of correct performance on each of several component tests (see Tables 1 and 3). Test scores were given equal weight in the derived composite score because each task sampled the construct of interest in a distinct manner. Composite scores were evaluated relative to the data obtained from a group of 31 control participants who ranged in age from 34 to 85 ($M = 63$, $SD = 11.25$) with an average of 16.29 years of education (range = 12–22).[2] Scores that were greater than two standard deviations below the mean of the control group were considered impaired.

Both participants demonstrated well-preserved semantic knowledge on four measures of semantic knowledge: the picture and written versions of the Pyramids and Palm Trees Test (Howard & Patterson, 1992) that examine knowledge of semantic relations, and the spoken-word to picture-matching and written-word to picture-matching tasks from the Psycholinguistic Assessment of Language Processing in Aphasia (PALPA Subtests 47 and 48; Kay, Lesser, & Coltheart, 1992). The semantic composite scores derived from these measures were not significantly different from the normal control group (see Tables 1 and 3).

Phonological processing abilities were examined with tasks that required identification, maintenance, and manipulation of sublexical phonology. Six tests of phonological ability that did not involve orthographic processing contributed to a phonological composite score: rhyme judgment, rhyme production, sound segmentation, phoneme deletion, sound blending, and phoneme replacement. Participant 1 was impaired on all phonological tasks, and her phonological composite score was 33.8% (see Tables 1 and 3). Participant 2 had a milder phonological impairment that was evident on the phoneme deletion and phoneme replacement tasks. Her phonological composite score was 75.4%, well below the average composite of 95.1% by the control participants. Another set of tasks that required transcoding between phonology and orthography included testing of individual sound–letter and letter–sound correspondences, as well as the ability to read and spell CVC nonwords. Participant 1 had difficulty with all of the transcoding tasks and obtained a composite score of 67.1% (see Tables 1 and 3). Participant 2 did well on single letter–sound transcoding but had some difficulty with CVC reading and spelling, lowering her composite score to 91.7%.

With regard to visual–orthographic processing of individual letters and words, both participants performed relatively well, with composite scores of 97.6% and 96.7%. They had little difficulty detecting mirror-reversed letters or matching upper- to lowercase letters but made more errors than control participants on the lexical-decision tasks. Both individuals demonstrated normal graphomotor control for the construction of letter shapes, but Participant 1 had a mild impairment of allographic

[2]Because Participant 1 had only 12 years of education, her performance was also examined relative to a subset of control participants with an average of 12.9 years of education ($n = 7$). The subtest scores that were significantly below the performance of the education-matched controls were the same as those indicated in Table 1 (based on the entire control group). In addition, when the lower educated controls were compared with the higher educated controls, there were no significant differences in the mean performance on any of the subtests.

Table 1. Pretreatment performances for Participants 1 and 2 and the mean performances and standard deviations of 31 control participants.

Behavioral measure	Possible	Participant 1	Participant 2	Controls *M*	Controls *SD*
Standardized test					
Western Aphasia Battery AQ	100	76[a]	96.4		
Boston Naming Test	60	31[a]	48[a]	56.3	2.30
Raven's Coloured Progressive Matrices	36	35	29	31.90	3.60
Composite scores from assessment battery[b]					
Semantic	100	96.8	97.9	99.0	1.02
Phonological	100	33.8[a]	75.4[a]	95.1	4.90
Phonology/orthography	100	67.1[a]	91.7[a]	98.2	0.71
Visual/orthographic	100	97.6[a]	96.7[a]	99.6	0.40
Allographic/graphomotor	100	94.9[a]	100	99.5	0.40

Note. AQ = aphasia quotient.

[a]Denotes impaired performance on standardized test or performance greater than 2 *SD*s below the mean of control participants. [b]See individual test scores in Table 3.

knowledge as indicated by some errors in case conversion (i.e., converting from lower- to uppercase, and vice versa), resulting in a composite score more than two standard deviations below that of the control group (see Tables 1 and 3).

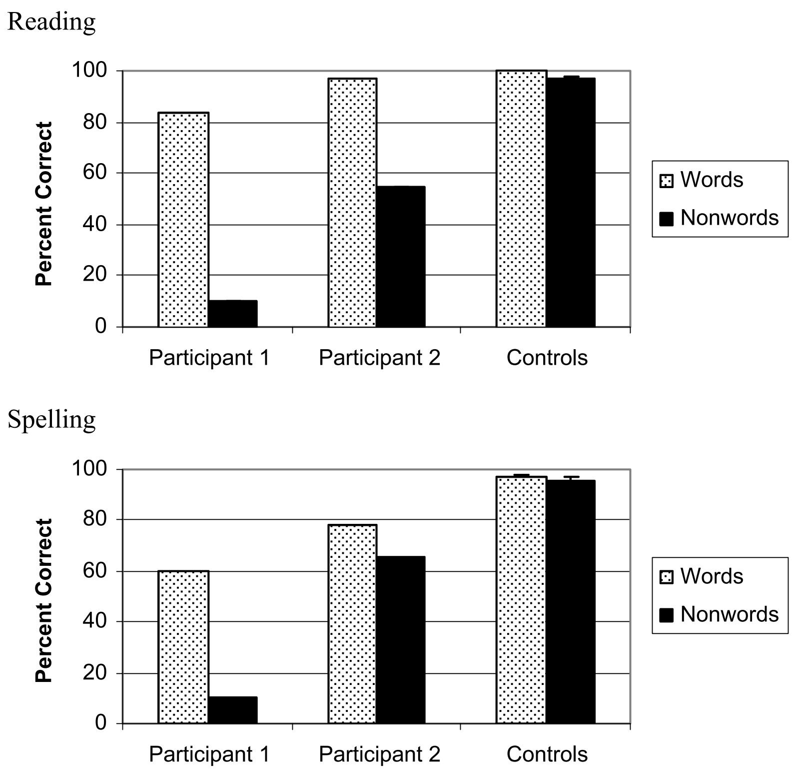
Oral reading and writing to dictation were examined using controlled lists of stimuli that included 60 words and 20 phonologically plausible nonwords that were balanced for length ($M = 5.3$ and 4.95 letters, respectively; Appendix A). Each participant's performance on the reading and spelling tasks is displayed relative to a group of 12 healthy adult control participants in Figure 2.[3] The control participants included 7 women and 5 men with an average age of 62.6 years and 15.4 years of education. In the case of Participant 1, minor articulatory errors associated with mild apraxia of speech were counted correct during oral reading. As shown in Figure 1, she demonstrated some decrement in reading and greater impairment of spelling, with significantly poorer performance on nonwords relative to real words in both modalities (Fisher's exact test, $p < .0001$), a profile consistent with phonological alexia and agraphia. Participant 2 had a milder overall impairment but also showed a significant lexicality effect for reading (Fisher's exact test, $p < .0001$). She spelled more words correctly than nonwords, but this difference was not statistically significant ($p = .18$). However, on a previous assessment of single-word reading and spelling 1 year prior, Participant 2 showed significant lexicality effects for both reading and spelling. Thus, her phonological alexia persisted, and she appeared to have evolved to a milder presentation of phonological agraphia. Both participants were significantly more impaired for spelling than reading of real words (Fisher's exact test, $p < .01$).

Error analyses were conducted on the real-word reading and spelling tasks. For reading, Participant 1 made roughly equal numbers of visual errors and phonologically implausible errors. On spelling, the majority of her errors were closely related to the orthographic target, including form-related errors (single- or multiple-letter errors) with at least half of the letters correct (33%), visually similar word errors (17%), or morphological errors (12%). She also made some phonologically plausible errors (8%), attempts with less than half of the word correct (21%), and miscellaneous errors (8%). Participant 2 made two visual errors when reading real words. On the spelling task, she made phonologically plausible errors (46%), visually similar word errors (31%), and form-related errors with at least half of the letters correct (23%). Neither participant made semantic errors on the reading or spelling tasks.

In summary, both participants demonstrated marked impairment of phonological processing skills in the face of preserved semantic knowledge. Their phonological weakness was evident on nonorthographic tasks and on tasks that required links between phonology and orthography, such as nonword reading and spelling. Overall, Participant 1 was more impaired than Participant 2 on the phonological battery as well as the reading and spelling tasks, which was consistent with her more extensive left perisylvian damage. The difference in phonological abilities was also evident in the greater proportion of phonologically

[3]The single-word reading and spelling data were collected from a subset of the 31 control participants because changes were made to the word lists that make up the Arizona Battery for Reading and Spelling after this treatment study was completed.

Figure 2. Pretreatment oral reading and spelling (writing to dictation) of words versus nonwords by Participants 1 and 2 and the average performance of 12 healthy control participants. Error bars indicate standard error of the mean for the control group.



plausible errors produced by Participant 2 (46%) compared with Participant 1 (8%). As noted for both individuals, spelling was more impaired than reading, and was a particular focus of treatment. Both individuals had mild impairment on tasks that simply required visual processing of orthographic information, and Participant 1 showed some difficulty in the recall of lowercase letters.

Treatment

Each participant completed two stages of behavioral intervention: phonological treatment followed by interactive treatment. Phonological treatment was directed toward improving sound–letter correspondences for consonants and vowels and retraining sublexical skills in the context of spelling nonwords. Interactive treatment guided participants to use phonological skills and residual orthographic knowledge to generate plausible spellings, and to detect and correct spelling errors. Treatment emphasized spelling rather than reading, but naturally the writing tasks inherently stimulated reading as well.

Phonological Treatment

The first phase of phonological treatment was implemented using a cuing hierarchy similar to that used by Hillis Trupe (1986; see also Beeson & Hillis, 2001) to retrain the relations between graphemes and phonemes for 20 consonants and 12 vowels. Prior to the initiation of phonological treatment, it was confirmed that both participants were able to read and spell a set of 20 monosyllabic words that were used to assist in the retrieval of sound–letter correspondences (Appendix B). These key words included the 20 target consonants in the initial position and the 12 vowels in the medial position. Consonant letter–sound correspondences were trained using a multiple baseline design across four sets of 5 consonants, and the vowels were subsequently trained in two sets of 6. All correspondences were probed a minimum of two sessions prior to the initiation of treatment. Sound–letter correspondences were probed by asking the participant to "Write the letter that goes with the sound ___." Letter–sound correspondences were probed by asking the participant to "Say the sound that goes with this letter" (letter presented visually). Training was implemented for each set of phonemes until the participant was able to correctly write and say each set with 80% correct accuracy over two sessions (i.e., 80% on both sound-to-letter and letter-to-sound probes).

The following cuing hierarchy was implemented by the clinician during the treatment sessions in order to retrain phoneme–grapheme correspondences for consonants:

1. "Write the letter that makes the sound /p/."
   - If correct, proceed to the next sound.
   - If incorrect, proceed to Step 2.
2. "Think of your key word for /p/. Try to write your key word."
   - If correct, say, "Yes, *pie* is your keyword. *Pie* starts with /p/. Underline the /p/ sound in *pie*."
   - If incorrect, go to Step 3.
3. Show picture and say, "Your key word for /p/ is *pie*. Write *pie*. Now underline the /p/ sound in *pie*."
   - If incorrect, go to Step 4.
4. Provide written model for key word. "Your key word is *pie*. Copy *pie*. Now underline the /p/ in *pie*."

The cuing hierarchy was complemented by other phonological training tasks, such as matching sounds to letters or words in a limited field (e.g., laying out pictures of all of the key words and having the participant point to the key word that goes with a specific target sound or letter). Other therapy activities included identification and segmentation of sounds in the initial and final positions of words. For example, the clinician would prompt the participant, "Listen to the first sound in the word I say, and write the letter that goes with the sound. What is the first sound in the word *pen*?" Nonwords were also used as stimuli for these types of segmentation tasks.

Vowel training followed generally the same procedure as consonant training, although there were two key words for each vowel, as some vowels have more than one "typical" corresponding grapheme (e.g., *ee* and *ea* for /i/). Once training for vowels was under way, it was clear that the participants had difficulty utilizing some of the key words with the vowel in the medial position. If a particular key word did not assist in retrieval of the target sound–letter correspondences, the participant was encouraged to generate a vowel-initial key word (e.g., "Ed" for /ɛ/). Also important to vowel training was the arrangement of vowel sounds into "long" and "short" vowel pairs (i.e., long and short *a, i,* and *e*) so that the concept of long and short vowel sounds could be trained directly. During vowel training, both participants required considerable instruction in the use of the "silent e" rule, and activities such as creating long/short minimal pairs (e.g., *hat* compared with *hate*) were used to enhance understanding of this rule.

After criterion was met for the targeted consonants and vowels, spelling performance was probed on sets of 20 regularly spelled words and 20 nonwords presented aurally (see Appendix B). Both participants were able to spell the regular words with at least 80% accuracy over three sessions, so training was initiated for the nonwords (see Appendix B), as a means to further increase phonological processing demands. Nonword spelling was probed using a multiple baseline design across four sets of 5 nonwords. The treatment procedures focused on training participants to segment nonwords into component sounds, convert the sounds to the corresponding letters, and then write the nonwords. Participants also practiced segmentation of multisyllabic real words and nonwords, starting with syllable segmentation and then saying and writing the component sounds in each syllable. They were trained to check their spelling of words and nonwords by reading them aloud, which required production and blending of the component sounds. Although progress was documented on the spelling of specific sets of nonword stimuli and participants practiced these stimuli for homework, they were never provided with the entire correct spelling of the items, nor were they given explicit feedback for responses during probes. Thus, the training focused on using a sublexical strategy rather than item-specific training of the spellings for the probed nonwords. After criterion was achieved on nonword spelling (80% or better performance on each set), the phonological battery was readministered in order to assess changes in phonological abilities, and then the participants advanced to interactive spelling treatment.

During the entire course of phonological treatment, daily homework was provided in video format on DVD. Homework initially consisted of clinician-directed practice in spoken repetition and writing of individual sound–letter correspondences. Each set of consonants and vowels was added to the homework as it was targeted for treatment. Participants were encouraged to continue homework on previously trained sets as needed to maintain a high level of performance. Upon mastery of single-letter correspondences, homework shifted to sounding out and writing nonwords to dictation. On average, participants were engaged in 45 min of homework per day for 5 days per week (~3.75 hr per week). Homework was reviewed during treatment sessions.

Interactive Treatment

Interactive treatment focused on training a problem-solving approach to spelling. Participants were trained to implement the following strategy when spelling difficulties were encountered:

1. Generate plausible spelling by relying on phonological skills.
2. Evaluate spelling on the basis of residual orthographic knowledge (lexical check).
3. Use electronic device sensitive to phonologically plausible renderings (Franklin Language Master) to check and correct spelling errors.

Training began with regularly spelled words to optimize success using a phonological strategy. Words were presented using a writing-to-dictation task, and participants were encouraged to sound out the words and transcode the component phonemes to graphemes. They learned how to enter responses into the speller and check for accuracy, including use of the "say" function to listen to the word they had spelled. Once the use of the speller was well established, training shifted to spelling irregular words, which typically required interactive use of lexical and sublexical knowledge to achieve correct responses. When a misspelled word is entered into the electronic speller, it generates a list of lexical options for the correct spelling. The speller is sensitive to both form-related (single- or multiple-letter errors) and phonologically plausible errors. When a spelling option is selected, the "say" button can be pushed in order to hear the word and determine whether it is the correct choice.

During interactive treatment sessions, low-frequency irregular words were randomly selected from a large corpus to provide stimuli for training and practice of the problem-solving approach. Daily homework included writing irregular words to dictation, which were presented auditorally via recordings on a "talking" photo album. The assignment was to generate, evaluate, and correct spellings using the external spelling device as needed. Homework was reviewed during each treatment session to check for accuracy and to maintain accountability.

Treatment Outcomes

Treatment outcomes were measured in several ways. During phonological treatment, sound–letter and letter–sound correspondences were probed at the beginning of each session using a multiple baseline design (first for consonants, then for vowels). When phonological treatment advanced to train blending of constituent sounds and letters, repeated probes of a standard set of nonwords were conducted using a multiple baseline design. These data were complemented by pre–post measures of phonological ability on the phonological tests. During interactive treatment, daily performance probes were not conducted because treatment was directed toward establishment of problem-solving strategies in a general manner, thus there were no appropriate items to sample in a repeated manner. Following interactive treatment, all of the pretreatment measures were repeated, with the intention of evaluating the effects of the treatment sequence (phonological to interactive).

Results

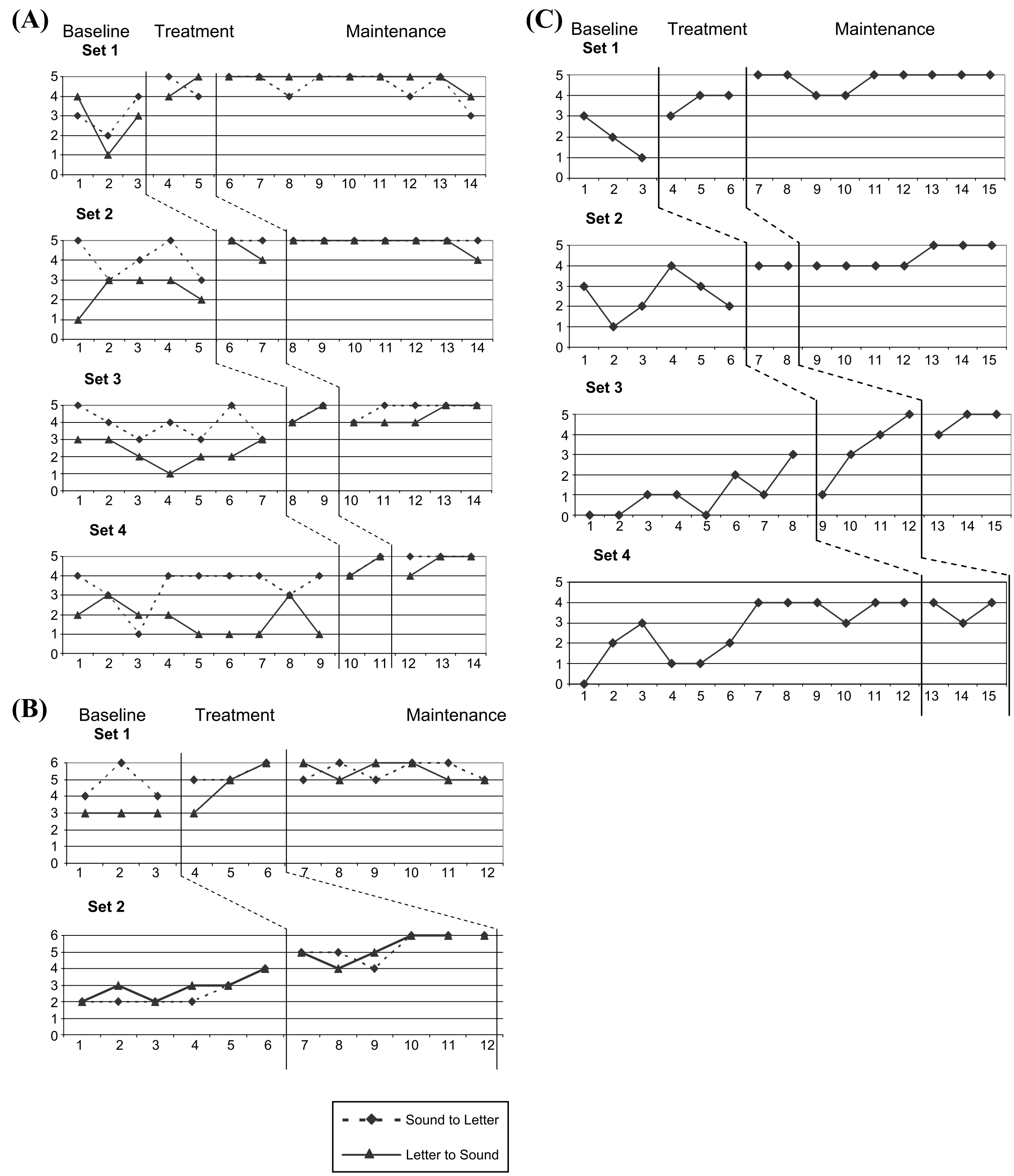
Participant 1 received 1-hr treatment sessions three times a week, achieving mastery of sound–letter correspondences and nonword spelling after 26 sessions (over 9 weeks), and completing interactive treatment in 15 sessions (over 5 weeks). The total number of clinician-administered treatment was 42 hr, and about 52 hr of homework were completed. Participant 2 attended two 1-hr treatment sessions per week, meeting criterion for phonological treatment in 14 sessions (over 7 weeks) and completing interactive treatment in an additional 9 sessions (over 5 weeks) for a total of 23 hr of treatment with approximately 45 hr of homework completed.

Response to Phonological Treatment

Figures 3 and 4 show the multiple baseline data reflecting the relearning of sound–letter correspondences for each participant. Participant 1 required training for both consonants and vowels, whereas Participant 2 demonstrated mastery of consonants prior to treatment and thus was trained only on vowels. For consonants, Participant 1 had greater difficulty with letter-to-sound correspondences, which were trained to criterion as indicated in Figure 3A. Both participants had difficulty with the correspondences for vowels, and training served to strengthen their performances (see Figures 3B and 4A). The mean performances on the pretreatment and posttreatment probes (across the baseline and maintenance phases of treatment) are indicated in Table 2. To quantify the magnitude of change for each participant, treatment effect sizes were calculated using Busk and Serlin's (1992) d statistic in the manner described by Beeson and Robey (2006). Specifically, the average of the difference between the mean performance during pretreatment and posttreatment was divided by the standard deviation of the pretreatment performance. The d statistic was computed for each set of trained items, and a weighted average was calculated taking into account the number of pre- and posttreatment observations for each set (see Table 2). The magnitude of the effect sizes is partially a reflection of the degree of impairment, and thus is limited by the room for improvement to criterion levels. This was evident in that the largest effect size was 6.48 for Participant 2's improvement on spelling vowels (from an average of 33.3% to 100%), and the smallest effect size (.95) was for her change on the reading of vowels (72.1% accurate prior to treatment relative to 98% correct after treatment).

The response to sublexical training was evaluated by the participants' spelling of four sets of nonwords that included all of the trained consonants and vowels (see Figures 3C and 4B). It was notable that during the sublexical training both individuals showed generalization to untrained nonwords, as indicated by an upward drift in baseline performance for the nonword Sets 2–4. This generalization confirmed that the participants were implementing sublexical skills that were not specific to individual items. The effect sizes for spelling of nonwords

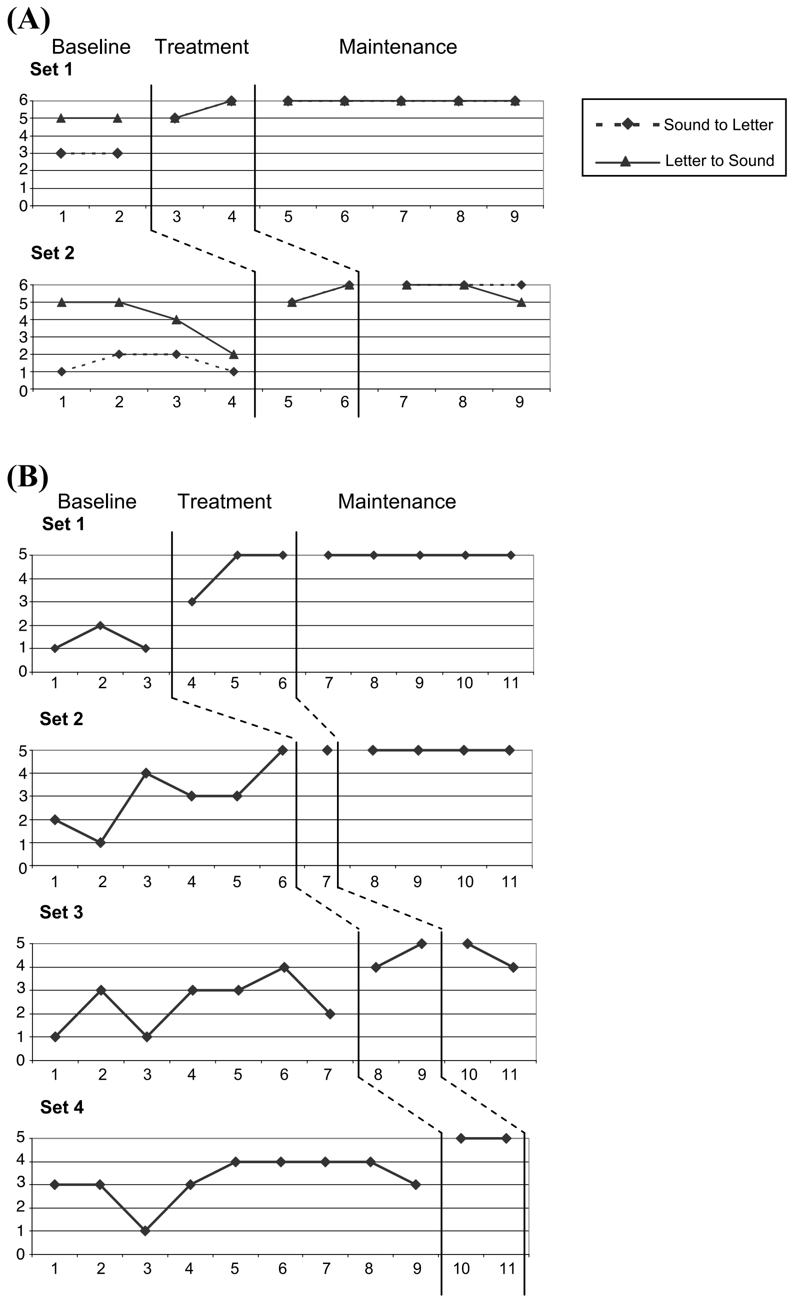
Figure 3. Participant 1's performance on sound–letter and letter–sound correspondences for consonants (3A) and vowels (3B) and her nonword spelling performance in response to phonological treatment directed toward sublexical spelling (3C). The ordinate depicts the number of items correct; the abscissa indicates treatment sessions.



were 2.31 and 3.01 for the 2 participants, which takes into account the upward drift of the baselines.

The phonological test battery was readministered following phonological treatment (see Table 3) and again following interactive treatment (see Table 3). Both participants made significant gains on phonological processing tasks that did not involve orthography, as well as on sound–letter and letter–sound transcoding tasks (see Table 3). Phonological composite scores significantly improved for both participants after phonological

Figure 4. Participant 2's performance on sound–letter and letter–sound correspondences for vowels (A) and her nonword spelling performance in response to phonological treatment directed toward sublexical spelling (B). The ordinate depicts the number of items correct; the abscissa indicates treatment sessions.



treatment, from 33.8 to 65.8 for Participant 1 ($\chi^2 = 19.22$, $p < .0001$) and from 75.4 to 85.8 for Participant 2 ($\chi^2 = 3.85$, $p = .049$). Their scores on the phonology–orthography tasks also improved (see Table 3), with the increase in the composite score significantly improved for Participant 1 ($\chi^2 = 8.8$, $p = .002$), and nearing significance for Participant 2 ($\chi^2 = 3.79$, $p < .052$).

Response to Interactive Treatment

Each participant received 5 weeks of interactive treatment during which they learned to evaluate their spelling attempts, self-correct errors, and make use of the electronic speller to assist in self-correction and confirmation of correct spellings. Responses given during the

Table 2. Summary of treatment outcomes—pretreatment and posttreatment mean percentage correct and standard deviations, and calculated effect sizes (*d* statistic).

Participant	Stimuli	Reading (letter–sound)					Spelling (sound–letter)				
		Pretreatment		Posttreatment			Pretreatment		Posttreatment		
		M	*SD*	*M*	*SD*	Effect size (*d*)	*M*	*SD*	*M*	*SD*	Effect size (*d*)
1	Consonants	43.0	18.4	95	20.8	2.62	72.6	19.4	95.8	10.2	1.29
	Vowels	44.5	18.5	94.5	8.6	3.99	38.8	20.3	92.8	8.8	2.52
	Nonwords						43.2	26.8	93	9.8	2.31
2	Vowels	72.1	20.1	98	5.8	0.95	33.3	14.8	100	0	6.48
	Nonwords						52.4	26	90	6.0	3.01

Note. Data reflect performance on 20 consonants, 12 vowels, and 20 nonwords.

treatment session and the written homework provided many examples of interactive use of lexical and sublexical information. It was common to observe sequential attempts to self-correct spelling errors in a manner that parallels the conduit d'approche phenomenon in spoken language wherein repeated phonological variations are produced while attempting to assemble the correct word form. The examples provided in Appendix C show consecutive attempts to spell target words and corrections made with the use of the electronic speller (indicated by an asterisk). Some spelling attempts provided evidence of partial lexical knowledge indicated by the inclusion of low-probability (but lexically correct) spellings (e.g., *jealish* for *jealous*; *anque* for *antique*). Other errors reflected combined output from lexical and sublexical spelling strategies, such as *anteeque* for *antique* (which includes *ee* from sublexical processing and *que* from lexical processing) and *rythum* for *rhythm* (which includes *thum* from sublexical processing and *rhy* from lexical processing).

Posttreatment Assessment

Pre–post treatment performance on the reading and spelling of untrained words and nonwords is shown in Figure 5. For real words, reading scores remained high, with some positive change for both participants (+5.2% for Participant 1 and +3.3% for Participant 2). Spelling performance significantly improved by 17% for Participant 1 (+20% for regularly spelled words and +13.3% for irregularly spelled words; McNemar, p = .021). Participant 2 improved by +6% for regularly spelled words and +10% for irregularly spelled words (McNemar, p = .113, *ns*). When using the electronic speller to detect and self-correct errors, overall spelling accuracy was 90% or better for both individuals, a statistically significant improvement over pretreatment spelling for both Participants 1 and 2 (McNemar, p = .0001 and p = .006, respectively). It is important to note that no feedback was provided during the reading or spelling assessment so that the use of the electronic speller was self-initiated only when the participant thought her response was in error. The few uncorrected errors were those that were undetected by the participant; in other words, they were items that were not entered into the spell checker.

Regarding residual reading and spelling errors, Participant 1's reading errors were still equally distributed between visually similar words and phonologically implausible attempts. Her spelling errors (without using the electronic speller) were predominantly form related with at least half of the word correct (79%); the few others were phonologically plausible errors (7%) and morphological errors (7%). Participant 2 made no errors on real-word reading after treatment. Her spelling errors included phonologically plausible errors (37.5%) and form-related errors with more than half of the word spelled correctly (37.5%) or substitution of visually similar words (25%). For both participants, the few errors that were not corrected with the use of the spell checker were single-letter deletions or substitutions, such as *sping* for *spring* (Participant 1) or *plaform* for *platform* (Participant 2).

With regard to nonwords, Participant 1 showed a significant improvement in nonword spelling (McNemar, p = .0107), and Participant 2 significantly improved nonword reading (p = .0107). As is evident in Figure 5, Participant 2 no longer showed a lexicality effect for either reading or spelling. Participant 1 had persistent lexicality effects, but the magnitude was reduced, particularly for spelling.

Posttreatment assessment of the measures of semantic, phonologic, visual/orthographic, and allographic/graphomotor skills showed maintenance of gains made after phonological treatment. Participant 1 also showed significant improvement on the visual lexical-decision task and in the ability to transcode letters from upper- to lowercase (see Table 3). Her AQ on the WAB improved from 76 to 81.1, a difference that was greater than the standard error of measurement of 5 AQ points calculated

Table 3. Pre- and posttreatment performances (percentage correct) for Participants 1 and 2 and mean performances and standard deviations of 31 control participants.

Behavioral measure	No. of items	Time of test	Participant 1	Participant 2	Controls	
					M	*SD*
Semantic processing						
Pyramids and Palm Trees Test (picture)	52	Pretreatment	96.2	96.2	98.3	3.8
		Posttreatment	94.2	98.1		
Pyramids and Palm Trees Test (written)	52	Pretreatment	96.2	98.1	98.0	1.9
		Posttreatment	92.3	94.2		
Spoken word–picture match task (PALPA 47)	40	Pretreatment	97.5	97.5	99.9	0.49
		Posttreatment	100.0	100.0		
Written word–picture match task (PALPA 48)	40	Pretreatment	97.5	100.0	99.9	0.49
		Posttreatment	100.0	100.		
Semantic composite		Pretreatment	96.8	97.9	99.9	1.02
		Posttreatment	96.6	98.1		
Phonological processing						
Rhyme judgment	40	Pretreatment	85.0	100.0	97.6	2.7
		Post–phon treatment	95.0*	100.0		
		Posttreatment	97.5**	97.5		
Rhyme production	10	Pretreatment	50.0	90.0	99.4	2.5
		Post–phon treatment	80.0**	80		
		Posttreatment	80.0**	90		
Phoneme segmentation	40	Pretreatment	7.5	92.5	97.4	4.10
		Post–phon treatment	82.5**	95		
		Posttreatment	67.5**	95		
Phoneme deletion	20	Pretreatment	20.0	55.0	98.2	3.04
		Post–phon treatment	55.0**	85.0**		
		Posttreatment	65.0**	75.0**		
Phoneme blending	20	Pretreatment	25.0	80.0	90.5	11.7
		Post–phon treatment	25.0	85.0		
		Posttreatment	35.0	90.0*		
Phoneme replacement	20	Pretreatment	15.0	35.0	87.3	8.9
		Post–phon treatment	60.0**	70.0**		
		Posttreatment	65.8**	60.0**		
Phonological composite		Pretreatment	33.8	75.4	95.1	4.9
		Post–phon treatment	65.3**	85.8*		
		Posttreatment	65.8**	84.6		
Phonology/orthography relations						
Letter–sound correspondences (consonants)	20	Pretreatment	50.0	100.00	98.6	2.9
		Post–phon treatment	90.0**	100.0		
		Posttreatment	85.0**	95.0		
Letter–sound correspondences (CVC nonwords)	60	Pretreatment	66.7	85.0	99.03	1.7
		Post–phon treatment	66.7	93.3		
		Posttreatment	73.3	91.7		
Sound–letter correspondences (consonants)	20	Pretreatment	85.0	95.0	97.9	4.6
		Post–phon treatment	95.0*	100.0		
		Posttreatment	100.0**	100.0		
Sound–letter correspondences (CVC nonwords)	60	Pretreatment	66.7	86.7	97.4	3.2
		Post–phon treatment	88.3**	98.3		
		Posttreatment	86.7**	93.3		
Phonology/orthography composite		Pretreatment	67.1	91.7	98.2	0.71
		Post–phon treatment	85.0**	97.9		
		Posttreatment	86.3**	95.0		

(Continued on the following page)

Table 3 *Continued.* Pre- and posttreatment performances (percentage correct) for Participants 1 and 2 and mean performances and standard deviations of 31 control participants.

Behavioral measure	No. of items	Time of test	Participant 1	Participant 2	Controls	
					M	*SD*
Visual/orthographic processing						
Mirror reversal letter identification (PALPA 18)	36	Pretreatment	97.2	100.0	99.5	1.7
		Posttreatment	91.7	100.0		
Upper- and lowercase match (PALPA 19)	26	Pretreatment	100.0	100.0	99.9	0.7
		Posttreatment	100.0	100.0		
Lower- and uppercase match (PALPA 20)	26	Pretreatment	100.0	100.0	100	0.0
		Posttreatment	100.0	100.0		
Lexical decision (PALPA 24): illegal nonwords	60	Pretreatment	100.0	98.3	99.9	0.4
		Posttreatment	100.0	100.0		
Lexical decision (PALPA 25): imageability/frequency	60	Pretreatment	98.3	93.3	99.1	2.2
		Posttreatment	—	90.0		
Lexical decision (PALPA 27): spelling/sound regularity	60	Pretreatment	90.0	88.3	99.3	1.4
		Posttreatment	98.3*	90.0		
Visual–orthographic composite		Pretreatment	97.6	96.7	99.6	0.4
		Posttreatment	98.0	99.6		
Allographic/graphomotor control						
Direct copy of words	55	Pretreatment	100.0	100.0	100.0	0.0
		Posttreatment	—	—		
Case conversion: upper to lower	26	Pretreatment	88.5	100.0	99.2	1.9
		Posttreatment	100.0**	100.0		
Case conversion: lower to upper	26	Pretreatment	96.1	100.0	99.4	2.3
		Posttreatment	100.0	100.0		
Allographic–graphomotor composite		Pretreatment	96.8	100.0	99.5	0.4
		Posttreatment	100.0	100.0		

Note. Pretreatment = before all treatment; Posttreatment = after interactive treatment; Post–phon treatment = after phonological treatment; PALPA = Psycholinguistic Assessment of Language Processing in Aphasia. Dash denotes posttreatment testing not performed.

*Denotes significant improvement from pretreatment, $p < .05$. **Denotes significant improvement from pretreatment, $p < .01$.

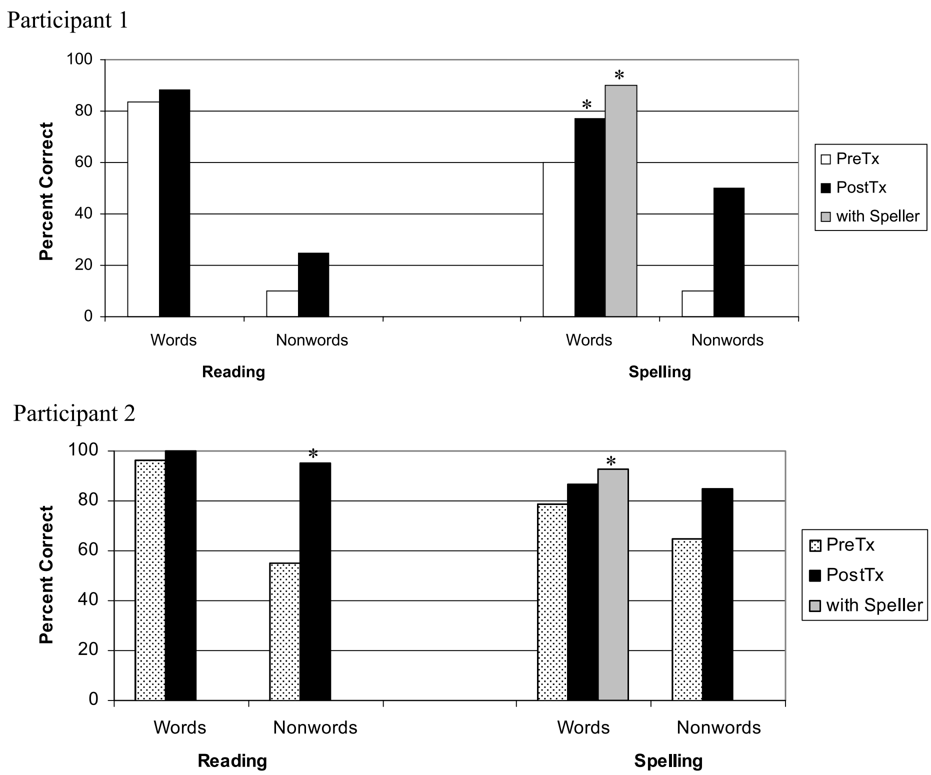
from the normative data provided by Shewan and Kertesz (1980); Participant 2 had little room for improvement on the WAB. Naming performance on the Boston Naming Test did not change significantly, with Participant 1 improving by 4 points, and Participant 2 declining by 1 point. Digit span remained impaired, limited to three digits for Participant 1 (<4th percentile) and four digits for Participant 2 (<3rd percentile).

Discussion

The purpose of this study was to examine the therapeutic effect of a treatment sequence intended to strengthen both sublexical and lexical procedures for reading and spelling. Whereas normal readers/spellers rely predominantly on lexical processing for familiar words, sublexical procedures provide a means to generate plausible responses when one fails to recognize or recall the spelling of a word. This strategy can yield correct responses for regularly spelled words and phonologically plausible responses for irregular words (which can sometimes help trigger retrieval of correct lexical responses). Individuals with weakened phonological skills, like the participants in this study, have limited resources to resolve spelling errors. Therefore, our goal was to first strengthen phonological skills and the relations between phonology and orthography at a sublexical level, and then to train an intentional interactive use of sublexical and lexical information for reading and spelling. We expected that a positive response to treatment would move the participants toward a more "normal" spelling competence and strategic compensation for their residual difficulties.

Both participants were responsive to the sequence of phonological and interactive treatment, showing improved phonological processing and ability to read/spell untrained words and nonwords. Their spelling improvement appeared to reflect stronger sublexical skills combined with the use of a strategy for self-detection and correction of misspelled words with the assistance of an electronic

Figure 5. Reading and spelling performance for words and nonwords before (PreTx) and after treatment (PostTx). Spelling accuracy when using the electronic speller is also indicated for real words. *denotes significant improvement from pretreatment ($p < .05$).



speller. The skills learned during interactive treatment provided a means to maximize the gains from phonological treatment and to provide strategic compensation for residual weakness in written language processing. Thus, the treatment sequence proved to be both restorative and compensatory in nature.

Over the course of 3 to 3½ months of treatment, both participants advanced their phonological and written language skills and reported satisfaction with the treatment. Specifically, they communicated that the improvement in performance was worth the time expended in treatment sessions and on the structured homework activities. Their residual spelling errors were close to the target, consisting of single-letter omissions or substitutions, some visually related word errors, and phonologically plausible errors. From a practical perspective, both individuals achieved close-to-normal spelling when the electronic speller was available. The uncorrected errors were those that they failed to detect as being misspelled, so they did not recognize the need to self-correct or enter the words into the spell checker. These errors were often so close to the target that they would be interpreted correctly in a functional context. In fact, some of these misspellings would be automatically corrected if typed while using a word processing program. For example, the residual errors made by Participant 2 included *plaform,* which corrects to *platform,* and *spendid,* which corrects to *splendid* when typed into Microsoft Word 2003. However, phonologically plausible misspellings are not typically corrected by word processing programs so that *circet* for *circuit* or *glasher* for *glacier* would not be corrected. Such misspellings are associated with their correct spelling when entered into the electronic spell checker, such as the Franklin Language Master used in this study, which is programmed for sensitivity to phonologically plausible errors. Both participants recognized the value of the spell checker and chose to retain the device for continued home use at the end of their treatment. Follow-up with Participant 2 confirmed that she continued to use the device in her written work for school and pleasure. Unfortunately, Participant 1 had subsequent medical problems that limited follow-up.

Although both participants benefited from treatment, they did not regain fully normal written language skills, so additional treatment to further advance performance might be considered. Posttreatment assessment indicated some residual phonological weakness suggesting persistent limitations in the ability to generate phonologically plausible spellings or to use sublexical information to select (or correct) orthographic representations. This was most evident for Participant 1 who generated a small proportion of phonologically plausible errors both before and after treatment. On the posttreatment assessment, Participant 1 showed difficulty with some phonological manipulation tasks (e.g., phoneme segmentation, deletion, blending, and replacement) and phoneme–grapheme correspondences for nonwords at the CVC level. Therefore, she might benefit from additional phonological training along with continued use of the interactive approach to resolve spelling errors. Participant 2's residual impairment was quite mild, but there was still room for improvement on the more difficult phonological tasks and the spelling of nonwords with more complex phonological/orthographic structure. To address this issue, additional sublexical training using multisyllabic nonwords and nonwords with consonant clusters might provide the opportunity to further strengthen phonological skills in the context of spelling. Thus, an increase in the duration of the treatment and additional performance criteria for more challenging phonological tasks might be considered in the next phase of treatment research or when applying this approach in a clinical setting. However, the persistent impairment of verbal working memory skills in these 2 participants with left perisylvian damage is likely to prevent achievement of fully normal performance on the phonological manipulation tasks, even if their sound–letter skills ultimately approximate normal. Therefore, treatment goals should remain focused on functional reading and spelling skills, and expectations must be tempered by these persistent deficits.

The treatment sequence examined in this study was a progression from the impairment-based phonological treatment to the subsequent interactive treatment that also provided a compensatory strategy for residual spelling difficulties. In our view, these two approaches compose part of a treatment continuum for the remediation of written language processing that includes *lexical treatment* to retrain item-specific spellings, *phonological treatment* to strengthen sublexical reading and spelling skills, and finally *interactive treatment* to maximize the use of residual lexical and phonological knowledge. The point of entry along the treatment continuum (lexical → phonological → interactive) is dependent upon the spelling profile. Lexical treatment serves to retrain specific orthographic representations, and the approach can be particularly appropriate for individuals with relatively severe language impairment and global agraphia as a means to establish written communication for personally relevant concepts (Beeson, Rising, & Volk, 2003; Clausen & Beeson, 2003).

Lexical treatment can also provide a means to establish a set of key words to facilitate relearning of sound–letter correspondences in the context of subsequent phonological treatment. In this study, the participants had adequate knowledge of key words for the target sounds so that lexical training was not necessary. Phonological treatment is appropriate for individuals with impaired sublexical skills, including phonological alexia/agraphia (like the participants in this study), as well as those with deep alexia/agraphia who also make semantic errors in reading and spelling. Phonological treatment would not be necessary for individuals with relatively preserved phonology, but degraded orthographic representations, such as those fitting the profile of surface alexia/agraphia. Rather, such individuals are logical candidates for interactive treatment because they can generate phonologically plausible attempts to spell words.

In this study, we showed that the implementation of interactive treatment with individuals with phonological alexia/agraphia also has potential value as a complement to phonological treatment. It was clear that Participant 1 required phonological treatment as a precursor to interactive treatment; we note, however, that Participant 2's residual phonological skills for consonants may have been adequate to support interactive treatment without the preceding phonological treatment. She clearly improved her reading and spelling of vowels over the course of phonological treatment, which was helpful as she embarked on interactive treatment. However, in a clinical rather than research context, it may be appropriate to initiate interactive treatment with an individual like Participant 2 with the intention of strengthening phonological skills concurrently with problem-solving skills.

The procedures implemented during interactive treatment were intended to facilitate feedback between lexical and sublexical processing, and to engage reading to assist in self-detection of errors. The observed spelling errors variously suggested reliance on degraded lexical information, contributions from sublexical processing, or a combination of both. Although reading skills were adequate for the participants to read correctly spelled words with high accuracy, they were not strong enough for consistent detection of their own spelling errors. The use of the spell checker offered an alternative means to examine lexical alternatives because misspellings entered into the device generate a list of potential spelling corrections. Thus, the speller provided external feedback for spelling attempts as well as explicit options for self-correction.

It is worth noting that although the treatment in this study focused more on spelling than reading, the written spelling tasks inherently provided stimulation of visual word forms for reading. Thus, the treatment offered an efficient means to simultaneously address central impairments affecting both reading and spelling. Given that spelling is the more demanding task for most individuals with phonological alexia/agraphia (Rapcsak et al., 2009), this perspective is consistent with the complexity account of treatment efficacy (CATE) proposed by Thompson and colleagues (Kiran & Thompson, 2003; Thompson, Shapiro, Kiran, & Sobecks, 2003; Thompson

& Shapiro, 2007). CATE suggests that treatment for more complex or demanding language tasks provides stimulation that serves to strengthen related, but less difficult language skills without direct intervention. In the context of treatment for syntactic deficits, the complexity account explicates the findings that training complex syntactic constructions results in generalization to linguistically related, but simpler sentence constructions (Thompson et al., 2003; Thompson & Shapiro, 2007). Similarly, regarding the treatment of naming deficits, Kiran and Thompson showed that training atypical exemplars within a semantic category served to improve naming for untrained exemplars within that category. With regard to written language, we propose that the treatment of single-word spelling should be considered as a means to improve both reading and spelling of target items, rather than training the easier task of word recognition (i.e., reading) prior to advancing to spelling treatment. This point is worth making because it is counter to a more traditional treatment hierarchy based on levels of increasing difficulty.

In summary, the improvements made by the two individuals reported here provide motivation to further pursue the investigation of the phonological → interactive treatment sequence. To fully understand the added value of interactive treatment, a more comprehensive reading and spelling assessment should be repeated at the end of phonological treatment, just prior to initiating interactive treatment. Additional knowledge would be gained by the implementation of this treatment sequence with a series of individuals with phonological alexia/agraphia of varying severity levels and lesion extent, thus providing insight regarding the characteristics of the best candidates. Finally, the extension of treatment beyond the 3 months provided here could help evaluate the ultimate recovery potential of individuals who are willing to continue their rehabilitation efforts for longer periods of time.

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Contact author: Pélagie M. Beeson, P.O. Box 210071, Department of Speech, Language, & Hearing Sciences, University of Arizona, Tucson, AZ 85721-0071. E-mail: pelagie@u.arizona.edu.

Appendix A. Reading and spelling stimuli.

Regular words	Irregular words	Nonwords
sort	tomb	flig
save	myth	hoach
kept	sure	snite
bump	urge	glope
fact	type	boak
pine	chef	cheed
point	talk	smode
reach	blood	dusp
fresh	chief	prane
barge	yacht	grest
bribe	sword	dringe
storm	broad	mofer
grill	floor	andon
spend	doubt	barcle
chant	gross	merber
drive	laugh	manver
slate	vague	nace
grave	choir	wape
blame	prove	trad
ground	ghost	squate
count	bright	
spring	should	
twenty	castle	
charge	island	
branch	answer	
grumble	subtle	
outside	glacier	
shampoo	circuit	
platform	biscuit	
splendid	mortgage	

Appendix B. Stimuli used for phonological treatment.

Key words: Consonants		Corresponding phonemes
Set 1	rug, top, leaf, safe, net	/r/, /t/, /l/, /n/, /s/
Set 2	cake, fire, moon, pie, dog	/k/, /f/, /m/, /p/, /d/
Set 3	book, goat, zoo, ship, van	/b/, /g/, /z/, /ʃ/, /v/
Set 4	hat, web, chin, judge, three	/h/, /w/, /ʧ/, /ʤ/, /θ/
Key words: Vowels		**Corresponding phonemes**
Set 1	hat/van, cake/safe, ship/chin	/æ/, /e/, /ɪ/,
	fire/pie, net/web, leaf/three	/aɪ/, /ɛ/, /i/
Set 2	top/dog, bone/goat, rug/judge	/ɑ/(/ɔ/), /o/, /ʌ/,
	moon/zoo, cow/mouth, foot/book	/u/, /ɑu/, /ʊ/

Regularly spelled real words used to train blending of phoneme–grapheme components.

Set 1 cheat, zone, vine, hood, maze
Set 2 nap, toad, fake, wedge, lime
Set 3 shower, thunder, golfer, breezy, robin
Set 4 cooler, debit, joker, planet, southwest

Nonwords used to train blending of phoneme–grapheme components.

Set 1 mog, rudge, noash, zook, glipe
Set 2 trib, peth, sneeve, voust, blafe
Set 3 lipen, flooner, theaky, jabble, wizrum
Set 4 cowbry, shastic, drumpy, hollish, chesper

Note. Underlined letters indicate letter–sound correspondences targeted in treatment.

Appendix C. Examples of spelling corrections.

Target	Consecutive spelling attempts
Participant 1	
"bomb"	*bomn → bon → bome → *bomb*
"jealous"	*jealish → jealus → *jealous*
"mustache"	*mustack → mustake → *mustang* (recognized it was incorrect, so returned to mustack) mustack → **mustache*
Participant 2	
"antique"	*anque → antquict → anteeque → *antique*
"beige"	*bache → bashe → baich → baij → *beige*
"rhythm"	*rystem → rizthem → rithem → rythum → *rhythm*

Note. Asterisk indicates use of electronic spell-checker.