Journal of Experimental Psychology:
Learning, Memory, and Cognition
2013, Vol. 39, No. 5, 1572–1584

0278-7393/13/$12.00 DOI: 10.1037/a0032189

Why Do We Mipsell the Middle of Words? Orthographic Texture and the Serial Position Effect

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In the current set of studies, a new hypothesis regarding the cause of the commonly observed U-shaped serial position effect (SPE) in spelling is introduced and tested. Instead of greater competition during output or weaker positional representation for word-medial letters, commonly accepted explanations for the cause of the SPE, the *orthographic texture hypothesis* suggests that variations in the activation strength of individual letters are responsible for the variations typically observed in spelling accuracy as a function of letter position. Sound-letter convergence, a measure of orthographic texture referring to how often a single letter appears in a sound's spelling, may be responsible for higher accuracy rates at word-flanking letter positions. Indeed, when sound-letter convergence was manipulated, spelling accuracy was as high as or higher in word-medial letter positions than in word-initial or -final letter positions indicating that letter position alone cannot account for the pervasive U-shaped serial position effect.

Keywords: spelling, orthographic texture, serial position

Although spelling may appear an easy, effortless process once mastered, consistent error patterns indicate otherwise. The analysis of error patterns, in fact, has driven the field of spelling research. Of particular interest is perhaps the most commonly observed error pattern in spelling—the U-shaped serial position effect. Beginning (e.g., Mendenhall, 1930; Treiman, Berch, & Weatherston, 1993), skilled (e.g., Wing & Baddeley, 1980), and neurologically impaired spellers (e.g., Caramazza, Miceli, Villa, & Romani, 1987) tend to misspell letters in word-medial positions compared to word-initial or -final letter position. This pervasive effect of serial position was originally attributed to competition among letters during output. More letters are activated, and therefore interfere with and compete with one another for selection, at word-medial letter positions than initial or final positions; flanking letters only have letters to one side, which may also be activated for output. However, this post hoc explanation for one of the most commonly observed patterns of spelling errors leaves much to be desired as it is not directly testable and "does not . . . have an explicit theoretical justification" (Caramazza et al., 1987, p. 83). The goal of the current study is to provide a theoretically motivated, testable hypothesis regarding the cause of the U-shaped serial position effect.

Current explanations of the serial position effect in spelling suggest that the effect is due specifically to the position a letter occupies in a word. These positional accounts attribute the effect as arising either from increased competition at word-medial letter positions (e.g., Caramazza et al., 1987; Wing & Baddeley, 1980) or from less distinct positional representations at word-medial positions than flanking ones (e.g., Shallice, Glasspool & Houghton, 1995). Alternatively, the *orthographic texture hypothesis* introduced in the current study suggests that the serial position effect may be driven by letter-level variables that influence activation strength, regardless of the position a letter occupies in a word. Word-medial letters tend to be misspelled not because they happen to be in word-medial positions, but because they differ from flanking letters in terms of other variables influencing activation strength. Before discussing the *orthographic texture hypothesis* and variables that may be related to it, however, a review of the research relevant to the serial position effect is first considered.

The U-shaped serial position effect was originally documented by Wing and Baddeley (1980) in an investigation of spelling errors made by applicants on Cambridge University entrance exams. Applicants' slips of the pen, those errors that were immediately self-corrected or produced correctly elsewhere in the essay, showed that the medial portions of words were most susceptible to errors. Importantly, because errors were immediately self-corrected or produced correctly elsewhere, they were clearly not the result of insufficient spelling knowledge. Wing and Baddeley concluded that these simple slips of the pen were the result of competition during output; competition results in a "read-out" failure for word-medial letters in the spellings of known words (see also Caramazza et al., 1987). There are simply fewer letters competing for output at word-initial and -final letter positions, thus fewer errors occur in these positions.

This explanation for the cause of the U-shaped serial position effect implicates the working memory processes necessary for spelling, or orthographic working memory (O-WM; commonly referred to as the *graphemic buffer* in the spelling literature; see Nolan & Caramazza, 1983), which is responsible for both maintaining the activation of letters and for correctly selecting activated letters for output during spelling (Costa, Fischer-Baum, Capasso, Miceli, & Rapp, 2011; Rapp & Kong, 2002). In fact, individuals with impairments to O-WM show rather pronounced U-shaped

This article was published Online First April 8, 2013.

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serial position effects (e.g., Caramazza et al., 1987; Jónsdóttir, Shallice, & Wise, 1996; Schiller, Greenhall, Shelton, & Caramazza, 2001; Tainturier & Rapp, 2004). This increased effect of serial position on spelling accuracy compared to unimpaired spellers supports the hypothesis that effects of serial position arise at the level of O-WM. The effect has been attributed to greater noise in O-WM, or an overall reduced level of activation strength of graphemes in O-WM as the result of damage (Schiller et al., 2001).

Computational competitive queuing (CQ) models of spelling output (e.g., Glasspool & Houghton, 2005; Glasspool, Shallice, & Cipolotti, 2006) are consistent with the hypothesis that the serial position effect may arise from increased noise in O-WM. Models with greater levels of noise lead to more pronounced serial position effects. However, it is important to note that effects in these models arise primarily because positional representations are less distinct at word-medial compared to -initial or -final letter positions; they do not address issues of competition. Regardless, both the competition accounts and CQ models treat serial position effects as due to the specific position a letter occupies within a word.

Although this U-shaped serial position effect is the most commonly observed effect of serial position, it is not the only effect found for those with O-WM impairments (e.g., Bormann, Wallesch, & Blanken, 2008; R. B. Katz, 1991; Kokubo, Suzuki, Yamadori, & Satou, 2001; Schiller et al., 2001; Ward & Romani, 1998). Several individuals have instead shown a monotonic decrease in accuracy as a function of letter position. Two hypotheses have been proposed as an explanation for the monotonic decrease in accuracy: the *rapid decay hypothesis* (R. B. Katz, 1991; Schiller et al., 2001) and the *lexical hypothesis* (Bormann et al., 2008; Cipolotti, Bird, Glasspool, & Shallice, 2004; Ward & Romani, 1998). The rapid decay hypothesis, like the competition and CQ accounts of the U-shaped serial position effect, implicates O-WM as the locus of the effect. However, evidence supporting the lexical hypothesis implicates damage to the long-term memory representations of word spellings.

The rapid decay hypothesis attributes the effect to a reduced O-WM capacity, leading to the rapid decay of information in O-WM. As such, word-initial letters are spelled with high levels of accuracy while subsequent information is lost as spelling proceeds. The performance of Patient HR (R. B. Katz, 1991) and Patients TH and PB (Schiller et al., 2001) support this position. HR was able to accurately produce word-final letters when asked to spell backward; spelling errors were instead made on word-initial letters that were produced last in backward spelling. Patients TH and PB were able to accurately spell (or identify) word-final letters when working memory load was reduced. The performance of these patients demonstrates that the orthographic representations in LTM were intact, but information was quickly lost based on O-WM load.

Alternatively, the performance of Patients BA (Ward & Romani, 1998), DA (Cipolotti et al., 2004), and MD (Bormann et al., 2008), who show the same general spelling profile and serial position effect as Patients HR, TH and PB, calls into question the role of decay (and O-WM) in the serial position effect and instead supports the lexical hypothesis. This hypothesis suggests that damage specifically affecting word-final portions of orthographic representations in LTM is the cause of the monotonic decrease in accuracy. In backward spelling tasks, Patients BA and MD still produced more errors on word-final letters than word-initial ones despite being produced first (e.g., bone → INOB). Also suggestive of an impairment specifically affecting word-final portions of orthographic representations, MD more successfully completed word fragments missing initial letters as opposed to those missing word-final letters. Furthermore, the introduction of a delay did not affect MD and DA's spelling accuracy, which would be expected to exacerbate the effect if decay were the cause. Taken together, these data demonstrate that disruptions to O-WM cannot be the sole cause of the monotonic decrease in spelling accuracy as a function of serial position.

Because there is evidence that the content of orthographic representations may be responsible for the monotonically decreasing serial position effect, it is worth considering how lexical variables may influence spelling accuracy in individuals with O-WM impairments demonstrating the typical U-shaped serial position effect. Patient BH (Sage & Ellis, 2004) made spelling errors suggesting a deficit to O-WM. Importantly, her spelling accuracy was also influenced by a variety of lexical factors including imageability, age of acquisition (AoA), frequency, and the number of orthographic neighbors (N). Sage and Ellis (2004) also reviewed data from 17 patients classified as having O-WM deficits and found that 12 of them also had lexical influences on their spelling accuracy. They suggested that lexical influences may be the result of differential activation of orthographic representations in O-WM. Consistent with this view, Buchwald and Rapp (2009) reported evidence from two patients with O-WM impairments that demonstrated lexical effects on their spelling accuracy, including word frequency, AoA, and N.

Jones and colleagues (Jones, Folk, & Rapp, 2009) recently demonstrated that not only may orthographic representations activated for spelling in O-WM vary due to lexical factors but that the activation strength of individual letters in a word may vary in O-WM, referred to as orthographic texture. As an operationalization of orthographic texture, they examined the influence of sound-letter convergence (SLC) on spelling accuracy in an individual with an O-WM impairment as well as in unimpaired spellers performing a distractor task that disrupted O-WM function. SLC refers to how often an individual letter appears in a sound's spelling. Consider, for example, the phoneme /e/ in BR*AI*D. There are a total of 16 different ways in which the phoneme /e/ can be spelled, 12 of which are possible in syllable-medial positions in English. Most all of those possible spellings include the letter A. In fact, the letter A is used 97.9% of the time in spelling the phoneme /e/, whereas the letter I is used in only 21.8% of observed spellings (Hanna, Hanna, Hodges, & Rudorf, 1966). Thus, although both the A and the I contribute to the spelling of the phoneme /e/ in BRAID, each letter does so to differing degrees overall in the English language. Supporting the hypothesis of orthographic texture in that individual letters are activated in O-WM at varying strengths, Jones et al. (2009) found that spellers were more likely to make errors on letters low in SLC than high in SLC when O-WM function was disrupted.

It is important to note that SLC is different from other measures of sublexical consistency, such as phoneme-grapheme (PG) probability which refers to the probability that a letter or letters maps onto a phoneme's spelling. For example, given the word BRAID, the grapheme "AI" has a PG probability of 17.86% (Hanna et al., 1966). SLC, however, is a subgraphemic variable in that it measures the contributions an individual letter within a grapheme makes toward a phoneme's spelling. In other words, the letters A and I both have different SLC values, but they share a single PG probability value for a word like BRAID. Furthermore, when a grapheme consists of a single letter, it may have a low PG probability but be high in SLC. For example, the letter A (to spell the word YANK) has a low PG probability but is high in SLC (PG: 12.51%; SLC: 97.9%). Although it has been demonstrated that PG probability is a major influence in spelling (e.g., Kreiner, 1992; Perry & Ziegler, 2004), Jones et al. (2009) demonstrated that SLC influences spelling accuracy even when PG probability is controlled.

Like other sublexical variables known to influence accuracy (e.g., consistency, PG probability), it is currently unclear what causes these effects. Jones et al. (2009) suggested that orthographic texture most likely arises from one of two sources: lexical-learning or online-competition during spelling. Orthographic texture may be the result of lexical-learning processes in that those letters that are easiest to learn in a word's spelling result in a stronger representation and are therefore more strongly activated during the course of spelling. Consistent with this idea, Perry and Ziegler (2000) demonstrated that factors known to influence the ease of learning for children resulted in more difficulty for skilled adult readers. Using SLC to operationalize orthographic texture, it may be that the letter A is easier to learn in the spelling of BRAID than the letter I because A appears so frequently in spellings of the phoneme /e/. As such, it is represented in the adult lexicon and activated more strongly during spelling than those letters low in SLC. Alternatively, orthographic texture effects may arise from online-competition during spelling. Information from the lexical and sublexical processes interact during the course of spelling (e.g., Folk & Jones, 2004; Folk, Rapp, & Goldrick, 2002; Rapp, Epstein, & Tainturier, 2002). This interaction may yield orthographic texture effects in that some letters will be activated by both the lexical and sublexical processes, but others will not. Again, as an example, both processes will produce the letter A for the word BRAID, but the sublexical process may not produce the grapheme AI for the /e/ phoneme as it does not have the highest PG probability. Instead, it may produce a spelling with a higher PG probability for the phoneme, like BRADE. Thus, the letter A is more strongly activated for spelling than the letter I because both spelling processes support its output, whereas only the lexical process may produce the I.

By using SLC to operationalize orthographic texture, the goal of the current study is to further examine the role of orthographic texture on spelling accuracy—specifically on spelling accuracy as a function of letter position. The current study will test the hypothesis that orthographic texture is actually responsible for the commonly observed U-shaped serial position effect. According to the *orthographic texture hypothesis*, variations in the activation strength of individual letters in O-WM are responsible for the U-shaped serial position effect. Specifically, it is hypothesized that the reduced levels of accuracy in word-medial positions typically observed are the result of words most often having letters low in SLC at those positions compared to flanking ones. This hypothesis differs from the current explanations of the serial position effect offered by the competition and CQ accounts in that letter-level variables account for the effect, not simply the position a letter occupies. In Study 1, the relationship between SLC and letter position is established. In Study 2, spelling accuracy at the typically error-free word-initial and -final letter positions is examined when SLC is manipulated. Finally, in Study 3, the *orthographic texture hypothesis* is directly tested when SLC is manipulated at word-initial, -medial, and -final letter positions.

Study 1

The purpose of Study 1 is to investigate the relationship between letter position and SLC in the English language. Given the variability in the spellings of sounds in the language, especially vowel sounds that often occupy word-medial letter positions, it is probable that SLC values are generally lower in word-medial letter positions. However, this has not been demonstrated. If analyses of randomly selected sets of English words demonstrate a relationship between SLC and letter position, and specifically a relationship that indicates lower SLC values in word-medial positions, then it is plausible that SLC may be responsible for the U-shaped serial position effect.

Study 1a

Method. Three hundred five-letter monosyllabic, monomorphemic words were randomly selected from the English Lexicon Project database (Balota et al., 2007). SLC, a type-based frequency measure, was calculated for each letter by considering each possible spelling of a phoneme based on its position in the syllable from the Hanna et al. (1966) PG mapping counts. As an example, consider again the phoneme /e/ in BR*AI*D. Of the 12 possible spellings of that phoneme in syllable-medial positions, eight include the letter A (A, A-E, AY, AI-E, EA, AIGH, AU-E) and six include the letter I (AI, AI-E, EIGH, EI, AIGH, EI-E). Those spellings that include the letter A are much more frequently occurring than those including the letter I. Of the 1,047 occurrences of the phoneme /e/ in syllable-medial positions tabulated by Hanna et al. (1966), spellings including the letter A occur 1,025 times and spellings including the letter I occur 228 times, resulting in SLC values of 97.9 and 21.8, respectively: $SLC_A = p((A + A\text{-}E + AY + AI\text{-}E + EA + AIGH + AU\text{-}E) \mid /e/)$, $SLC_I = p((AI + AI\text{-}E + EIGH + EI + AIGH + EI\text{-}E) \mid /e/)$.

Results. Figure 1a shows the variation in SLC as a function of letter position, $F(4, 1196) = 7.228$, $MSE = 861.1$, $p < .001$; SLC values decreased from word-initial letter positions but increased again at word-final positions. Comparisons of Figure 1a and Figure 1b, which illustrates spelling accuracy as a function of letter position for dysgraphic individual, JRE (adapted from Jones et al., 2009), illustrate the striking similarity between SLC and spelling accuracy as a function of letter position.

Study 1b

The decision to restrict items in Study 1a to five-letter monosyllabic, monomorphemic words was made for several reasons. Spelling accuracy has been demonstrated to vary as a function both of letter position within the syllable (Caramazza & Miceli, 1990) and morphemic status (Badecker, Hillis, & Caramazza, 1990); it is possible that SLC also varies as a function of these variables. Furthermore, Olson, Romani, and Caramazza (2010) suggested that measures of spelling accuracy as a function of letter position not be collapsed across word length for a single five-letter word

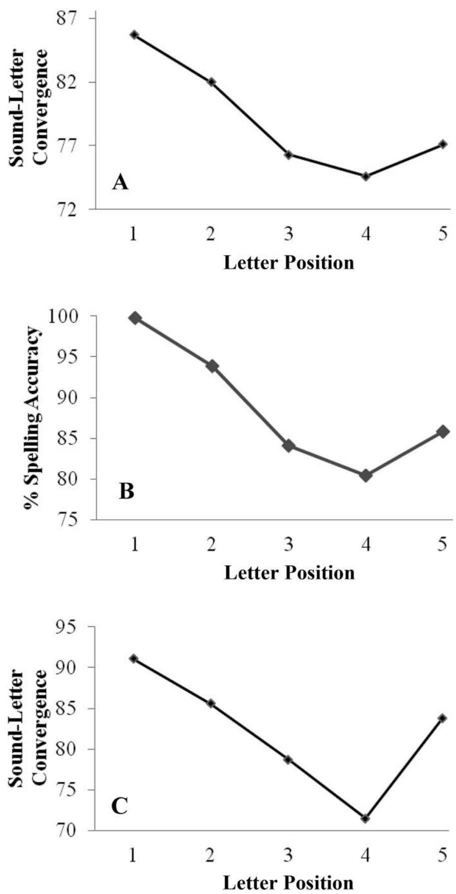

Figure 1. A. Sound-letter convergence as a function of letter position for the 300 randomly selected five-letter words in Study 1a. B. Sound-letter convergence as a function of letter position for the 300 randomly selected three- to eight-letter words in Study 1b. C. Spelling accuracy as a function of letter position for dysgraphic individual, JRE. Adapted from "All Letters Are Not Equal: Subgraphemic Texture in Orthographic Working Memory," by A. C. Jones, J. R. Folk, and B. Rapp, 2009, *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35,* p. 1395. Copyright 2009 by the American Psychological Association.

accuracy function; instead, serial position effects should be investigated separately for different word lengths. However, because most studies reporting serial position effects include multisyllabic and -morphemic words and collapse across word length, Study 1b was conducted with a second, independently selected sample of 300 words that varied in word length and number of syllables and morphemes.

Method. Three hundred words were randomly selected from the English Lexicon Project database (Balota et al., 2007). They included three- ($N = 7$), four- ($N = 26$), five- ($N = 40$), six- ($N = 76$), seven- ($N = 83$), and eight-letter words ($N = 68$). SLC was calculated for each letter by considering each possible spelling of a phoneme based on its position in the syllable from the Hanna et al. (1966) PG mapping counts.

In order to create a single, five-letter word serial position effect as a function of SLC for these items, a method similar to that of Wing and Baddeley (1980) was used. For all word lengths, the SLC value of the first letter was assigned to Position 1 and the SLC value of the last letter was assigned to Position 5. For three-letter words, the SLC value of the second (middle) letter was assigned to Position 3. For four-letter words, the SLC value of the second letter was assigned to Position 2 and the SLC value of the third letter was assigned to Position 4. For six-letter words, the SLC value for the second letter was assigned to Position 2, SLC values for the third and fourth letters were averaged and assigned to Position 3, and the SLC value for the fifth letter was assigned to Position 4. For seven-letter words, SLC values for the second and third letters were averaged and assigned to Position 2, the SLC value for the fourth letter was assigned to Position 3, and SLC values for the fifth and sixth letters were averaged and assigned to Position 4. For eight-letter words, SLC values for the second and third letters were averaged and assigned to Position 2, SLC values for the fourth and fifth letters were averaged and assigned to Position 3, and SLC values for the sixth and seventh letters were averaged and assigned to Position 4.

Results. Figure 1c shows that the pattern of results for the second set of items was consistent with that obtained for the first; SLC varied as a function of letter position, $F(4, 1064) = 30.532$, $p < .001$. SLC values decreased from word-initial letter positions and increased again at word-final letter positions.

Study 2

Because results from Study 1 indicate that SLC is related to letter position and that SLC is lowest at word-medial positions, the purpose of Study 2 is to examine whether spelling accuracy can be influenced at the typically error-free word-initial and -final letter positions when SLC is manipulated. The only other investigation of the influence of SLC on spelling accuracy manipulated SLC with word-medial vowel digraphs (Jones et al., 2009). As such, it is unclear whether effects of SLC on spelling accuracy will arise in word-initial and -final positions given the high levels of accuracy demonstrated by most spellers at these positions.

SLC may not influence spelling accuracy at word-initial and -final letter positions if these letters are privileged due to their flanking positions in words. These letters may be immune to error regardless of SLC. It is possible that SLC only influences spelling accuracy at word-medial positions where competition is greatest or position representation is weakest. Alternatively, SLC may influence spelling accuracy at word-flanking letter positions. The high accuracy rates typically observed may simply be due to the fact that SLC tends to be high at these positions and its influence on spelling accuracy at these positions has never been examined.

Method

Participants. Forty-one Kent State University undergraduates participated in this study in exchange for course credit. All were native English speakers and reported no reading or spelling disabilities.

Materials. Materials consisted of 100 words (536 letters) for a writing-to-dictation task. Sixty-eight words were included to assess effects of SLC on spelling accuracy at word-initial and -final letter positions; the remaining words were filler items. Seventeen words had initial letters with high-SLC ($M = 97$; e.g., *t*hug) that were matched with 17 words with low-SLC initial letters

(M = 8.2; e.g., *k*nob). Items were matched in length, word frequency,[1] number of phonemes, syllabic and morphemic structure, and all letters were matched in consonant/vowel status. Seventeen items included words with high-SLC final letters (M = 96.2; e.g., gros*s*); these items were also matched on the aforementioned characteristics with 17 words containing low-SLC final letters (M = 3.9; e.g., clim*b*). See Appendix A for critical experimental items.

Procedure. Participants completed two experimental sessions, spaced 1 week apart, in which they spelled all 100 words in two different writing-to-dictation conditions: control and shadow. These conditions are the same used and reported by Jones et al. (2009). The purpose of the control condition was to assess long-term knowledge of word spellings. In this condition, participants were simply asked to spell each word to dictation. Items were presented by the experimenter. Participants were required to repeat each item aloud before writing its spelling to ensure they heard items correctly. After repeating the item, they wrote its spelling on a sheet of paper at their own pace. The shadow condition, however, was a speeded writing-to-dictation task that included a secondary, distractor task for participants to complete. Instructed to write as quickly as possible, participants had 3 s to spell each item while they also heard and had to repeat randomly presented nonsense syllables consisting of a consonant + vowel sound (e.g., "ba . . . ri . . . fa"). All items in the shadow condition were presented over headphones. In addition to repeating the nonsense syllables, participants were also required to repeat the to-be-spelled word. The purpose of the shadow condition, by means of the distracting secondary task, was to disrupt the operation of the working memory processes necessary for spelling (O-WM).

In order to familiarize participants with the task, there were two practice phases before the experiment began: (a) Participants simply repeated the to-be-spelled words and nonsense syllables (presented over headphones) but were not required to actually write the word spelling, then (b) participants practiced the experimental procedure itself—they listened to and repeated to-be-spelled words and nonsense syllables and wrote the spellings of the words.

During each experimental session, participants spelled half of the words in the control condition and the other half in the shadow condition. All words were spelled a total of two times, once in each experimental condition, but never twice during the same session. Condition was counterbalanced such that experimental sessions started with the shadow condition for half of the participants while the other half began with the control condition. Furthermore, there were two randomized lists of materials so that there were a total of four possible list presentations for participants.

Results and Discussion

Of current interest is only spelling accuracy when working memory processes were disrupted—that is, performance in the shadow condition. As mentioned, the purpose of the control condition was to assess each participant's long-term knowledge of word spellings. If an item was misspelled in the control condition, it was considered to result from a lack of knowledge. As such, a participant's response to that item in the shadow condition was not scored or included in further analyses as any errors produced could not necessary be considered the result working memory disruption resulting from the secondary, distracting task. A total of 8.6% of responses were excluded from analyses due to errors in the control condition, all of which were phonologically plausible misspellings (e.g., thief → THEIF, caress → CARRESS).

Scoring. Participant responses were scored as they were by Jones et al. (2009), a commonly used procedure in the scoring of spelling responses (e.g., Caramazza et al., 1987; McCloskey, Badecker, Goodman-Schulman, & Aliminosa, 1994; Schiller et al., 2001). One point was awarded to each letter correctly produced in the correct position. A target letter was awarded one-half point if it was produced, but in the wrong position (e.g., brave → BARVE). In addition, letters received one-half point (instead of one) if it was adjacent to an erroneously inserted letter (e.g., touch → TROUCH). A letter was awarded zero points if it was not produced.

Disruption to O-WM. Before examining the influence of SLC on spelling accuracy, analyses were first conducted to establish that the shadowing task did indeed disrupt O-WM. Typical patterns of impairment for individuals with neurological deficits affecting O-WM include letter level errors consisting of additions (e.g., salt → SARLT), deletions (e.g., banana → BANA), substitutions (e.g., trophy → TRIPHY), and shifts/transpositions (e.g., reward → RERWAD, grieve → RGIEVE). Furthermore, their substitution errors reflect preserved knowledge of consonant/vowel status; that is, vowels are substituted for vowels and consonants for consonants. Finally, they show word length effects in that accuracy is lower on long words than short words (see Miceli & Capasso, 2006).

Considering the entire list of words administered to participants, patterns of performance were consistent with those indicating O-WM impairment. Participants produced letter errors that included additions, deletions, substitutions, and shifts/transpositions; 64.31% of spelling errors resulted in spellings that were not phonologically plausible. See Table 1 for error distributions and example errors. Furthermore, given participants' substitution errors, there were high rates of consonant/vowel (C/V) preservation (e.g., climb → CLAMB, auction → AUNTION) with vowels being substituted for vowels 88.7% of the time and consonants for consonants 98.4% of the time, with an overall C/V preservation rate of 95%. Finally, there were fewer letter errors on short (four- and five-letter) words than on long (six-, seven-, and eight-letter) words, 1.7% and 2.9%, respectively, $t(40) = -3.317$, $p < .005$. Thus, patterns of performance confirm that the shadowing task successfully disrupted O-WM.

SLC and spelling accuracy. Having confirmed that the shadowing task disrupts O-WM, analyses performed across participant (*F1, t1*) and item (*F2, t2*) variability now turn to the influence of SLC on spelling accuracy for word-initial and -final letters. Overall accuracy on word-initial (97.7%) and -final letters (96.9%) was not different, $F1(1, 40) = 1.01$, $MSE = 0.002$, $p > .30$, $F2(1, 32) < 1$. More important, analyses yielded a main effect of SLC, $F1(1, 40) = 11.761$, $MSE = 0.003$, $p = .001$, $\eta_p^2 = .23$, $F2(1, 32) = 11.716$, $MSE = 0.002$, $p = .002$, $\eta_p^2 = .27$; accuracy was higher on high-SLC letters (98.7%) than on low-SLC letters (95.9%). Figure 2 illustrates the reduced accuracy at word-initial and -final letter

[1] Items (in both Study 2 and Study 3) were originally frequency-matched based on the Francis and Kucera (1982) counts. However, appendices include updated frequency counts (Brysbaert & New, 2009).

Table 1
Distribution of Letter Errors in the Shadow Condition in Study 2 (N = 341) and Study 3 (N = 362)

Error type	Distribution		Example
	Study 2	Study 3	
Addition	19%	15%	psalm → PLSALM
Deletion	28%	31%	limb → LMB
Substitution	43%	40%	climb → CLAMB
Transposition/shift	9%	13%	wrong → WORGN
Other	1%	1%	epidemic → EPT

Note. "Other" refers to an error that could not unambiguously be classified as an addition, deletion, substitution, or transposition/shift.

positions when SLC was low compared to high (word-initial: 96% vs. 99.4%; word-final: 95.8% vs. 98.1%). There was no interaction, $F1(1, 40) < 1$, $F2(1, 32) = 1.935$, $MSE = 0.004$, $p > .15$.

The current results provide further evidence that shadowing disrupts O-WM and that SLC influences spelling accuracy (Jones et al., 2009). Importantly, the current results extend beyond prior research by demonstrating that effects of SLC are not confined to vowel digraphs in word-medial positions; SLC influences spelling accuracy for consonants and vowels at the typically error-free word-initial and -final letter positions. Furthermore, spelling accuracy for the high and low-SLC letters at word-initial (high: 99.4%; low: 96%) and -final letter positions (high: 98.1; low: 95.8) in this experiment is quite similar to the spelling accuracy for high and low-SLC letters in word-medial positions reported by Jones et al. (2009) using the same method in unimpaired spellers (high: 98.5%; low: 96.1%).

Study 3

Results from Study 2 demonstrate that SLC influenced spelling accuracy at the relatively error-free word-initial and -final letter positions. As such, Study 3 is aimed at more directly testing the hypothesis that the U-shaped serial position effect may be due to letter-level factors, specifically SLC, instead of letter position. SLC is again manipulated in this experiment, but this time at word-initial, -medial, and -final letter positions. Comparisons of spelling accuracy will be made within words as opposed to between words. In Study 2, performance was compared between different words (those low or high in SLC at critical positions). However, in Study 3, accuracy is assessed based on critical positions within the same words (e.g., *gno*me) instead of between words. This experiment addresses two critical questions: 1) if SLC is held constant across letter position, will accuracy be equivalent? and 2) will accuracy be higher in word-medial positions compared to flanking positions if SLC is higher in medial positions? If orthographic texture, as operationalized by SLC, is responsible for the U-shaped serial position effect, then the answer to both questions is yes. However, if letter position alone accounts for the effect, then the answer is no; accuracy will always be reduced in word-medial positions compared to flanking ones.

Method

Participants. Forty-two Kent State University undergraduates participated in this study in exchange for course credit. All were native English speakers, reported no reading or spelling disabilities and did not participate in Study 2.

Materials. Materials consisted of 100 (541 letters) words ranging in length from five to eight letters. There were two lists of five-letter words included to assess the influence of SLC on spelling accuracy at different letter positions within a word. The *Initial-Medial List* consisted of 10 word triplets matched in overall word frequency to assess the influence of SLC on accuracy at word-initial and -medial positions (see Appendix B). One member of each triplet (HH) had high-SLC letters at word-initial and -medial letter positions (94.1 and 97.3, respectively; e.g., *sle*ek). The second member of each triplet (LH) had a low-SLC letter in the initial position and a high-SLC letter in the medial position (7.33 and 98.1, respectively; e.g., *gno*me); the final member of each triplet (HL) had the reverse pattern with high-SLC letters in initial positions and low-SLC letters in medial positions (98 and 20, respectively; e.g., *mau*ve). In the triplets, all word-initial letters were consonants and all word-medial letters were vowels. The *Medial-Final List* consisted of 18 frequency-matched word triplets to assess the influence of SLC on spelling accuracy at word-medial and -final letter positions (see Appendix B). Item construction was similar to the Initial-Medial List. One member of each triplet (HH) had high-SLC letters at both the medial and final letter positions (95.6 and 95.4, respectively; e.g., ni*ece*). The second member of each triplet (HL) had a high-SLC letter in the medial position and a low-SLC letter in the word-final position (95.4 and 18.3, respectively; e.g., mo*use*); the final member of the triplet (LH) had the reverse pattern with low-SLC letters in medial positions and high-SLC letters in word-final positions (20.7 and 93.2, respectively; e.g., ga*uge*). Unlike the Initial-Medial List, items in the Medial-Final List contained a mix of consonants and vowels at each critical letter position. For 14 of the triplets, the consonant/vowel status of the critical letters was matched across words; consonant/vowel status could not be matched across the remaining four triplets.

Procedure. The procedure was identical to that of Study 2.

Results and Discussion

Responses were scored in the same way as Study 1; analyses were conducted only on responses in the shadow condition if they were correctly spelled in the control condition. 11.6% of responses were excluded from analyses due to errors in the control condition.

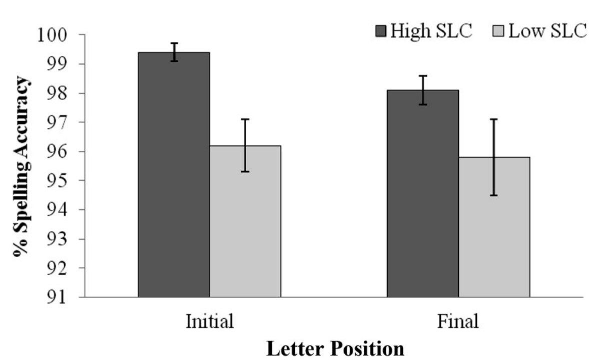

Figure 2. Spelling accuracy as a function of sound-letter convergence (SLC) and letter position in Study 2. Error bars represent standard error.

Disrupting O-WM. As in Experiment 1, patterns of performance were examined to confirm O-WM disruption. Again, errors consisted of additions, deletions, substitutions, and shifts/transpositions (see Table 1), 72.83% of errors were not phonologically plausible misspellings, and substitution errors indicated high levels of consonant/vowel preservation (vowel: 91.7%; consonant: 98.2%; overall: 94.8%). Word length effects were not examined because most all words were five letters in length.

Initial-Medial list. Contrary to predictions of positional accounts, accuracy at word-initial (97.4%) and -medial (96.8%) letter positions was equivalent; there was no main effect of letter position (Fs < 1). The main effect of item type, $F1(2, 82) = 8.397$, $MSE = 0.003$, $p < .001$, $\eta_p^2 = .17$, $F2(2, 16) = 3.167$, $MSE = 0.004$, $p < .07$, $\eta_p^2 = .28$, indicated that participants had higher accuracy on HH items (99%; ps $< .005$) than on HL (95.7%) and LH item (96.6%), which did not significantly differ (ps > 0.30). More important, though, was the interaction, $F1(2, 82) = 16.451$, $MSE = 0.002$, $p < .001$, $\eta_p^2 = .29$, $F2(2, 16) = 6.368$, $MSE = 0.003$, $p < .01$, $\eta_p^2 = .44$. Comparisons indicate that for HH words, spelling accuracy was higher for word-initial letters (100%) compared to word-medial letters (98%), $t1(41) = 2.488$, $p < .05$, Cohen's $d = 0.54$, $t2(9) = 2.321$, $p < .05$, Cohen's $d = 1.03$. For LH words, spelling accuracy was lower in initial compared to medial positions (94.6% and 98.6%, respectively), $t(41) = –3.79$, $p < .001$, Cohen's $d = 0.67$, $t2(9) = –1.862$, $p < .10$, Cohen's $d = 0.78$. For HL words, spelling accuracy was higher in initial compared to medial positions (97.6% and 93.9%, respectively), $t1(1) = 3.232$, $p < .005$, Cohen's $d = 0.60$, $t2(9) = 4.298$, $p < .005$, Cohen's $d = 2.12$.

Results from the Initial-Medial List are mixed, with some support for both hypotheses. Accuracy on initial and medial letters in HL words is relatively uninformative as both hypotheses predict better performance on initial compared to medial letters. Although a strong positional position account was disconfirmed by the null effect of letter position, spelling accuracy on critical letters in the HH words lends some support to the positional accounts as accuracy was significantly lower on medial letters compared to initial ones, though both were high-SLC. However, the practical significance of this is questionable. The effect for word-initial letters in the HH condition may be spurious as 100% accuracy has not been observed elsewhere to date for this task and these types of items. Furthermore, accuracy on these high-SLC word-initial letters was higher than on the high-SLC HL word-initial letters, $t(41) = 3.507$, $p = .001$, Cohen's $d = 0.76$. Comparisons also indicate that accuracy on the high-SLC HL word-initial letters was no different than accuracy on high-SLC HH word-medial letters, $t(41) = -0.429$, $p = .67$, and LH conditions, $t(41) = –1.363$, $p = .18$. It is most important to consider the results for the LH words; they provide the strongest evidence against positional accounts. Accuracy was higher on high-SLC word-medial letters than on low-SLC word-initial letters (see Figure 3).

Medial-Final List. Reported results include analyses with the full set of 18 triplets. Because the analysis of position from the Initial-Medial List demonstrated that spelling accuracy was similar for consonants and vowels, the four nonmatched triplets were included in analyses.[2]

As was the case for the Initial-Medial List, there was no effect of letter position, $F1(1, 41) < 1$, $F2(1, 17) = 3.007$, $MSE = 0.001$, $p > .10$. Contrary to predictions of positional accounts, spelling

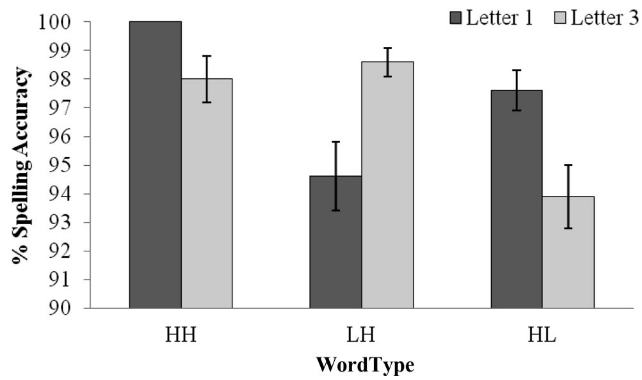

Figure 3. Spelling accuracy as a function of word type and letter position on the Initial-Medial List in Study 3. HH indicates high-SLC letters in Positions 1 and 3. LH indicates low-SLC letters in Position 1 and high-SLC letters in Position 3. HL indicates high-SLC letters in Position 1 and low-SLC letters in Position 3. Error bars represent standard error. SLC = sound-letter convergence.

accuracy on word-medial letters (97.5%) was equivalent to accuracy for word-final letters (97.9%). The main effect of item type approached significance, $F1(2, 82) = 2.658$, $MSE = 0.002$, $p = .076$, $\eta_p^2 = .06$, $F2(2, 34) = 5.310$, $MSE = 0.001$, $p = .01$, $\eta_p^2 = .24$; accuracy on HH words was significantly higher than on LH words (ps $< .05$) and trended toward being higher than on HL words only by subjects analyses ($p1 = .124$, $p2 = 1.0$), neither of which differed from each other (ps $> .15$). More important, the interaction, $F1(2, 40) = 14.045$, $MSE = 0.001$, $p < .001$, $\eta_p^2 = .26$, $F2(2, 34) = 14.220$, $MSE = 0.001$, $p < .001$, $\eta_p^2 = .46$, indicates that spelling accuracy at each letter position varied as a function of SLC (see Figure 4). For HH words, accuracy at word-medial and -final letter positions was equivalent (ts < 1; 98.7% and 98.5%, respectively). For HL words, accuracy was higher at word-medial positions (98.4%) than at word-final positions (96.4%), $t1(41) = 2.646$, $p < .05$, Cohen's $d = 0.37$, $t2(17) = 2.871$, $p < .05$, Cohen's $d = 0.68$. Accuracy was lower at word-medial letter positions (95.4%) for LH words than at word-final positions (98.8%), $t1(41) = -3.639$, $p = .001$, Cohen's $d = 0.72$, $t2(17) = –3.591$, $p < .005$, Cohen's $d = 1.04$. Taken together, these results also call into question the positional accounts of the U-shaped serial position effect. Again, accuracy in word-medial letter positions was equivalent to or higher than flanking letter positions.

General Discussion

The purpose of the current studies was to introduce and test a new hypothesis regarding the cause of the commonly observed U-shaped serial position effect in spelling. According to the *orthographic texture* hypothesis, the activation strength of individual

[2] Separate analyses conducted on only the set of 14 consonant/vowel matched triplets yielded similar results. There was no effect of letter position, $F(1, 41) < 1$, but there was an interaction, $F(2, 40) = 14.885$, $MSE = 0.002$, $p < .005$. There were no differences in spelling accuracy when both letters were high-SLC, $F(1, 41) = 3.676$, $MSE = 0.001$, $p > .05$. Accuracy was higher for high-SLC medial letters than low-SLC final letters, $F(1, 41) = 5.709$, $MSE = 0.001$, $p < .05$; the reverse pattern held for LH words, $F(1, 41) = 11.490$, $MSE = 0.003$, $p < .005$.

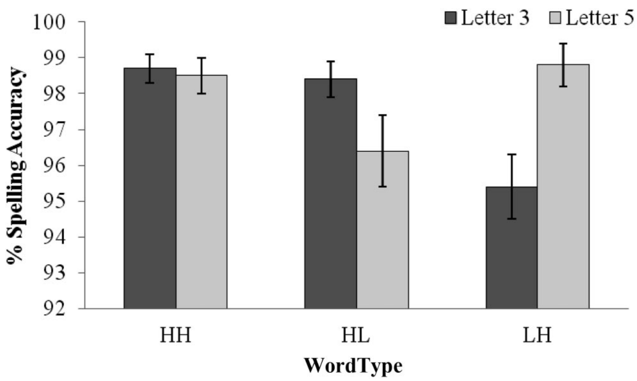

Figure 4. Spelling accuracy as a function of word type and letter position on the Medial-Final List in Study 3. HH indicates high-SLC letters in Positions 3 and 5. HL indicates high-SLC letters in Position 3 and low-SLC letters in Position 5. LH indicates low-SLC letters in Position 3 and high-SLC letters in Position 5. Error bars represent standard error. SLC = sound-letter convergence.

letters in a word may vary in O-WM; this variation in activation strength influences spelling accuracy and may contribute to the serial position effect. Specifically, the influence of sound-letter convergence (SLC), a subgraphemic variable, was examined to assess effects of orthographic texture. Results from Study 1 simply demonstrated that SLC varies in the English languages similarly to accuracy measures; it decreases from word-initial positions and increases again at word-final positions. Results from Studies 2 and 3 more directly tested the *orthographic texture hypothesis* and demonstrated the relationship between SLC and spelling accuracy. In Study 2, results demonstrated that SLC influenced accuracy at the typically error-free word-initial and -final letter positions. Results from Study 3 most strongly support the *orthographic texture hypothesis* and pose a serious challenge to positional accounts of the serial position effect; spelling accuracy at word-medial positions was as high or higher than flanking letter positions when SLC was manipulated.

The current results demonstrate that letter position alone cannot account for the U-shaped serial position effect so pervasive in spelling. Instead, SLC was demonstrated to clearly play a role in spelling accuracy as a function of letter position. If comparisons are made between accuracy rates for word-initial and -final letters in Study 2 and accuracy for word-medial letters reported by Jones et al. (2009; Study 2) using the same task, it is clear that spelling accuracy at word-initial, -medial, and -final letter positions is similar when examined as a function of SLC. High-SLC letters were spelled at equally high rates (initial: 99.4%; medial: 98.5%; final: 98.1%) and accuracy was comparably reduced for low-SLC letters in those positions (initial: 96%; medial: 96.1%; final: 95.8%). More important, direct (statistical) comparisons of accuracy across letter position in Study 3 demonstrate that word-medial letter cannot only be spelled as accurately as word-initial and -final letters but can be spelled more accurately than letters in flanking positions. Indeed, these particular results are most damaging to positional accounts of the effect as they would suggest that spelling accuracy can never be highest at word-medial positions.

Although the current results clearly argue against a strict, position-only account of the serial position effect, the data do not conclusively rule out the influence of letter position. As noted in Study 3, although possibly anomalous, spelling accuracy for high-SLC word-medial letters was lower than for high-SLC word-initial letters. Furthermore, accuracy rates were numerically lower for the low-SLC letters in word-medial positions compared to accuracy for low-SLC letters in word-initial and -final letter positions. As such, these results may provide some evidence that letter position exacerbates effects of SLC (or vice versa).

If the maximal activation any letter can receive during the course of spelling is not the same, as assumed by the orthographic texture hypothesis, then models of spelling regarding activation strength and letter position can be modified to incorporate the current results. CQ models (e.g., Glasspool & Houghton, 2005; Glasspool et al., 2006) use a graded both-edges positional coding scheme for spelling. Each letter to be spelled in a word is maximally activated in the correct position but is also activated, to lesser degrees, in nearby positions relative to the edges of the word. Fischer-Baum, McCloskey, and Rapp (2010) provided compelling empirical evidence for this coding scheme in spelling by analyzing the perseveration errors made by two dysgraphic individuals (see Fischer-Baum, Charny, & McCloskey, 2011, for consistent evidence in reading). Both individuals produced misspellings for words that included intruded letters from previously spelled responses. Importantly, the location of these intruded letters was at the same (or a near) letter position relative to the word's beginning or ending. If CQ models incorporate differences in the maximal activation that any one letter can receive based on orthographic texture (in this case, SLC) with graded both-edges positional coding, then the current results can likely be accommodated.

The current results not only speak to serial position effects in spelling but also bear relevance to discussions of grain size in linguistic processing. Most research concerning grain size in spelling involves graphemes or larger units. It is hypothesized that individuals prefer difference grain sized based on the consistencies of the language, or how regularly sounds and letters map onto one another; smaller units (e.g., graphemes) are preferred in relatively consistent orthographies (e.g., German), whereas larger units (e.g., bodies) are preferred in less consistent orthographies (e.g., English; see Ziegler & Goswami, 2005). Indeed, it has been demonstrated that English readers use larger grain sizes than German readers when reading identical words because English is a much less consistent language (Ziegler, Perry, Jacobs, & Braun, 2001). Despite the evidence that English readers/spellers rely on relatively large grain sizes during processing and that contextual information helps in predicting word spellings (Kessler & Treiman, 2001; but see Perry, Ziegler, & Coltheart, 2002), the current results provide converging evidence that SLC, a subgraphemic letter-level variable, clearly influences spelling accuracy (Jones et al., 2009). Furthermore, the current results extend prior research by demonstrating that SLC influences spelling accuracy at word-initial and -final letters positions in addition to -medial ones and is not simply a variable that affects only vowel digraphs. However, current models of spelling do not break down complex graphemes into their constituent units; digraphs are represented as single units (e.g., Houghton & Zorzi, 2003). Such models may not account for the current data as there is currently no instantiation of SLC within these models.

Given how SLC is calculated, it is clear that it is related to PG probability, a more commonly studied grapheme-sized variable.

Although Jones et al. (2009) demonstrated that SLC influences spelling accuracy when PG probability is controlled for, it was not controlled for in the current studies. In fact, considering critical items from Studies 2 and 3, PG probability and SLC were highly correlated ($r = .74$, $p < .001$), and both predicted spelling accuracy (PG: $r = .366$, $p < .001$; SLC: $r = .434$, $p < .001$). The question, therefore, remains as to whether SLC was responsible for the observed effects. Regressions including letter position, PG probability, and SLC were run as predictors of spelling accuracy. Before SLC was entered as a variable, both letter position and PG probability predicted spelling accuracy, $\beta = .134$, $t(233) = 2.193$, $p < .05$, $\beta = .384$, $t(233) = 6.308$, $p < .001$, respectively. However, after entering SLC into the regression equation, neither variable significantly predicted spelling accuracy, $\beta = .096$, $t(232) = 1.604$, $p = .11$, $\beta = .129$, $t(232) = 1.448$, $p = .15$, respectively; only SLC significantly predicted spelling accuracy, $\beta = .338$, $t(232) = 3.819$, $p < .001$ (see Appendix C). These particular results indicate that SLC not only influences spelling accuracy above and beyond effects of PG probability but may actually underlie effects of PG probability.

Although the current results demonstrate that the spelling of individual letters within a grapheme may vary due to activation strength, the exact locus of the effect is still unclear. As discussed in the introduction, orthographic texture may arise from lexical-learning of from online-competition. The current results do not speak to the source of the effect; however, a post hoc analysis may support a lexical-learning view over an online-competition account. Given the entire corpus of words spelled (not just critical items), substitution errors were examined. Of all substitution errors, 63.3% included phonologically plausible misspellings for that particular phoneme. Of those, participants substituted lower PG probability spellings (60.8%) more often than higher PG probability spellings (39.2%), $t(76) = 3.221$, $p = .002$. If, according to an online-competition account, the sublexical spelling process is partially responsible for orthographic texture effects, then the expectation would be reversed for substitution errors—they should have included more higher PG probability spellings. Although misspellings included those individual letters high in SLC more often than those low in SLC, the misspellings did not include graphemes with higher PG probabilities. More research, however, is needed to directly assess the locus of orthographic texture effects.

Data in the reading literature are consistent with the proposal of orthographic texture. Although in spelling the implication of orthographic texture is that not all letters are activated equally for production, in reading the implication is that not all letters are equally important for word identification. It has been demonstrated that, during reading, some letters within a word may not be as crucial as others for word identification. For example, Lee (2007) found that readers could more easily process words missing silent letters (e.g., champa_ne) than those missing nonsilent letters (e.g., passen_er) in lexical decision, naming, and semantic organization tasks. Similarly, L. Katz and Frost (2001) found that readers accepted misspellings as correct only if they were phonologically acceptable misspellings (e.g., camouflage spelled as camoflage; see Schiff & Ravid, 2004, for similar evidence in Hebrew). Furthermore, consistent with the suggestion that orthographic texture results from variables affecting the ease of learning, Perry and Zieger (2000) demonstrated that skilled readers were influenced by variables affecting early language development.

In addition to providing evidence of orthographic texture, the current results also provide further evidence that the shadowing task disrupts O-WM in unimpaired spellers. In Studies 2 and 3, spelling errors produced by participants were consistent with disruption to O-WM. Similar to individuals with acquired dysgraphia affecting O-WM, letter-level spelling errors included additions, deletions, substitutions and transpositions/shifts, substitution errors preserved consonant/vowel status at high rates, and more errors were made on long than short words. Importantly, the errors in the shadow condition were not simply due to a lack of knowledge; spelling in the control condition ensured that participants knew the spellings of words analyzed in the shadow condition. As such, this task can be used to further explore issues pertaining to O-WM in spelling and provide converging evidence for the complex nature of what is activated in O-WM in an unimpaired population.

Conclusions

In the current set of studies, sound-letter convergence was demonstrated to vary as a function of letter position in the English language and that this variable, a measure of orthographic texture, may play a large role in the commonly observed U-shaped serial position effect. Contrary to predictions of positional accounts, spelling accuracy at word-medial letter positions was demonstrated to be equal to or higher than accuracy at flanking letter positions. As such, models of spelling (both theoretical and computational) must likely be revised to accommodate the current findings regarding SLC, orthographic texture, and the U-shaped serial position effect.

References

Badecker, W., Hillis, A. E., & Caramazza, A. (1990). Lexical morphology and its role in the writing process: Evidence from a case of acquired dysgraphia. *Cognition, 35,* 205–243. doi:10.1016/0010-0277(90)90023-D

Balota, D. A., Yap, M. J., Cortese, M. J., Hutchinson, K. A., Kessler, B., Loftis, B., . . . Treiman, R. (2007). The English Lexicon Project. *Behavior Research Methods, 39,* 445–459. doi:10.3758/BF03193014

Bormann, T., Wallesch, C., & Blanken, G. (2008). "Fragment errors" in deep dysgraphia: Further support for a lexical hypothesis. *Cognitive Neuropsychology, 25,* 745–764. doi:10.1080/02643290802315834

Brysbaert, M., & New, B. (2009). Moving beyond Kucera and Franices: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavioral Research Methods, Instruments & Computers, 41,* 977–990. doi:10.3758/BRM.41.4.977

Buchwald, A., & Rapp, B. (2009). Distinctions between orthographic long-term memory and working memory. *Cognitive Neuropsychology, 26,* 724–751. doi:10.1080/02643291003707332

Caramazza, A., & Miceli, G. (1990). The structure of graphemic representations. *Cognition, 37,* 243–297. doi:10.1016/0010-0277(90)90047-N

Caramazza, A., Miceli, G., Villa, G., & Romani, C. (1987). The role of the graphemic buffer in spelling: Evidence from a case of acquired dysgraphia. *Cognition, 26,* 59–85. doi:10.1016/0010-0277(87)90014-X

Cipolotti, L., Bird, C. M., Glasspool, D. W., & Shallice, T. (2004). The impact of deep dysgraphia on graphemic buffer disorders. *Neurocase, 10,* 405–419. doi:10.1080/13554790490893995

Costa, V., Fischer-Baum, S., Capasso, R., Miceli, G., & Rapp, B. (2011). Temporal stability and representational distinctiveness: Key functions of orthographic working memory. *Cognitive Neuropsychology, 28,* 338–362. doi:10.1080/02643294.2011.648921

Fischer-Baum, S., Charny, J., & McCloskey, M. (2011). Both-edges representation of letter position in reading. *Psychonomic Bulletin & Review, 18,* 1083–1089. doi:10.3758/s13423-011-0160-3

Fischer-Baum, S., McCloskey, M., & Rapp, B. (2010). Representation of letter position in spelling: Evidence from acquired dysgraphia. *Cognition, 115,* 466–490. doi:10.1016/j.cognition.2010.03.013

Folk, J. R., & Jones, A. C. (2004). The purpose of lexical/sublexical interaction during spelling: Further evidence from dysgraphia and articulatory suppression. *Neurocase, 10,* 65–69. doi:10.1080/13554790490960512

Folk, J. R., Rapp, B., & Goldrick, M. (2002). The interaction of lexical and sublexical information in spelling: What's the point? *Cognitive Neuropsychology, 19,* 653–671. doi:10.1080/02643290244000184

Francis, W. N., & Kucera, H. (1982). *Frequency analysis of English usage: Lexicon and grammar*. Boston, MA: Houghton Mifflin.

Glasspool, D. W., & Houghton, G. (2005). Serial order and consonant-vowel structure in a graphemic output buffer model. *Brain and Language, 94,* 304–330. doi:10.1016/j.bandl.2005.01.006

Glasspool, D. W., Shallice, T., & Cipolotti, L. (2006). Towards a unified process model for graphemic buffer disorder and deep dysgraphia. *Cognitive Neuropsychology, 23,* 479–512. doi:10.1080/02643290500265109

Hanna, R. R., Hanna, J. S., Hodges, R. E., & Rudorf, E. H. (1966). *Phoneme-grapheme correspondences as cues to spelling improvement*. Washington, DC: U. S. Department of Health, Education, and Welfare, Office of Education, U. S. Government Printing Office.

Houghton, G., & Zorzi, M. (2003). Normal and impaired spelling in a connectionist dual-route architecture. *Cognitive Neuropsychology, 20,* 115–162. doi:10.1080/02643290242000871

Jones, A. C., Folk, J. R., & Rapp, B. (2009). All letters are not equal: Subgraphemic texture in orthographic working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 35,* 1389–1402. doi:10.1037/a0017042

Jónsdóttir, M. K., Shallice, T., & Wise, R. (1996). Phonological mediation and the graphemic buffer disorder in spelling: Cross-language differences? *Cognition, 59,* 169–197. doi:10.1016/0010-0277(95)00693-1

Katz, L., & Frost, J. (2001). Phonology constrains the internal orthographic representation. *Reading and Writing, 14,* 297–332. doi:10.1023/A:1011165407770

Katz, R. B. (1991). Limited retention of information in the graphemic buffer. *Cortex: A Journal Devoted to the Study of the Nervous System and Behavior, 27,* 111–119.

Kessler, B., & Treiman, R. (2001). Relationship between sounds and letters in English monosyllables. *Journal of Memory and Language, 44,* 592–617. doi:10.1006/jmla.2000.2745

Kokubo, K., Suzuki, K., Yamadori, A., & Satou, K. (2001). Pure Kana agraphia as a manifestation of graphemic buffer impairment. *Cortex: A Journal Devoted to the Study of the Nervous System and Behavior, 37,* 187–195.

Kreiner, D. S. (1992). Reaction time measures of spelling: Testing a two strategy model of skilled spelling. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 765–776. doi:10.1037/0278-7393.18.4.765

Lee, C. H. (2007). Phonological activation in multi-syllabic word recognition. *Journal of Psycholinguistic Research, 36,* 1–14. doi:10.1007/s10936-006-9029-4

McCloskey, M., Badecker, W., Goodman-Schulman, R. A., & Aliminosa, D. (1994). The structure of graphemic representations in spelling: Evidence from a case of acquired dysgraphia. *Cognitive Neuropsychology, 11,* 341–392. doi:10.1080/02643299408251979

Mendenhall, J. E. (1930). The characteristics of spelling errors. *Journal of Educational Psychology, 21,* 648–656. doi:10.1037/h0073356

Miceli, G., & Capasso, R. (2006). Spelling and dysgraphia. *Cognitive Neuropsychology, 23,* 110–134. doi:10.1080/02643290500202730

Nolan, K. A., & Caramazza, A. (1983). An analysis of writing in a case of deep dyslexia. *Brain and Language, 20,* 305–328. doi:10.1016/0093-934X(83)90047-0

Olson, A., Romani, C., & Caramazza, A. (2010). Analysis and interpretation of serial position data. *Cognitive Neuropsychology, 27,* 134–151. doi:10.1080/02643294.2010.504580

Perry, C., & Ziegler, J. C. (2000). Linguistic difficulties in language and reading development constrain skilled adult reading. *Memory & Cognition, 28,* 739–745. doi:10.3758/BF03198408

Perry, C., & Ziegler, J. C. (2004). Beyond the two-strategy model of skilled spelling: Effects of consistency, grain size, and orthographic redundancy. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology, 57,* 325–356.

Perry, C., Ziegler, J. C., & Coltheart, M. (2002). A dissociation between orthographic awareness and spelling production. *Applied Psycholinguistics, 23,* 43–73. doi:10.1017/S0142716402000036

Rapp, B., Epstein, C., & Tainturier, M. C. (2002). The integration of information across lexical and sublexical processes in spelling. *Cognitive Neuropsychology, 19,* 1–29. doi:10.1080/0264329014300060

Rapp, B., & Kong, D. (2002). Revealing the component functions of the graphemic buffer. *Brain and Language, 27,* 112–114.

Sage, K., & Ellis, A. (2004). Lexical influences in graphemic buffer disorder. *Cognitive Neuropsychology, 21,* 381–400.

Schiff, R., & Ravid, D. (2004). Vowel representation in written Hebrew: Phonological, orthographic and morphological contexts. *Reading and Writing, 17,* 241–265. doi:10.1023/B:READ.0000017668.48386.90

Schiller, N. O., Greenhall, J. A., Shelton, J. R., & Caramazza, A. (2001). Serial order effects in spelling errors: Evidence from two dysgraphic patients. *Neurocase, 7,* 1–14. doi:10.1093/neucas/7.1.1

Shallice, T., Glasspool, D. W., & Houghton, G. (1995). Can neuropsychological evidence inform connectionist modeling? Analyses of spelling. *Language and Cognitive Processes, 10,* 195–225. doi:10.1080/01690969508407094

Tainturier, M.-J., & Rapp, B. (2004). Complex graphemes as functional spelling units: Evidence from acquired dysgraphia. *Neurocase, 10,* 122–131.

Treiman, R., Berch, D., & Weatherston, S. (1993). Children's use of phoneme-grapheme correspondences in spelling: Roles of position and stress. *Journal of Educational Psychology, 85,* 466–477. doi:10.1037/0022-0663.85.3.466

Ward, J., & Romani, C. (1998). Serial position effects and lexical activation in spelling: Evidence from a single case study. *Neurocase, 4,* 189–206. doi:10.1080/13554799808410621

Wing, A. M., & Baddeley, A. D. (1980). Spelling errors in handwriting: A corpus and a distributional analysis. In U. Frith (Ed.), *Cognitive processes in spelling* (pp. 251–286). New York, NY: Academic Press.

Ziegler, J. C., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin, 131,* 3–29. doi:10.1037/0033-2909.131.1.3

Ziegler, J. C., Perry, C., Jacobs, A. M., & Braun, M. (2001). Identical words are read differently in different languages. *Psychological Science, 12,* 379–384. doi:10.1111/1467-9280.00370

(*Appendices follow*)

Appendix A

Items From Study 2

High sound-letter convergence			Low sound-letter convergence		
Item	Frequency	SLC	Item	Frequency	SLC
Critical letter: First					
THUG	2.25	100	KNOB	2.10	3.2
CLAW	2.35	93.3	CHEF	2.78	9.1
SWAY	2.11	81.8	KNIT	1.99	3.2
TROLL	2.14	100	GNARL	0	0.4
WHALE	2.76	95.6	GNOME	1.52	0.4
THORN	2.42	100	PSALM	1.43	0.6
GHOST	3.27	100	WRIST	2.73	2.7
THUMB	2.78	100	WRECK	2.84	2.7
THONG	2.03	100	WRONG	4.41	2
THIEF	3.09	100	KNEEL	2.44	3.2
THICK	2.85	100	KNOCK	3.52	3.2
CRUTCH	1.83	93.3	WRENCH	1.51	2.7
FRECKLE	1.49	88.8	WRANGLE	1.27	2.7
BRACKET	1.52	100	PHANTOM	2.32	11.2
OATMEAL	2.23	100	AUCTION	2.66	44.7
OUTWARD	1.85	100	AUGMENT	1.30	44.7
WHISTLE	2.90	95.6	KNUCKLE	1.83	3.2
Average	2.35	96.96		2.16	8.23
Critical letter: Last					
YAWN	1.72	100	WOMB	2.25	1.9
MATH	2.92	100	LIMB	2.38	1.9
JEWEL	2.57	100	VALET	2.42	0.9
GENIE	3.49	98.8	CANOE	2.26	22.1
FEVER	3.01	100	DEPOT	2.18	0.01
LIVER	2.86	100	DEBUT	2.12	0.01
CROWN	2.84	100	GRAPH	1.59	17.5
SOBER	2.71	100	WIDOW	2.79	6.1
GROSS	2.89	79.5	CLIMB	3	1.9
COFFIN	2.66	100	CURFEW	2.37	4.4
DOMINO	2.31	99.3	SAFARI	2.03	1.5
CARESS	1.85	79.5	SOLEMN	2.05	0.5
PUPPET	2.45	100	NEPHEW	2.93	4.4
GLAMOUR	2.2	100	CROQUET	1.65	0.9
BOYCOTT	1.7	99.2	SUCCUMB	1.3	1.9
GLITTER	2.02	100	CHIMNEY	2.33	0.3
CONFESS	2.91	79.5	CONDEMN	2.09	0.5
Average	2.54	96.22		2.22	3.92

Note. SLC = sound-letter convergence.

(*Appendices continue*)

Appendix B

Items From Study 3

High-high				High-low				Low-high			
		SLC				SLC				SLC	
Item	Frequency	POS1	POS3	Item	Frequency	POS1	POS3	Item	Frequency	POS1	POS3
Initial-Medial List											
FLOSS	2	88.8	100	GAUZE	1.87	100	16.2	GNARL	0	0.4	99.5
SQUID	2.15	81.8	100	MAUVE	1.45	100	16.2	KNAVE	1.3	3.2	97.9
SLEEK	1.64	81.8	97.6	BEIGE	1.85	100	21.6	GNOME	1.52	0.4	99.8
GRAPE	2.31	100	97.9	TAUNT	1.52	100	16.2	WRATH	2.3	2.7	100
MOIST	1.97	100	98.8	WEIRD	3.71	95.6	11.1	PHOTO	3.07	11.2	99.8
GHOST	3.27	100	99.8	FEAST	2.54	88.8	34.5	WRIST	2.72	2.7	92.9
BLEED	2.71	100	97.6	LEASE	2.51	100	34.5	WRECK	2.84	2.7	97.6
MOUSE	2.99	100	81.5	BOAST	1.74	100	15.4	KNEEL	2.44	3.2	97.6
FLOAT	2.58	88.8	99.8	GAUGE	2.05	100	0.1	SHAME	3.33	23.4	97.9
BLAST	2.92	100	100	WEAVE	2.03	95.6	34.5	SHEEP	2.84	23.4	97.6
Average	2.45	94.12	97.3		2.13	98	20.04		2.24	7.33	98.06

Medial-Final List

High-high				High-low				Low-high			
		SLC				SLC				SLC	
Item	Frequency	POS3	POS5	Item	Frequency	POS3	POS5	Item	Frequency	POS3	POS5
STRAP	2.42	100	100	LYMPH	1.18	100	17.5	LATCH	2	44.9	80.2
WORST	3.46	100	99.2	STRAW	2.5	100	34.9	TIGHT	3.41	10.4	99.2
NIECE	2.69	97.6	97.6	MOUSE	2.99	81.5	21.7	GAUGE	2.05	0.1	69
CHESS	2.58	97.6	79.5	CRUMB	1.97	87.7	1.9	FEIGN	1.38	21.6	100
FLINT	2.35	92.9	99.2	BLITZ	1.81	92.9	0.2	FEAST	2.54	34.5	99.2
BLEND	2.34	97.6	100	THIGH	2.28	97.5	10.4	WEIRD	3.71	11.1	100
GHOST	3.27	99.8	99.2	THUMB	2.78	98.2	1.9	BOAST	1.74	15.4	99.2
BLOOM	2.45	77.4	100	TOUGH	3.66	87.7	17.5	COACH	3.39	15.4	80.2
JOINT	3.15	98.8	99.2	ROUGH	3.28	87.7	17.5	FRUIT	3.04	26.46	99.2
CYCLE	2.45	86.5	98.2	VAGUE	2.37	90.3	4.9	WEDGE	2.08	20	97.6
PRIZE	3.06	97.5	69.8	NOISE	3.25	98.8	11.5	CEASE	2.65	34.5	97.6
MOUNT	2.78	81.5	99.2	CLIMB	3	97.5	1.9	BEACH	3.46	34.5	80.2
SQUID	2.15	100	100	SHACK	2.46	100	39.5	GOURD	1.4	5.2	100
BLESS	3.25	97.6	79.5	CHEEK	2.56	97.6	39.5	FAULT	3.73	16.2	99.2
CHEAP	3.27	97.6	100	MERGE	1.86	100	48.3	LEASE	2.51	34.5	97.6
SCRAP	2.35	100	100	MINCE	1.45	100	11.7	YACHT	2.62	0.1	99.2
HOIST	2.03	98.8	99.2	WALTZ	2.45	100	0.2	HUTCH	2.27	44.9	80.2
BIBLE	2.97	100	98.2	WORSE	3.7	100	48.3	OUGHT	3.61	2.4	99.2
Average	2.72	95.62	95.44		2.53	95.41	18.29		2.52	20.68	93.17

Note. SLC = sound-letter convergence; POS = position.

(*Appendices continue*)

Appendix C

Regressions Examining the Influence of Sound-Letter Convergence on Spelling Accuracy When Controlling for the Effects of Letter Position and Phoneme-Grapheme Probability

Predictor	R^2	Adj. R^2	β	*t*	Sig.	VIF
Complete data set	0.202	0.192				
Letter position			.096	1.604	.110	1.046
PG probability			.129	1.448	.149	2.314
SLC			.338	3.819	.000	2.273
Study 2	0.173	0.135				
Letter position			.047	0.410	.638	1.041
PG probability			.143	0.725	.471	3.072
SLC			.292	1.493	.140	3.008
Study 3—Initial-Medial List	0.297	0.258				
Letter position			−.038	−0.290	.773	1.348
PG probability			.000	0.001	.999	3.456
SLC			.546	2.677	.010	3.252
Study 3—Medial-Final List	0.226	0.204				
Letter position			.152	1.759	.082	1.003
PG probability			.122	1.052	.295	1.802
SLC			.365	3.155	.002	1.798

Note. Adj. = adjusted; Sig. = significance; VIF = variance inflation factor; PG = phoneme-grapheme; SLC = sound-letter convergence.

Received July 24, 2012
Revision received January 28, 2013
Accepted January 28, 2013 ■