

# Letter Selection and Letter Assembly in Acquired Dysgraphia

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**Objective:** We explored the constituents of the graphemic buffer in a patient with acquired dysgraphia and tested the hypothesis that the graphemic buffer is composed of 2 dissociable components: letter selection and letter assembly.

**Background:** Research on dysgraphia has established the graphemic buffer as a component of the spelling mechanism, and the buffer is considered a short-term memory store that is critical for letter production. However, little is known about the components within the buffer.

**Method:** We devised 2 spelling tasks that rely differentially on letter selection and letter assembly. In the selection task, our patient produced the letters that composed a target word, but she did not have to provide serial position information. In the assembly task, B.H. was given all the letters of a target word and was asked to spell the word by arranging the letters in the proper serial order.

**Results:** Compared to spelling to dictation, our patient did not benefit from being given letter identity information (ie, assembly task), but her performance improved significantly when position information was available (ie, selection task).

**Conclusions:** Based on these data, and the comparison of her performance with another dysgraphic patient, we propose that the graphemic buffer engages in both letter selection and letter assembly.

**Key Words:** dysgraphia, graphemic buffer, spelling disorder, neuropsychology, case study

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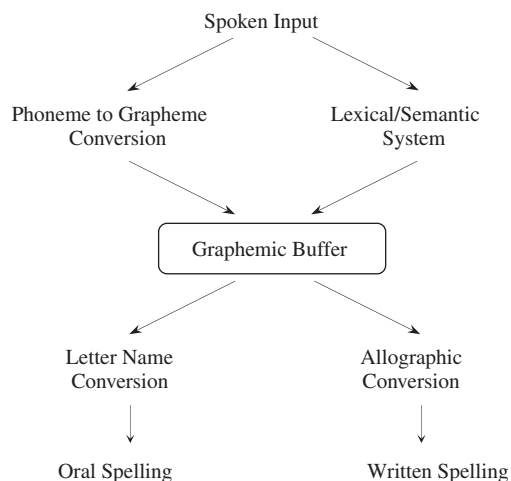
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Many spelling theories incorporate a working memory component referred to as the graphemic buffer into spelling models (Fig. 1). For example, Caramazza and colleagues<sup>1–3</sup> described this component as a buffer that maintains graphemic representations for conversion into specific written (ie, letter shapes) or oral output (ie, letter names). Case studies of patients with selective damage to the graphemic buffer have been used as evidence to establish the graphemic buffer as a separable component of the spelling architecture (eg, Refs. 4–10).

Caramazza and colleagues<sup>1–3</sup> assigned a fairly central role to the graphemic buffer in their spelling model. They proposed that given the nature of the buffer (ie, working memory) and its relative position within the spelling system (ie, between the levels of retrieval and production), damage to the buffer will lead to a spelling profile with the following characteristics. (1) Word length effect: The hypothesized role of the graphemic buffer is to temporarily store graphemic representations until production. If the graphemic buffer functions like a working memory buffer, and that the buffer has a limited capacity, one would expect better performance with shorter words than with longer words because the damaged system may have trouble maintaining words that are near and/or over its capacity. (2) Serial position effect: Following from the



**FIGURE 1.** Components involved in the spelling process. Adapted from Caramazza et al, 1987.

idea that the graphemic buffer is a temporary memory store, one would expect higher accuracy for beginning and end positions within a word. This is similar to classic primacy and recency effects in studies of the short-term memory system, and this pattern can also be observed in skilled adult spellers.<sup>11,12</sup> (3) Spelling errors on a graphemic level: Because the graphemic buffer specializes in processing graphemic units, damage to this system is expected to affect the integrity of the graphemic representations. As such, spelling errors should take the form of graphemic substitution, transposition, deletion, and insertion. (4) Modality invariance: Because the graphemic buffer is situated between lexical retrieval and production, effects of damage to this module should not selectively affect different input and output modalities.

As suggested earlier, much of the existing research on graphemic buffer dysgraphia has focused on establishing the buffer as a separate component within the spelling system (eg, Refs. 1, 4, 6, 13). In this paper, we explore the possible constituents within the graphemic buffer by presenting evidence from a case study of a patient whose spelling profile is the most consistent with damage to the graphemic buffer. Specifically, we propose that the graphemic buffer consists of at least 2 dissociable components: letter selection and letter assembly.

### CASE STUDY—B.H.

B.H. was a 72-year-old, right-handed woman who suffered from a myocardial infarction in May of 2000. No acute hypotension was documented during her myocardial infarction, and her magnetic resonance imaging scan showed noticeable atrophy in the white matter undercutting the left posterior temporal lobe. B.H. received 14 years of education and worked as a secretary before her heart attack. As a secretary, she was a very fast and accurate typist, and she was proficient at composing complex reports and proofreading long documents.

B.H. first noticed a degradation in her spelling after the initial heart attack. During her first clinic visit, B.H. performed normally on the Mini Mental State Examination,<sup>14</sup> except on the writing component. Her digit span was 5 digits forward and 4 digits backward. She continued to read books and newspapers without any difficulty. Her other language functions also seem intact. She was able to engage in long conversations without any impediment. Furthermore, she was able to recall conversational topics discussed during her previous visit a few months ago.

To assess B.H.'s overall language abilities and spelling performance, the Western Aphasia Battery (WAB)<sup>15</sup> and sections 39 to 45 of the Psycholinguistic Assessments of Language Processing in Aphasia (PALPA, Ref. 16) were administered. Results from these subsections of the PALPA provided a rough assessment of B.H.'s spelling profile in terms of word length effect, grammatical effect, and lexical effect. The results are summarized in Tables 1 and 2, and the data confirmed

**TABLE 1.** Summary of B.H.'s and J.D.'s Performance on Sections I Through VI of the WAB

Section	Test (Maximum Score)	B.H.'s Score	J.D.'s Score	
I	Spontaneous speech (20)	18	19	
II	Auditory verbal comprehension			
	A. Yes/no questions (60)	60	57	
	B. Auditory word recognition (60)	60	54	
III	C. Sequential commands (80)	72	41	
	Repetition (100)	88	84	
IV	Naming			
	A. Object naming (60)	54	55	
	B. Word fluency (20)	4	10	
	C. Sentence completion (10)	10	8	
V	D. Responsive speech (10)	10	10	
	Reading			
	A. Sentence reading comprehension (40)	32	40	
	B. Reading commands (20)	20	20	
VI	Prorated Score (100)	84	100	
	Writing			
	A. Writing on request (6)	5.0	5.5	
	B. Written output (34)	9.5	4.5	
	C. Writing to dictated sentence (10)	7.5	3.0	
	D. Writing of dictated words (10)	7.5	3.0	
	E1. Alphabet (12.5)	12.5	12.0	
	E2. Numbers (10)	10.0	10.0	
	F1. Dictated letters (2.5)	2.5	2.0	
	F2. Dictated numbers (5)	4.0	4.0	
	G. Copying of visually presented sentence (10)	10.0	10.0	
	<i>Aphasia Quotient</i>		88.4	86.6

that B.H.'s impairment is relatively isolated to her spelling abilities (see also Appendix A for further description of language and spelling assessment). Furthermore, B.H. performed perfectly on single letter dictation, and her letters were all well-formed, indicating that her deficit in spelling to dictation could not be attributed to a degradation in her long-term graphemic representations nor a deficit in motor programming (Fig. 2).

As outlined by Caramazza and colleagues,<sup>1-3</sup> the spelling performance of a patient with graphemic buffer dysgraphia is expected to fit a certain profile: word length effect, serial position effect, spelling errors on a graphemic level, and modality invariance. To demonstrate that B.H.'s spelling profile fits that of graphemic buffer dysgraphia, we explore each of these features using a standard spelling to dictation task. Each word was read to B.H., and she was given as much time as she needed to write each word on a piece of paper.

### MATERIALS

A corpus of 417 nouns, ranging from 3 to 10 letters, was used to assess B.H.'s spelling abilities (Table 3). The words across different lengths were matched on Kucera-Francis written frequency ( $F = 0.48$ ,  $P = 0.85$ ); however, a one-way analysis of variance (ANOVA) on the

**TABLE 2.** Summary of B.H.'s Performance on Sections 39 Through 45 of the Psycholinguistic Assessments of language Processing in Aphasia (PALPA)

Section	BH # Correct	# Total Items	Norm	SD
39 Letter length				
• Three	6	6	n/a	n/a
• Four	6	6	n/a	n/a
• Five	4	6	n/a	n/a
• Six	4	6	n/a	n/a
40 Imageability and Frequency				
• High image/high freq	7	10	9.68	0.67
• High image/low freq	3	10	9.25	0.75
• Low image/high freq	3	10	9.11	1.37
• Low image/low freq	5	10	8.36	1.97
41 Grammatical class				
• Adjectives	4	5	4.82	0.48
• Functors	3	4	4.68	0.55
• Nouns	2	5	4.79	0.42
• Verbs	3	5	4.82	0.39
42 Grammatical class (controlled for imageability)				
• Functors	4	10	9.39	0.92
• Nouns	7	10	9.04	1.26
43 Lexical morphology				
• Derived	5	10	n/a	n/a
• Derivational control	2	10	n/a	n/a
• Regular inflection	5	10	n/a	n/a
• Regular control	4	10	n/a	n/a
• Irregular inflection	3	10	n/a	n/a
• Irregular control	5	10	n/a	n/a
44 Regularity				
• Exception	7	20	8.63	1.18
• Regular	15	20	9.19	0.88
45 Nonwords and Length effect				
• Three	4	6	5.43	0.88
• Four	2	6	5.25	1.14
• Five	3	6	5.25	1.24
• Six	3	6	4.96	1.45

familiarity ratings revealed a significant main effect across different word lengths ( $F = 4.63, P < 0.01$ ).

**Error Analyses**

Each word was scored for accuracy, and each error was categorized into one of 5 error types. The 5 error types were adapted from guidelines suggested by Caramazza and colleagues<sup>1</sup> and by Schiller and colleagues.<sup>9</sup> The error types are: Substitution (S: “bump” —> “bomp”), Insertion (I: “cloud” —> “cloud<sub>e</sub>”), Deletion (D: “hospital” —> “hosptal”), Transposition (T: “sword” —> “sowrd”), and Transposition with substitution (TS: “cathedral” —> “cathedrle,” with an “e” substituted for the “a” and with the “e” and “l” transposed).

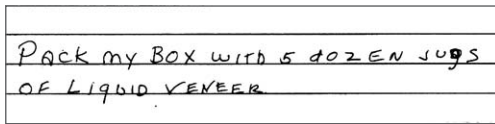
Whenever the error analysis was ambiguous, a minimum error rule was applied. That is, when an error could be coded in more than one way, we would select the alternative that yielded the minimum number of errors. For example, the erroneous spelling “heous” for the word “house” could be scored in one of 2 ways: (a) as 4 transposition errors: “o” from second to third position, “u” from third to fourth, “s” from fourth to fifth, and

“e” from fifth to second, or (b) as one insertion error (inserting “e” into second position) and one deletion error (deleting “e” from the last position). According to the minimum error rule, we would choose the latter alternative.

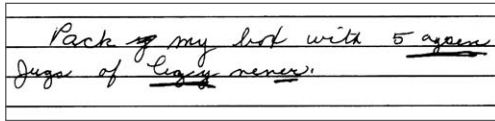
To determine the position for each error, we used the following guidelines. Target word and response were arranged to achieve maximum overlap, starting from left to right. Substitution, deletion, transposition, and transposition with substitution errors were assigned to the original position in the target word. Insertion errors were assigned to the preceding position. For example, if the target word “house” was spelled as “heous,” her errors were coded as: first position—correct; second position—insertion; third position—correct; fourth position—correct; fifth position—deletion. Furthermore, if the target word “alligator” was spelled as “alegeate,” her errors were coded as: first position—correct; second position—correct; third position—substitution; fourth position—substitution; fifth position—substitution; sixth position—correct; seventh position—correct; eighth position—substitution; ninth position—deletion.

Copying from visual stimulus:

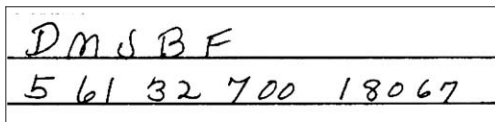
“Pack my box with 5 dozen jugs of liquid veneer”



Spelling to dictation: “Pack my box with 5 dozen jugs of liquid veneer”



Single letter and number dictation:



Spelling to dictation:

<i>gun</i>	“gun” (gun)
<i>watch</i>	“watch” (watch)
<i>nose</i>	“nose” (nose)
<i>hammer</i>	“hammer” (hammer)
<i>telephone</i>	“telephone” (telephone)
<i>screw driver</i>	“screwdriver” (squadirve)

FIGURE 2. Writing samples from patient B.H.

## RESULTS

### Word Length Effect

Of the 417 nouns, B.H. committed at least one error in 54% of the words (ie, 225 words). When error rates were examined as a function of word length, a positive correlation was observed ( $r = 0.92$ ). Specifically, B.H.’s spelling error rate rose from 8.3% for 3-letter words to 78.0% for 10-letter words (Fig. 3). When analyzed in terms of number of errors per word (scaled for word length), the same pattern was found, ranging from 0.04 errors per word for 3-letter words to 0.29 errors per word for 10-letter words (Fig. 3). The same pattern persisted

TABLE 3. Stimulus Characteristics

Word Length (Letters)	No. Items	K-F Frequency	Familiarity
3	48	46.35	551.23
4	63	57.97	549.25
5	61	58.62	532.58
6	63	48.27	527.23
7	47	45.68	521.48
8	46	38.46	512.31
9	48	42.25	507.89
10	41	43.24	513.15
	Total = 417	Mean = 47.61	Mean = 526.89

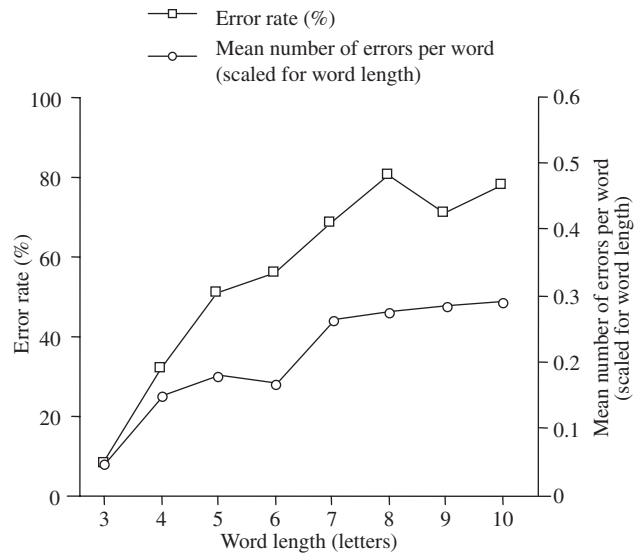


FIGURE 3. Spelling performance as a function of word length (patient B.H.).

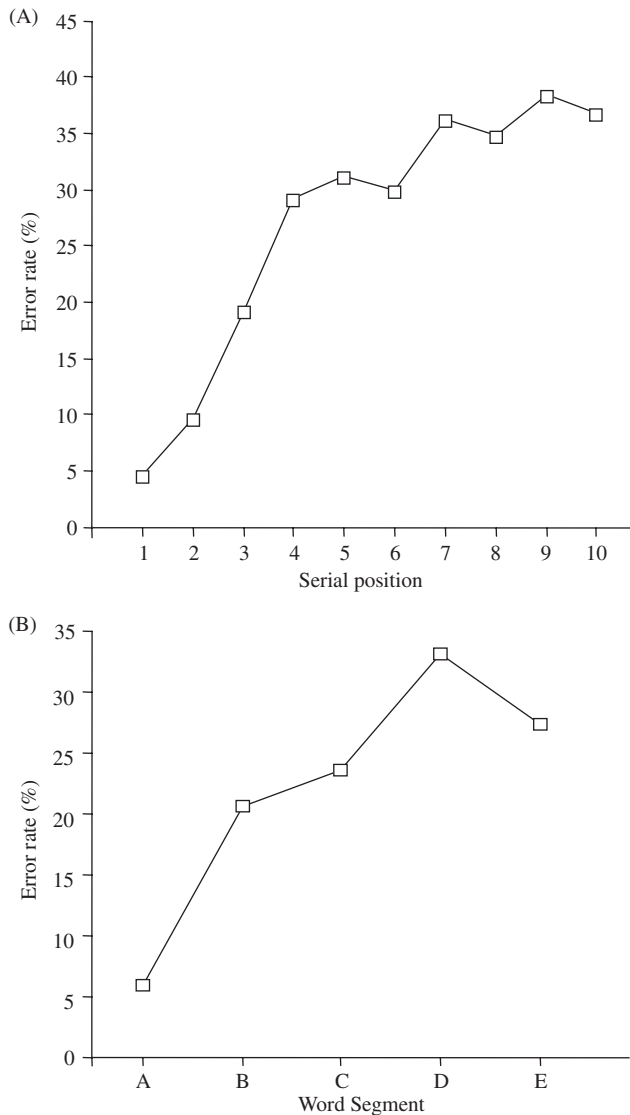
when word length is calculated in terms of number of syllables: 1 syllable—31.7% error; 4 syllables—62.4% error. The observed word length effect is consistent with the idea that the graphemic buffer functions as a temporary storage buffer for graphemic units.

### Serial Position Effect

Another hallmark feature of graphemic buffer dysgraphia is serial position effect. As such, we examined B.H.’s spelling errors as a function of serial positions within each word. Position of each error within a word was determined based on the classification scheme described earlier (see Error Analyses section). Figure 4A summarized the data and showed that B.H. made fewer errors in the beginning positions than in the end positions (first position: 4.5% error; tenth position: 36.6%). However, because of varying lengths of the stimuli, the distribution of letters is skewed toward the beginning positions. That is, all words, regardless of length, have a first position, but only some of the words have a tenth position.

Thus, it is difficult to make direct comparisons across different word lengths by looking at absolute serial position. To normalize the distribution of letters, we employed a binning procedure proposed by Wing and Baddeley<sup>12</sup> and Caramazza and colleagues.<sup>1</sup> Each letter within a word was assigned to one of 5 bins, as illustrated in Table 4. Figure 4B summarized the error analysis based on this binning procedure. Overall, a bow-shaped serial position curve was observed.

The observed serial position effect is consistent with the classic profile of a graphemic buffer deficit. It is assumed that after the graphemes for each word have been selected, they are held in the graphemic buffer for temporary storage until production. Wing and Baddeley<sup>12</sup>



**FIGURE 4.** Spelling performance as a function of serial position (patient B.H.).

explained the serial position effect in terms of neighborhood interference. Because letters in medial positions have more neighbors than letters in the beginning or the

end of a word, letters in middle positions are more prone to interference from their neighbors than letters in the ends. In other words, spelling errors are more likely to occur in the middle positions because memory for middle letters is more susceptible to interference.

**Error Types**

As illustrated in Figure 1, the graphemic buffer is hypothesized to be a postlexical and postsemantic module. Therefore, damage to the graphemic buffer should produce spelling errors that are attributable to mistakes on a grapheme level. In other words, a graphemic buffer deficit should not produce semantic or phonologic paraphasia errors. Instead, errors should be mostly insertions, deletions, transpositions, and substitutions on a graphemic level.

B.H.’s spelling errors were analyzed based on the classification scheme described earlier (see Error Analyses section). Of the 225 words spelled incorrectly, less than 3% of the errors (ie, 6 words) resulted in homophone errors (eg, spelling “lone” as “loan”). In fact, all other errors occurred at a graphemic level (Fig. 5).

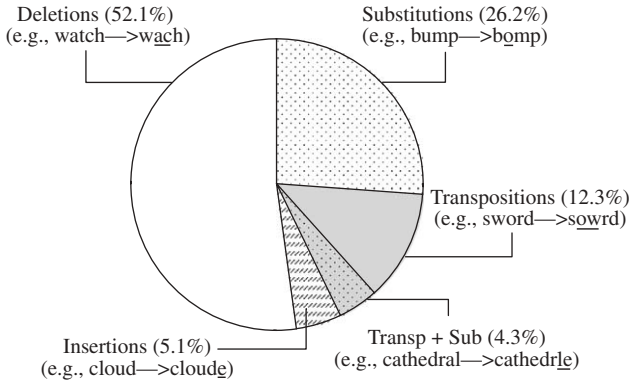
Previous case reports of acquired dysgraphia have documented a high consonant-vowel substitution consistency among the substitution errors produced by dysgraphic patients (eg, Refs. 1, 10, 17–20). Consistent with those reports, B.H.’s substitution errors also exhibited a relatively high consonant-vowel substitution consistency: consonant-to-consonant substitution was 74.3% and vowel-to-vowel substitution was 78.8%. Ward and Romani<sup>20</sup> proposed that given the proportion and frequency of consonants and vowels in the English language, chance level consonant-to-consonant and vowel-to-vowel substitution would be 52.1%. Based on this estimate, B.H.’s substitution consistency was significantly above chance for both consonant-to-consonant ( $\chi^2 = 10.38, P < 0.01$ ) and vowel-to-vowel ( $\chi^2 = 14.86, P < 0.001$ ) substitutions.

**Modality Invariance**

B.H. was asked to spell the same 30 words in 4 different conditions, which represented the factorial combination of input modality (visual vs. auditory) and output modality (written vs. oral). These conditions were designed to examine modality effects. Specifically, in the visual input conditions, words were presented on a

**TABLE 4.** Binning Procedure Used in Serial Position Analysis

Word Length	Letter Position									
	First	Second	Third	Fourth	Fifth	Sixth	Seventh	Eighth	Ninth	Tenth
3	A	C	E	n/a	n/a	n/a	n/a	n/a	n/a	n/a
4	A	C	C	E	n/a	n/a	n/a	n/a	n/a	n/a
5	A	B	C	D	E	n/a	n/a	n/a	n/a	n/a
6	A	B	C	C	D	E	n/a	n/a	n/a	n/a
7	A	B	B	C	D	D	E	n/a	n/a	n/a
8	A	A	B	C	C	D	E	E	n/a	n/a
9	A	A	B	B	C	D	D	E	E	n/a
10	A	A	B	B	C	C	D	D	E	E



**FIGURE 5.** Types of spelling errors committed by B.H. (total number of graphemic errors: 747 errors).

computer screen for 900 ms, and in the auditory input conditions, words were read aloud by the experimenter. In the written output conditions, B.H. was asked to write each word on a piece of paper immediately after stimulus presentation, and in the oral output conditions, B.H. was asked to spell each word orally immediately after stimulus presentation.

B.H.'s performance on these tasks was summarized in Table 5. Overall, B.H. seemed to perform better when stimuli were presented visually than when stimuli were presented auditorily. Although there was a trend for better performance in the visual input condition, a  $\chi^2$  test revealed no difference across the conditions ( $\chi^2 = 0.20$ ,  $P = n.s.$ ), suggesting modality invariance in B.H.'s spelling performance.

**Summary**

Our data demonstrated that B.H.'s spelling performance is compatible with the classic profile of graphemic buffer dysgraphia, as outlined by Caramazza and colleagues.<sup>1-3</sup> In the following section, we examine the proposal that the graphemic buffer may consist of at least 2 dissociable components: selection and assembly of letter information.

**MATERIALS**

To spell the word "chair" correctly, an individual must *select* the appropriate letters and must also *assemble*

the letters into the appropriate serial order. To understand these 2 processes, we devised 2 tasks that rely differentially on these 2 hypothesized components.

**Assembly (Scrabble) Task**

In the assembly (scrabble) task, letter identity information was provided to B.H., and her task was to assemble the given letters in the correct order. ("Scrabble" is a popular board game, in which players arrange letter tiles to create words.) On each trial, the experimenter read aloud a word (eg, balloon), and the patient was given the letter tiles necessary to spell the target word. For each word, the tiles were presented in a predetermined random order (eg, nblolao). B.H. was told that all the letters necessary to spell the target word were included in the set, and that there were no extraneous letters present. She was asked to rearrange the tiles to spell the target word, and she was given as much time as needed to complete each trial. After B.H. indicated that she has finished a trial, the experimenter recorded her response and presented her with the next set of tiles. Each trial was scored according to the guidelines described earlier (see Error Analyses section). This task relies on the assembly of letters (ie, letter location information), rather than the selection of letters (ie, identity information).

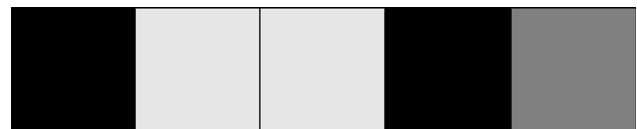
**Selection (Wheel of Fortune) Task**

Unlike the scrabble task, the wheel of fortune task emphasizes the selection component of the spelling process. ("Wheel of Fortune" is a popular American TV game show, in which contestants decipher the identity of words and phrases by guessing letters one at a time.) On each trial, a target word was read to B.H., and she was asked to spell the word orally, one letter at a time, but she was not required to produce letter location information. As B.H. produced each letter, the experimenter provided the location information by writing each letter down on a colored grid tailored for that stimulus, which was shown to B.H. at the time of stimulus presentation. The grid was colored in such a way that it provided word length and letter repetition information (Fig. 6). For example, the colored grid for the word "tooth" was composed of five boxes in the following colors: blue, yellow, yellow, blue, and gray. B.H. was told

**TABLE 5.** Modality Effects

	Input Modality	
	Visual	Auditory
Output modality		
Written	67% correct	47% correct
Oral	53% correct	47% correct

B.H.'s performance (% accuracy) in 4 different spelling conditions: visual input/written output; visual input/oral output; auditory input/written output, and auditory input/oral output.



**FIGURE 6.** Example of a grid used in the selection (wheel of fortune) task. Above is a gray-scale version of the grid for the stimulus "tooth." The actual grid used in the experiment was printed in the following colors for the 5 boxes: blue, yellow, yellow, blue, and gray. Gray-scale version of the grid was presented here for illustration purposes only.

that boxes of the same colors represented the same letter in different locations.

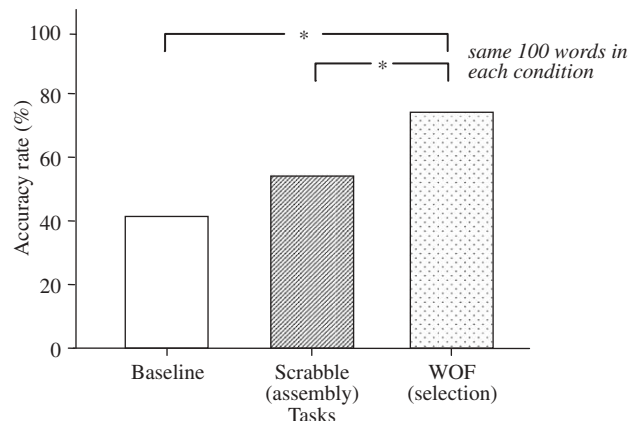
For example, a colored grid was shown to B.H. as a stimulus word was read (eg, “tooth”). She was asked to spell the target word one letter at a time, and she was also told that she could produce the letters in any order she wanted. That is, she was not required to produce the letters based on their serial positions. Despite that fact, B.H. began with the first letter of each word on all trials on which the first letter was correct. If a letter provided by B.H. belonged in the word, the experimenter would write the letter in the correct location and asked her for the next letter. If a letter appeared in more than one location (eg, “t” in “tooth”), all locations would be filled in. On the other hand, if B.H. provided an incorrect letter, the experimenter would record her error, and she would be informed of her mistake and would be asked to try again. However, B.H. was discouraged from guessing randomly because the total number of guesses was limited to the total number of unique letters in the word (eg, three guesses for the word “tooth”).

### Stimulus Characteristics

B.H. was asked to spell the same 100 words in 3 different tasks: baseline spelling to dictation, assembly, and selection. All words were presented auditorily, and the words varied in length from 3 to 10 letters. The 300 trials were administered across 4 sessions, within a 9-month period. Within each session, the order of the tasks was counterbalanced across a subset of stimuli.

## RESULTS

B.H.’s performance on the assembly (scrabble) and selection (wheel of fortune) tasks was summarized in Figure 7. When compared to baseline spelling to dictation trials (41% correct), B.H. performed significantly better on the selection task (74% correct,  $P < 0.001$ ). However, her performance on the assembly task (54% correct) was only marginally better than that on the baseline task ( $P = 0.07$ ). Critically, B.H. performed significantly better on the selection task than the assembly task ( $P < 0.01$ ). To summarize, although B.H. had difficulties with both letter selection and letter assembly, she was more impaired at retrieving letter location information than accessing letter identity information [An astute reviewer noted a seemingly inconsistent pattern of performance between B.H.’s deficit in letter assembly and the relatively low proportion of transposition errors in spelling to dictation. The argument is that if B.H. is disproportionately impaired at letter assembly, her spelling to dictation errors should consist primarily of transposition errors. We believe that the paradoxical pattern in our data may be an artifact of the “minimum error rule” that we adopted in error coding. As described in the “Error Analyses” section, the same error can be coded in different ways. For example, the error “heous” for the word “house” can be coded either as 4 transposition errors or as one insertion error and one deletion error.



**FIGURE 7.** B.H.’s performance on a baseline spelling to dictation task, the assembly (scrabble) task, and the selection (wheel of fortune) task.

According to the minimum error rule, we followed the latter coding scheme. As such, the true proportion of transposition errors may be obscured. This apparent inconsistency notwithstanding, the main goal of that error analysis was to demonstrate that, consistent with a graphemic buffer dysgraphia, most (97%) of B.H.’s spelling errors were on a graphemic level. It also points out that while the minimum error rule is a useful heuristic, it may not always be an accurate reflection of the true error patterns].

### Does B.H.’s Assembly Deficit Generalize to Other Domains?

Based on B.H.’s performance on the assembly and selection tasks, we proposed that the graphemic buffer consists of 2 dissociable components and that B.H. is relatively more impaired in letter assembly than letter selection. Here, we examined whether B.H.’s assembly deficit was specific to spelling or whether her letter assembly deficit stemmed from a more general sequencing impairment.

To evaluate B.H.’s sequencing abilities in a non-spelling domain, we administered the picture arrangement tests from the Wechsler Adult Intelligence Scale, Revised (WAIS-R)<sup>21</sup> and the Wechsler Adult Intelligence Scale, Third Edition (WAIS-III).<sup>22</sup> Because some of the items across the 2 editions are the same, only unique items were included in this analysis. A total of 16 trials were included—5 items from WAIS-R and 11 items from WAIS-III. On each trial, a collection of black and white picture cards that depict a story was presented to B.H., and the number of pictures varied from 3 to 6. The cards were presented to B.H. in a predetermined random order, and her task was to rearrange the cards to convey a logical story. Although it was not possible to evaluate her combined score on the 2 versions of the WAIS, we were able to compare her scaled score on the set of pictures from WAIS-III to normal performance. Her scaled score of 16 points on the set of pictures from WAIS-III was

within normal range, which supports the idea that her assembly problem may in fact be spelling-specific and does not generalize to the picture domain.

### Could B.H.'s Differential Performance on the Selection and Assembly Tasks be Attributed to Inherent Task Differences?

Because the selection and assembly tasks that we report here are relatively novel, it is conceivable that there exists inherent task differences that might have contributed to B.H.'s performance. In other words, it is possible that the pattern that we observed was due to differences in task difficulty. To address this issue, we administered the baseline spelling to dictation, selection, and assembly tasks to another patient with graphemic buffer dysgraphia (patient J.D.) and also to a group of 4 control subjects who were matched to B.H. in terms of age ( $M = 69.0$  y,  $SD = 4.8$  y) and education ( $M = 13.3$  y,  $SD = 0.96$  y). Patient J.D. is a 48-year-old right-handed man with a left temporal-parietal intracerebral lesion from a ruptured arteriovenous malformation. He also completed 14 years of education. Based on previous testing,<sup>23</sup> we have established that J.D.'s spelling profile is most compatible with that of graphemic buffer dysgraphia (see Appendix B). Furthermore, J.D. and B.H. performed similarly on the WAB, and they are both classified as anomic aphasics (Table 1). If the pattern of data we observed in B.H. were a function of inherent task differences, we would expect to see a similar pattern of data in J.D., who presented with similar cognitive and spelling profiles as B.H.

Procedures used to test J.D. were identical to that used to test B.H., with the exception that J.D.'s testing was administered across 2 sessions, spaced approximately 3 weeks apart. Contrary to the testing procedures used with the patients, control subjects performed all 3 tasks (baseline, selection, assembly) within the same session. Rather than using the same 100 stimuli in all 3 tasks, 3

different subsets of the stimuli totaling 100 items were used in the different tasks for each subject. Items were counterbalanced in the different conditions across subjects.

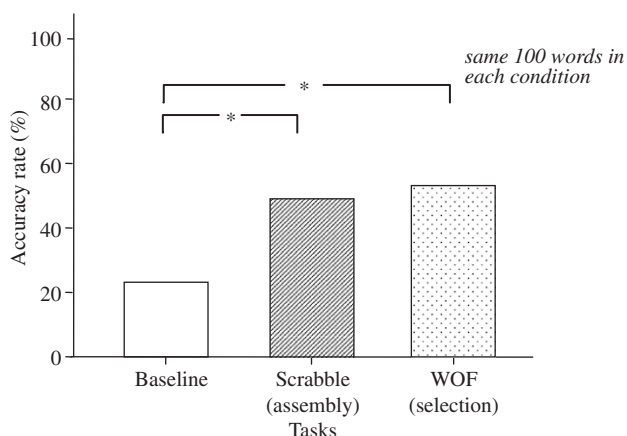
J.D.'s performance on the baseline, selection, and assembly tasks was summarized in Figure 8. Compared to baseline spelling to dictation, J.D. benefited from both letter identity information in the assembly task ( $P < 0.001$ ) and letter location information in the selection task ( $P < 0.001$ ). However, J.D.'s performance between the assembly and selection tasks did not differ ( $P = 0.29$ ). Control subjects, on the other hand, performed at ceiling on all tasks (baseline  $M = 95\%$ , assembly  $M = 95\%$ , selection  $M = 99\%$ ). A one-way non-parametric analysis of variance revealed no task differences ( $\chi^2 = 4.00$ ,  $P = 0.14$ ). Taken together, these data suggest that B.H.'s pattern of performance (ie, improved performance on selection task compared to assembly task) is unlikely to be attributable to a simple artifact of inherent task differences.

## CONCLUSIONS

In this paper, we tested the hypothesis that the graphemic buffer differs from a simple working memory buffer and that it is composed of 2 dissociable components—letter selection and letter assembly. Patient B.H.'s spelling performance fits within the generally accepted pattern that is associated with graphemic buffer deficits. Most notably, B.H.'s spelling profile featured hallmarks outlined by Caramazza and colleagues<sup>1-3</sup>: word length effect, serial position effect, spelling errors on a graphemic level, and modality invariance. In examining the components within the graphemic buffer, we observed significant improvement in B.H.'s spelling performance when assembly demands were minimal (ie, wheel of fortune task), but not when letter selection demands were minimal (ie, scrabble task). In other words, B.H.'s performance was enhanced when location information was made available to her, but she did not benefit when letter identity information alone was provided. This pattern of data is consistent with the idea that the graphemic buffer consists of at least 2 components—letter selection and letter assembly (see Ref. 24 for a similar proposal).

Two other lines of evidence support our proposal that letter assembly can be selectively disrupted. First, B.H. did not demonstrate a general deficit in her ability to assemble sequences. When given picture panels to be placed in a sequence that depicts a coherent narrative, she performs within the normal range. Second, it does not seem that the assembly task is intrinsically more difficult than the selection task. Patient J.D., whose cognitive and spelling profiles are similar to those of B.H.'s, is aided similarly by letter identity and location information.

The functional distinction that we have proposed for the graphemic buffer is similar to the functional division of working memory proposed by Petrides and colleagues.<sup>25,26</sup> They suggested that human working



**FIGURE 8.** J.D.'s performance on a baseline spelling to dictation task, the assembly (scrabble) task, and the selection (wheel of fortune) task.



memory consists of at least 2 functionally and anatomically dissociable components—temporary maintenance of information and online manipulation of information. In the context of the spelling process, we have presented evidence that the graphemic buffer may also involve 2 dissociable components for temporary maintenance and online manipulation of graphemic representations: letter selection and letter assembly. It remains to be seen whether the opposite dissociation, a deficit in letter selection and not of assembly, can occur.

### ACKNOWLEDGMENTS

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### APPENDIX A

#### B.H.’s Overall Language Abilities

B.H. did not suffer from an overall language impairment and her spelling impairment was relatively isolated. To assess her overall language function, we administered subsections of the Western Aphasia Battery.<sup>15</sup> B.H. had an aphasia quotient of 88.4 and was classified as an anomie aphasic. Her performance is summarized in Table 1.

Aside from occasional word finding difficulties, her overall language performance was quite good. Specifically, she did not experience any major difficulties in the following subtests: spontaneous speech, repetition, object naming, sentence completion, responsive speech, and reading comprehension. Based on this profile, we concluded that B.H.’s deficit in spelling cannot be explained by an overall language impairment.

When asked to describe a black and white line drawing, she told a coherent story using complete sentences (eg, “I see maybe a man and a dog and a son flying a kite with little doggie”). However, when asked to describe the same picture in writing, she only managed to produce short and incomplete sentences (eg, “Mom and Dad, boy with a kite, another son in the water”). Similarly, she was able to read and copy a sentence that she could not write to dictation (“Pack my box with five dozen jugs of liquid veneer”). Although she was only able to repeat 4 of the 10 words in this sentence, her inability to write to dictation cannot be explained by a memory failure because her dictation errors were spelling errors and not word omission errors (see Fig. 2).

The discrepancy between her spelling performance and her overall language abilities was further illustrated in Section VI of the WAB. Although her knowledge for single letters and numbers was intact, as indicated by her

maximum scores on written production of individual numbers and letters, her ability to spell was extremely impaired, as evidenced by her score of 9.5 out of 34 in the written output section (Table 1).

Was B.H.'s deficit a result of an apraxic dysgraphia? One subtype of dysgraphia, apraxic dysgraphia, is a result of motor programming deficits. To explore whether B.H.'s dysgraphia was of this variant, we tested her ability to produce single letters and numbers. B.H. was capable of producing well-formed individual letters and numbers. We concluded that her inability to produce written spelling was not due to an apraxia (Fig. 2).

Was B.H.'s deficit a result of degraded long-term graphemic representations? B.H. was able to spontaneously write all of the letters in the alphabet and all of the integers from 0 to 20. Therefore, it is unlikely that her spelling deficit is a result of not knowing or remembering individual alphabets used in the English language.

Was B.H.'s deficit a result of inaccurate grapheme selection? Our patient also performed perfectly on single letter dictation. Thus, it was unlikely that she has lost the ability to map sounds to letters.

**APPENDIX B**

**Patient 2—J.D.**

J.D. is a 48-year old right-handed man with a left temporal-parietal intracerebral lesion from a ruptured AVM. He completed 14 years of education and was a professional bus driver. J.D. performed normally on

reading, remote memory, object naming, and comprehension tasks. His digit span was 5 digits forward and 2 digits backward, and he had mild difficulties when repeating complex sentences. His production and comprehension seem intact, as he was able to engage in long conversations without any impediment. Because of personal reasons, J.D. was unavailable for further testing. As a result, the data that we have available on his spelling performance are limited.

**Overall Language Abilities**

To assess J.D.'s overall language functions, we administered subsections of the Western Aphasia Battery.<sup>15</sup> J.D.'s aphasia quotient was 86.6, and his profile fits that of an anomic aphasic. A summary of his performance can be found in Table 1. Similar to B.H., J.D. scored quite well on most sections of the WAB. His most pronounced deficits seem to be following sequential commands and in spelling. Despite his intact knowledge of individual letters and numbers, he performed very poorly on the written output test.

Similar to B.H., when asked to describe a black and white line drawing, J.D. told a sensible story using complete sentences (eg, "It's a family going on vacation. ... The whole family is having a good time.") However, when asked to tell a story about the same picture in writing, he produced only one sentence that was filled with spelling errors ("Avocion in the summery wish the family in the beach"). He was also able to read and copy a sentence ("Pack my box with five dozen jugs of liquid veneer") that he could not produce in writing ("Pack my back with 5 geg of liewood vernier").

Based on J.D.'s performance on the WAB, we are able to conclude the following: (1) that his dysgraphia is not a result of apraxia because his individual letters and

Copying from visual stimulus:

"Pack my box with 5 dozen jugs of liquid veneer"

Pack my box with five dozen jugs  
of liquid veneer.

Spelling to dictation: "Pack my box with 5 dozen jugs of liquid veneer"

Pack my back with  
5 geg of liewood vernier

Single letter and number dictation:

M D G B F  
5 61 32 700 1817

Spelling to dictation:

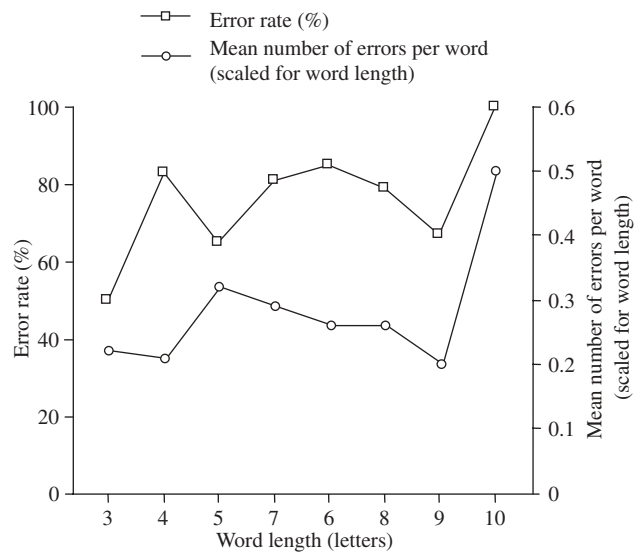
Gun Whoc Nose Hamer

"gun"(gun) "watch"(whoc) "nose"(nosie) "hammer"(hamer)

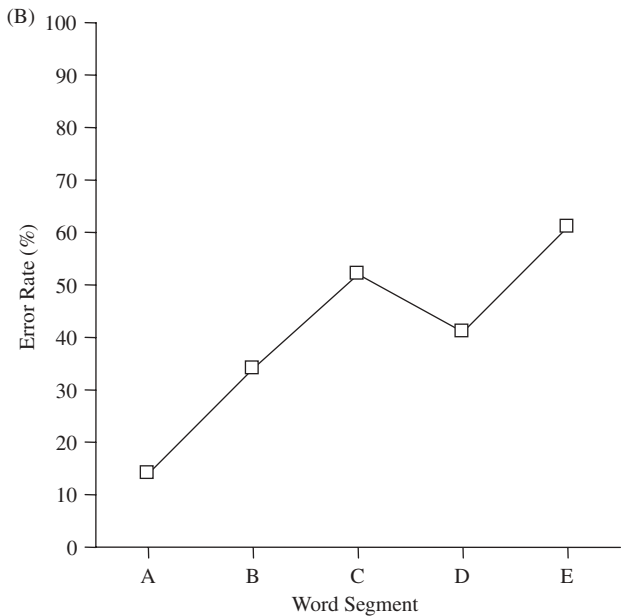
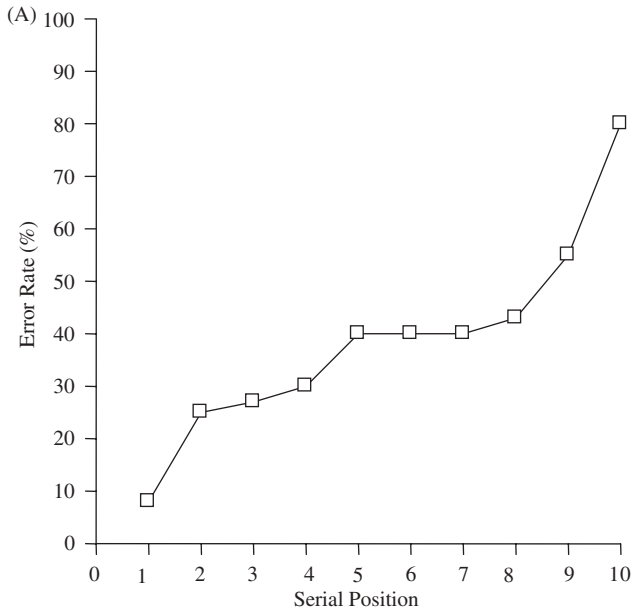
Telephone. Crou.

"telephone" (telephone) "screwdriver" (crou)

**FIGURE 9.** Writing samples from patient J.D.

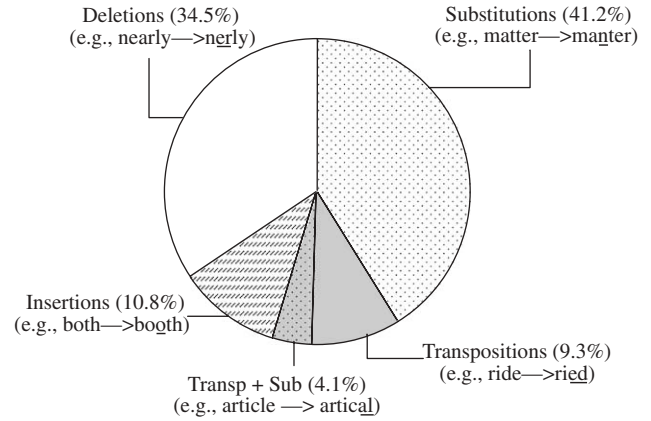


**FIGURE 10.** Spelling performance as a function of word length (patient J.D.).



**FIGURE 11.** Spelling performance as a function of serial position (patient J.D.).

numbers were well formed (see Fig. 9); (2) it is unlikely that his deficit is a result of degraded long-term graphemic representations because he was able to recall all of the letters in the alphabet. (It is interesting to note, however, that the positions of the letters G and J were transposed. Incidentally, when asked to dictate individual letters, he produced the letter “G” when asked to write “J.” However, he did not commit this error in whole word spelling. For example, he spelled “glass” and “jacket” correctly).



**FIGURE 12.** Types of spelling errors committed by J.D. (total number of graphemic errors: 194 errors).

**Spelling Performance**

As outlined earlier, there are 4 hallmark features of the graphemic buffer deficit—word length effect, serial position effect, error types, and modality invariance. We will discuss each of these features in turn.

**Spelling to Dictation—Word Length Effect**

J.D. was asked to spell a total of 103 nouns, and he committed at least one error in 77% of the words (ie, 79 nouns). As illustrated in Figure 10, J.D.’s error rates rose from 50% to 100% from 3-letter words to 10-letter words. When error rates were examined as a function of word length, a marginally significant positive correlation was observed ( $r = 0.59, P = 0.06$ ).

**Spelling to Dictation—Serial Position Effect**

Figures 11A, B summarized J.D.’s spelling performance as a function of serial position. Similar to patient B.H., J.D. also made fewer errors in the beginning position than in the final position (first position: 7.8% error; tenth position: 80.0%). When letter distribution is normalized based on a binning procedure proposed by Wing and Baddeley<sup>12</sup> and Caramazza and colleagues,<sup>1</sup> a similar pattern of error distribution was observed (first bin: 13.7% error; fifth bin: 60.8%). Although the error distribution pattern observed in J.D. is slightly different from that observed in B.H., J.D.’s pattern is also consistent with patterns that have previously been observed in other graphemic buffer dysgraphic patients (eg, Ref. 9).

**Spelling to Dictation—Error Types**

J.D.’s spelling errors were analyzed based on the classification scheme outlined earlier (see Error Analyses section). A total of 194 errors were made, and less than 2% of errors resulted in real words (eg, spelling “both” and “booth”). The remaining errors occurred at a

graphemic level (Fig. 12). This pattern of error distribution is consistent with a graphemic buffer deficit.

#### **Spelling to Dictation—Modality Invariance**

We were unable to assess the effects of modality on J.D.'s spelling performance because he was unavailable for further testing.

#### **Summary**

To summarize, we have demonstrated that, similar to B.H., J.D.'s spelling is disproportionately impaired, and that his spelling profile is largely compatible with a graphemic buffer deficit.