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Temporal stability and representational distinctiveness: Key functions of orthographic working memory

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Abstract

A primary goal of working memory research has been to understand the mechanisms that permit working memory systems to effectively maintain the identity and order of the elements held in memory for sufficient time as to allow for their selection and transfer to subsequent processing stages. Based on the performance of two individuals with acquired dysgraphia affecting orthographic WM (the graphemic buffer) we present evidence of two distinct and dissociable functions of orthographic WM. One function is responsible for maintaining the temporal stability of letters held in orthographic WM, while the other is responsible for maintaining their representational distinctiveness. The failure to maintain temporal stability and representational distinctiveness give rise, respectively, to decay and interference effects that manifest themselves in distinctive error patterns, including distinct serial position effects. The findings we report have implications beyond our understanding of orthographic WM, as the need to maintain temporal stability and representational distinctiveness in WM is common across cognitive domains.

Keywords

working memory; spelling; dysgraphia; orthographic representations

Introduction

For most cognitive domains, processing theories have posited working memory (WM) systems that are responsible for maintaining active the representations of multiple elements while they await further processing (Anderson, Reder, & Lebiere, 1996; Just & Carpenter, 1992; Martin, 1993; Morton & Morris, 1995; Papagno, Valentine, & Baddeley, 1991; for a review, see Miyake & Shah, 1999). Depending on the domain, the elements manipulated by WM may be such things as a series of spatial locations that constitute targets of movements, words in a list or a sentence to be spoken, or letters in a word to be spelled. A primary goal of research has been to understand the mechanisms that permit working memory systems to effectively maintain the identity and order of the elements for sufficient time as to allow for their selection and transfer to subsequent processing stages. A common strategy for investigating these WM mechanisms has been to examine the conditions under which elements are forgotten from WM. In the work we report on here, we present evidence from

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two individuals with a form of acquired dysgraphia that has affected the WM system involved in spelling: orthographic WM (commonly referred to as the graphemic buffer). We will argue that the performance of these individuals reveals two distinct and dissociable functions of orthographic WM. Specifically, these functions are responsible for maintaining the temporal stability and the representational distinctiveness of letters held in orthographic WM.

Orthographic working memory

Caramazza, Miceli and Villa (1986) proposed that an orthographic WM system is a necessary part of the spelling process because of the computational incommensurability between central components of the spelling process that generate multi-letter orthographic sequences and the more peripheral components of the spelling process that operate on a single letter at a time, providing each letter with a specific format. Given the difference in unit size (sequences versus single elements), an intermediate WM component is required to ensure that sequence representations remain active during the serial selection of the elements for processing by the peripheral components.

Empirical evidence for this orthographic WM system comes from detailed analyses of the spelling performance by individuals who, as a result of acquired neurological damage, have suffered disruption to Orthographic WM (which we will refer to as O-WM). The essential behavioral features of disruption to O-WM can be predicted on the basis of the putative role of O-WM within the larger spelling system. As represented schematically in Figure 1, spellings are either retrieved from a long-term memory store commonly referred to as the Orthographic Lexicon or they are assembled from sublexical phoneme-to-grapheme conversion procedures that make use of stored information regarding the relationships between letters and sounds. Strings of abstract letter representations that are generated by either of these lexical or sublexical procedures are processed by O-WM. O-WM is assumed to be a limited capacity system responsible for maintaining active letter identity and order information and selecting letters in their proper order for further processing by peripheral components. These, in turn, are responsible for assigning specific letter shapes or letter names to each of the abstract letter representations, information that is then used to guide the appropriate motor systems.

Given this functional architecture of spelling, in the event of damage to O-WM, spelling performance should be comparable across spelling tasks, regardless of input (written picture naming, writing-to-dictation, delayed copy or spontaneous writing) or output modality (written or oral spelling). In addition, response accuracy should be unaffected by lexicality (familiar vs. novel words), frequency, or grammatical class (but see Sage & Ellis, 2004 and Buchwald and Rapp, 2009). Instead, performance accuracy should be affected by word length, such that the probability of producing a letter accurately is affected by the length of the to-be-written string. Finally, disruption of O-WM should result in segmental errors (i.e., letter substitutions, omissions, insertions, transpositions) rather than lexical errors (semantic, morphological, other word errors) or phonologically plausible errors.

A number of cases with these characteristics have been reported (Blanken, Schafer, Tucha, & Lange, 1999; Buchwald & Rapp, 2009; Cantagallo & Bonazzi, 1996; Cotelli, Aboutalebi, Zorzi, & Cappa, 2003; Cubelli, 1991; Jónsdottír, Shallice, & Wise, 1996; Kan, Biran, Thompson-Schill, & Chatterjee, 2006; Kay & Hanley, 1994; McCloskey, Badecker, Goodman-Schulman, & Aliminosa, 1994; Miceli, Benvegnù, Capasso, & Caramazza, 1995, 2004; Posteraro, Zinelli, & Mazzucchi, 1988; Schiller, Greenhall, Shelton, & Caramazza, 2001; Tainturier & Rapp, 2004) including the seminal case of LB described by Caramazza, Miceli, Villa & Romani (1987, and see also Caramazza & Miceli, 1990).

Identifying the constituent functions of O-WM

Considerable research has been directed at understanding the internal structure of WM systems. In fact, the current view is largely that WM is a multi-component system, with the number and nature of the components or processes still to be agreed upon. In this regard, some proposals posit a number of processes or sub-components, including: attention switching (Rogers & Monsell, 1995), inhibition (Roberts, Hager, & Heron, 1994), monitoring and updating (Van der Linden, Brédart, & Beerten, 1994), temporal tagging (Jonides & Smith, 1997) planning and sequencing intended actions (Ward & Allport, 1997).

Specifically with regard to O-WM, recent evidence from individuals with acquired dysgraphia has suggested that this system may also be composed of separable subcomponents. Based on the contrasting patterns of spelling performance of two individuals with O-WM deficits, Rapp & Kong (2002) proposed a distinction between a process responsible for the activation of the letters held in O-WM and another one responsible for their serial selection in the “hand off” to subsequent mechanisms. Kan et al. (2006) proposed a similar distinction, referring to these processes as selection and assembly, respectively, and reported on an individual who, they argued, suffered specific disruption to assembly processes.

Another source of information regarding the component functions of O-WM may come from differences across individuals with O-WM deficits in terms of the distribution of the rate of spelling errors across letter positions. Two basic patterns have been reported. In the first pattern, errors predominate in central positions, thus yielding a bow-shaped error distribution (e.g., Buchwald & Rapp, 2009; Caramazza & Miceli, 1990, Jónsdottír, Shallice & Wise, 1996, McCloskey et al., 1994, Tainturier & Rapp, 2004). The second pattern is characterized by errors increasing roughly monotonically from initial to final position in the written string (e.g., Katz, 1991; Ward & Romani, 1998; Schiller, et al., 2001; Miceli et al., 2004). These different error distributions have been attributed to disruption to different mechanisms of O-WM, including mechanisms responsible for lateral inhibition and decay. For example, Wing & Baddeley (1980), in discussing the bow-shaped error curve that was observed in the spelling errors of neurologically normal individuals, attributed the bow-shape to the effects of lateral interference between neighboring letters in O-WM. In cases of O-WM damage, it has been suggested that the normal bow-shape may be accentuated (and the consequences of lateral interference are increased) due to the weaker than normal activation of the letter representations within O-WM (Goldberg & Rapp, 2008). The monotonic error function, on the other hand, has been attributed by some researchers to the rapid decay of the orthographic representations within O-WM (Katz, 1991; Schiller et al., 2001; but see Sage & Ellis, 2004; Ward & Romani, 1998). However, the source of the observed differences in serial order effects in O-WM deficits is still an open matter.

Certainly additional work is required to determine the sub-processes involved in O-WM. In fact, even though individuals with O-WM deficits share specific behavioral features that identify O-WM as the locus of their spelling difficulties (e.g., a length effect in the absence of lexical-semantic influences, and performance that is independent of input or output modality) even a cursory look at the literature reveals differences that justify the statement that “the term Graphemic Buffer Disorder is no more than a convenient label for a pattern of behaviors shown by a group of subjects and does not reflect a homogeneous cognitive deficit” (Miceli & Capasso, 2006; p. 126). However, it is precisely this heterogeneity that can be exploited as a rich source of information regarding the internal organization and mechanisms of O-WM.

The relationship between temporal stability/representational distinctiveness and decay/interference

It is reasonable to assume that in any domain, WM requires both temporally stable and well-specified representations of the elements comprising the to-be-produced string. We will refer to these critical properties as *temporal stability* and *representational distinctiveness*. Under normal conditions, these two properties are necessary for the elements of the representation to be selected and passed on to subsequent processes in the correct order. In the context of spelling, temporal stability ensures that the orthographic string, whether it is retrieved from long-term memory or assembled by phoneme-grapheme conversion procedures, remains active during serial selection and production of individual letters. Representational distinctiveness ensures that the elements of the string are well-specified at each moment, so that the correct element can be selected for production. The concepts of temporal stability and representational distinctiveness are invoked (although not always with the same terminology) throughout the WM literature when trying to explain the failures of WM that cause (neurologically intact) individuals to forget items when lists get too long. In fact, we can refer to the consequences of failures of temporal stability or representational distinctiveness as “decay” and “interference”, respectively.

According to one school of thought within the WM literature (which has not typically included O-WM), temporal decay is responsible for forgetting in working memory. Memory traces decay over time, though rehearsal may serve to limit the effects of this decay (e.g. Baddeley, 1986; Burgess & Hitch, 1992, 1999; Cowan, 1992; Page & Norris, 1998; Towse & Hitch, 1995). According to the decay account of forgetting, items in working memory are forgotten because they fail to stay sufficiently active during serial recall. An alternative set of proposals explains working memory limitations in terms of competition between items being represented in WM. Shared-resources accounts (e.g. Anderson & Matessa, 1998; Just & Carpenter, 1992) argue that items in working memory compete for a limited resource. The additional observation that the similarity of items in WM increases interference (competition) is an indication that the limitations may specifically affect representational resources (e.g., Farrell & Lewandowsky, 2002; Lewandowsky & Farrell, 2008; Oberauer & Kliegl, 2001; Oberauer & Lewandowsky, 2008). Along similar lines, distinctiveness accounts of WM failures (e.g. Brown, Neath & Chater, 2007; Murdock, 1960; Nairne, Neath, Serra, & Byun, 1997; Neath, 1993) posit that the likelihood that an item will be remembered is a function of how much it stands out relative to the other items in the list.

Given these two positions, much of the research on causes of forgetting in WM has pitted temporal decay accounts against distinctiveness or interference accounts (e.g. Lewandowsky, Oberauer & Brown, 2008). However it is not clear that the overall pattern of results can be captured either by an account that exclusively relies on temporal decay or by one that relies on interference (or lack of representational distinctiveness). Along these lines, a number of recent theories of working memory (e.g., Anderson & Matessa, 1997; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Henson, 1998) attribute forgetting to both temporal decay and a lack of representational distinctiveness.

Temporal stability and representational distinctiveness in O-WM

Interestingly, the debate in the larger WM literature resembles the much more limited debate (summarized earlier) that has occurred in the O-WM literature and that has centered largely around explanations for differences in the shape of serial position error functions. If decay and interference are both possible, and if they are supported by independent WM mechanisms, then it may be possible to find individuals with O-WM deficits who exhibit the consequences of either or both.

Both impairments should result in a length effect such that segmental errors are more likely for longer words than shorter words. However, the length effect is caused by different mechanisms in the two cases and, as we will argue, under certain conditions these length effects would be expected to be qualitatively different. Moreover, the two deficit types predict the different serial position effects that have already been observed in different cases of O-WM impairment. In the event of disruption to temporal stability (i.e., abnormally rapid decay of information in working memory), since longer words must be maintained in working memory for more time than shorter words, the likelihood that an element will be under-activated at the time of selection should increase for longer vs. shorter words. Further, since the likelihood that an element is under-activated increases with the distance of each letter from the beginning of the string, a roughly monotonic increase in error rates should be observed (Schiller, et al., 2001; Katz, 1991). In contrast, in the case of reduced representational distinctiveness (i.e., increased interference), a length effect arises because sequences with more letters will “crowd” the representational space more than sequences with fewer letters, resulting in higher error rates for longer vs. shorter words. In addition, this disruption is predicted to give rise to a bow-shaped serial position effect if we assume that reducing the representational distinctiveness will exaggerate the normal effect of crowding (Wing & Baddeley, 1980; Jones, Folk & Rapp, 2009) in central positions relative to the peripheral positions.

Consonants and vowels in orthographic WM

Disruptions to O-WM have been used to investigate the internal organization and content of the orthographic representations that are manipulated by the O-WM system. The degradation of the information held in any WM system can result in the dissolution of the units and bundles of information that are processed by the system, revealing their internal content and organization (Caramazza & Miceli, 1990; for a recent review see Rapp & Fischer-Baum, in press). Of particular interest for the current study is the claim that orthographic representations distinguish consonants and vowels. This claim has been supported by the observation of a very high rate of preservation of the CV status of target letters in substitution errors produced by individuals with damage to O-WM. That is, although the wrong letter is produced in substitution errors (“sleigh” spelled as SLEIGT or “tavola” spelled as TOVOLA), the substituted letter often preserves the CV status of the target letter. This indicates that although letter identity information may be disrupted, information regarding the CV status of the letters may be available. Rates of CV preservation have been demonstrated to be above chance and are reported to be as high as 99% in some cases (see Miceli & Capasso, 2006 for review and Buchwald and Rapp, 2006 for evidence that CV status is specifically orthographic and not phonological).

Further support for the distinction between consonants and vowels at the level of O-WM comes from reports of individuals with O-WM deficits who have selective difficulties with either consonants (Kay & Hanley, 1994, Miceli, et al., 2004) or vowels (Cubelli, 1991, Cotelli, et al., 2003; see also Rapp, McCloskey, Rothlein, Lipka, & Vindiola, 2009 for a case of vowel-specific synesthesia). For example, the individual described by Miceli et al. (2004) (and who is also included in this report) produced 98% of his errors on consonants. These selective deficits reveal that consonants and vowels are represented with sufficient neural independence that brain injury can disrupt the processing of one more than the other.

There has been little discussion of the implications of the neural independence of consonants and vowels for the operation of O-WM (but see Miceli, et al., 2004). If indeed O-WM includes distinct mechanisms for maintaining the temporal stability and representational distinctiveness of letters, then it is plausible that the neuroanatomical separability of consonants and vowels requires the independent application of these processes to each letter category. In that case, it would be possible for mechanisms responsible for temporal stability or representational distinctiveness to be selectively disrupted for either consonants or vowels. In this study, given our poor understanding of the detailed functioning of O-WM and its interactions with the representational stores (lexical and graphemic) that contribute to it, we make as few assumptions as possible regarding the specific implementation of these mechanisms. Therefore, with regard to a consonant-specific disruption of the mechanisms of temporal stability, we simply assume that this would involve an acceleration of the normal decay rate for the consonants that are manipulated by O-WM. In terms of representational distinctiveness, we assume that there is a representational space for consonants (presumably with its own neural substrates) and that some form of disruption will have the effect of reducing the representational space (or the distinctiveness of the representations within it), creating greater interference among consonant representations. The approach we take in this study is to assume such category-specific processes and then derive and test predictions for what would be expected if they were to be selectively disrupted. We would like to be clear, however, that the focus of the investigation is not to establish the category-specificity of O-WM mechanisms but rather to use category (consonant)-specific deficits to derive novel predictions for the hypothesis that O-WM includes distinct processes responsible for maintaining temporal stability and representational distinctiveness. Evidence consistent with the predictions would then provide confirmatory support for the hypothesis.

Predictions of decay vs. interference deficits (representational stability vs. distinctiveness) in cases of consonant-specific O-WM impairment

What is important for the purposes of this investigation is that decay and interference deficits in the context of consonant-specific deficits yield predictions that go beyond the simple differences in serial position curves (bow-shaped vs. increasing) that have motivated previous decay vs. interference proposals in cases of O-WM deficits. (Note that we will refer to the deficits as abnormal-decay and abnormal-interference deficits, as some degree of decay and some degree of interference are normal).

Briefly, the basis for the differences in predictions lies in the fact that letter accuracy in a consonant-specific, abnormal-decay deficit should be affected by the total number of letters to be produced, whereas letter accuracy in a consonant-specific, abnormal-interference deficit should be primarily affected by the number of the consonants to be produced. We elaborate on this below as we describe the three different sets of predictions regarding the following questions: (1) Are word length effects are determined by the number of letters or the number of consonants? (2) Is consonant accuracy affected by the serial position of a consonant relative to all other letters in the word? and (3) Are serial position curves are affected by the total number of consonants in the word?.

1-Length effect: Number of letters or number of consonants—In the case of a consonant-specific, abnormal-decay deficit, because all the letters in a word must be selected serially for production, the total number of letters (both consonants and vowels) to be spelled will contribute to the accuracy with which the consonants are produced. This is because activation decays as a function of the absolute distance (time elapsed or number of letters produced) from the beginning of the word, not just as a function of the distance in terms of number of consonants. So, while it is true that this type of deficit assumes that consonants are decaying more quickly than vowels, the time taken to produce vowels affects the amount of decay that will have occurred for upcoming consonants. As a result, the total number of letters in a word and not only the number of consonants will affect consonant accuracy.

In contrast, for a consonant-specific, abnormal-interference deficit it is the number of consonants in any given word that is relevant for determining consonant accuracy. This is because only consonants are subject to abnormal interference from one another, while the number of intervening vowels has no effect on consonant representations. Thus, for an abnormal-interference deficit, we predict comparable accuracy for consonants in words matched in total number of consonants, although differing in total number of letters. However, consonants should be spelled with different accuracy in words differing in the total number of consonants, although matched for total number of letters.

2- Serial position: Letter position vs. consonant position—For a consonant-specific abnormal-decay deficit, the effect of serial position on consonant accuracy should be determined by the position of a consonant relative to all the letters in the word, rather than its position relative to only the other consonants in the word. As a result, accuracy should differ for consonants in different letter positions (e.g., the T in sTadio vs. paTria) because they are in different letter positions, regardless of the fact that they are both the second consonant of the word.

In contrast, for a consonant-specific abnormal-interference deficit, it is only the position of a consonant relative to other consonants that should affect accuracy. In the example of sTadio vs. paTria, the T’s should be spelled with the same accuracy because they are both the second consonant of words with three consonants, regardless of the fact that they occur in different letter positions.

3-Serial position curves: Interaction with number of consonants in a word?— For a consonant-specific abnormal-decay deficit, the total number of consonants in a word should not affect serial position accuracy. That is, for any consonant, the key factor is how far it is from the beginning (or end) of the word and it is largely irrelevant how many other consonants there are in the word. As a result we expect generally comparable serial position curves regardless of the number of consonants in a word. For example, if we consider tRomba vs. gRazia, the R is in the second letter and consonant position in both words and accuracy should be comparable, regardless of the fact that “tromba” has a total of four consonants and “grazia” has three.

For an abnormal-interference deficit, the situation is different. Accuracy at a given serial position will be influenced by the number of other consonants in the word that are creating interference. In the example of tRomba vs. gRazia, the limited representational space for consonants is more crowded in TRoMBa. Consequently, the R in tRomba should be spelled less accurately than the R in gRazia, even though both consonants are in the second consonant position in each word.

In sum, contrasting predictions can be derived in the case of damage to either the temporal stability or the representational distinctiveness functions of O-WM (see Table 1). These differences yield specific predictions in cases of individuals with selective impairments to consonants (though the logic would, of course, apply to individuals with selective impairments to vowels as well). We will argue that these predictions are borne out by the pattern of performance of the individuals we report on in this paper, thus providing evidence in support of the proposed roles of temporal stability and representational distinctiveness in O-WM.

METHODS AND RESULTS

1-BACKGROUND TESTING

GSI was a right-handed, 60-year old, native Italian speaker and university professor of physics who suffered from mild Broca’s aphasia with dysarthric and dysfluent speech, following a left middle cerebral artery stroke involving the frontal and parietal lobes and the superior temporal gyrus. A smaller lesion was also present in the left posterior-inferior parietal lobe (Figure 2; see also Miceli et al., 2004 for further neuroradiological documentation).

A language evaluation was carried out using the BADA and results are presented in Table 2. The BADA is a screening battery for aphasia (Miceli, Laudanna, Burani & Capasso, 1994). In addition, Miceli et al. (2004) provide an extensive report on GSI that can be consulted for further details. Testing showed that repetition and reading aloud were slightly below normal for words, and mildly but clearly pathological for pseudowords. In these tasks error types were related to the target (repetition pseudoword: *fupro*, > /supro/; *perfino*, event > /ferfino/; reading aloud: *geba*, > /djeva/; *dilatava*, he/she was dilating > /tilatava/). Written and spoken comprehension was good for nouns, just below normal for verbs. Oral picture naming was more accurate for nouns than verbs. Errors on this task resulted mostly in semantic substitutions (*leg* > *knee*) and failures to respond. Written picture naming was more impaired; in this task GSI mainly produced segmental errors (*fungo*, mushroom > fu_o; *pennello*, brush, > penne_o). Performance on auditory and visual sentence-picture matching tasks was slightly below normal; the errors resulted mostly in choosing the picture representing the reversal of thematic roles (4/70, 6%) and the semantic alternative (6/70, 8%). Spontaneous speech was characterized by ungrammatical production due to errors on verb agreement, omission of functors and of main verbs and use of general verbs.

CRI was a right-handed, 70-year-old, native Italian speaker, who worked as a clerk. In July 2001 he suffered a left middle cerebral artery stroke, damaging the inferior and middle frontal gyrus, the claustrum, the insula, and the anterior and middle third of the superior temporal gyrus. More posteriorly, portions of the angular gyrus and the structures on both banks of the intraparietal sulcus were damaged (Figure 2).

Spelling and language data were collected between October 2001 and March 2002. The results of the BADA are summarized in Table 2. Repetition of words and pseudowords and reading aloud of words were slightly below normal; pseudoword reading was more clearly impaired. Incorrect responses always resulted in segmentally related errors (repetition: *delitti*, crimes > /di:litti/; *gralive*, pseudoword > /gra:dive/; reading aloud: *cirtallo*, pseudoword > /cis:tallo/). Reading aloud also yielded one segmentally related word response (*tomba*, tomb > *tromba*, trumpet) and a possible morphological error (*volpe*, fox > *volpi*, foxes). CRI's performance was within normal limits on auditory lexical decision, but slightly below normal in visual lexical decision. Oral picture naming was moderately impaired. Errors on this task were mostly semantic substitutions (tiger > panther; to saw > to slice). Written picture naming was more impaired, due to the additional presence of segmental errors (see below); in oral and written picture naming, no difference was observed between nouns and verbs. Performance on auditory and visual word-picture matching were slightly below normal for nouns, and mildly impaired for verbs. Performance on auditory and visual sentence-picture matching tasks was clearly below normal; most errors in these tasks resulted in choosing the picture representing the reversal of thematic roles (12/35, 34.3%). Several errors also resulted in the selection of semantic (7/35, 20%) or morphological foils (4/35, 11.4%). Sentence reading and repetition were errorless. Prosody and articulation were normal. The amount of information conveyed was normal, although sentence structure was simplified and there were anomic pauses, especially with verbs (the target verb was sometimes substituted by a semantically related verb).

2- GENERAL SPELLING EVALUATION

GSI and CRI were administered spelling-to-dictation and written picture naming tasks. In the spelling-to-dictation task, five lists of words were administered. Within lists, stimuli were matched across sub-lists in order to evaluate the effects of psycholinguistic variables, such as abstractness/concreteness, grammatical class, length, frequency, orthographic structure, morphological structure and presence/absence of opaque segments (e.g., *bosco*, forest). For example, the effect of grammatical class was evaluated by contrasting performance on sublists of nouns, adjectives, verbs and function words that were exactly matched for length and frequency; the effect of orthographic structure by contrasting performance on sublists of regular-CV (eg, *tavolo*, table) and irregular-CV nouns (*albero*, tree), exactly matched for length and frequency; and so on. Frequency values were based on Bortolini, Tagliavini & Zampolli (1971). For written picture naming, pictures depicting high and low frequency nouns (matched for length) were presented. For pseudowords, length effects were evaluated by comparing sets of pseudowords of different lengths that were matched for their morphological decomposability and the presence/absence of opaque segments (e.g., *raschelo*).

Results for both individuals are reported in Table 3. For GSI, performance in spelling-to-dictation tasks was influenced by length ($\chi^2(2) = 55.35$; $p<.0001$) but not by lexicality ($\chi^2(1) = 0.03$; $p = .86$) or lexical variables, like frequency ($\chi^2\ (1) = 0.05$; $p = .82$), grammatical class ($\chi^2(3)= 3.81$; $p = .28$), concreteness/abstractness ($\chi^2(1)= 0.01$; $p = .75$) (see table 3). Errors consisted of segmental deviations from the target. Deletions were by far the most frequent error type; some transpositions and substitutions were also present. Overall, GSI was asked to spell-to-dictation 731 words, containing 4374 letters. He misspelled 376/731 (51.4%) words and 542/4374 (12.4%) letters. He also incorrectly spelled 66/80 pseudowords (82%), producing errors on 99/412 (24%) letters. Note that for words and pseudowords matched for length and orthographic structure, the error rate difference was not significant (words: 56/89(63%); pseudowords: 13/21(62%); $\chi^2(1)= 0.03$; $p =$ n.s).

For CRI, spelling accuracy was uninfluenced by the concreteness of the stimulus ($\chi^2(1) = 0.17$; $p = .68$), by its frequency ($\chi^2(1) = 0.28$; $p = .59$) or grammatical class ($\chi^2(3) = 2.97$; $p = .39$), but was significantly affected by length ($\chi^2(2) = 31.72$; $p<.0001$). Overall, CRI spelled incorrectly to dictation 287/720 (40%) words and 45/80 (56%) pseudowords. He misspelled 402/4574 (9%) letters in words and 58/520 (11%) in pseudowords ($\chi^2\ (1)= 2.9$; $p = 0.08$. CRI's errors were predominantly letter omissions (168/402, 42%, *comincia*, s/he starts > comicia), and substitutions (172/402, 43%, *cervello*, brain > cerlello), followed by letter transpositions (55/402, 14%, *paesi*, countries > pasei) and rare insertions (7/402, 2%, *giovane*, young > giovanne). These error types were observed in spelling to dictation both with words and pseudowords.

In sum, for both GSI and CRI, the pattern of spelling performance clearly indicated a deficit at the level of the O-WM system: significant effects of length, segmental errors, comparable performance for words and pseudowords, and the absence of effects of lexical variables.

Selective impairment of consonants—For both individuals, the most striking feature of their dysgraphia was a strong dissociation between impaired consonants and relatively spared vowels. Table 4 shows the error rate on consonants and vowels within words in different spelling tasks. GSI wrote incorrectly 705/5421 (13%) letters, misspelling 692/2833 (24%) of the consonants and 13/2588 (0.5%) of the vowels. This means that, across tasks, 98% of GIS's errors occurred on consonants and 2% occurred on vowels. CRI, overall, wrote incorrectly 527/6297 (8%) letters, misspelling 443/3277 (13%) of the consonants and 84/3020 (3%) of the vowels ($\chi^2(1)= 231.94$; $p<.0001$). In other words, 84% of his spelling errors affected consonants, and 16% vowels. Therefore, CRI can be added to the other two subjects (JH, Kay and Hanley, 1994; GSI, Miceli et al., 2004) who have been reported as exhibiting disproportionate difficulty in spelling consonants.

While the consonant/vowel dissociation is quite striking, in order to control for differences in the total numbers of consonants and vowels in the stimuli, we followed the procedure suggested by Ward & Romani (2000) to determine if the distribution of consonant and vowel errors was significantly different from the distribution of consonants and vowels in the correct spellings of those words. For each individual, the total number of consonants and vowels in the corpus of words administered for spelling (GSI: n= 718; CRI: n= 720) was compared with the total number of errors on consonants and vowels. The results are reported in Table 5 and confirm that GSI and CRI suffered from a selective deficit for consonants: a significant difference was found between the distribution of consonants and vowels in the set of errors and their distribution in the target spellings (GSI: χ^2 (1)= 414.57; $p<.0001$; CRI:χ^2 (1)= 149.27; p<.0001). Thus, for both subjects, a larger proportion of errors were produced on consonants and a smaller proportion on vowels than would be expected from the distribution of consonants and vowels within the corpora of words they were asked to spell.

Distinct serial position effects—Given that the deficits were largely restricted to consonants, the effect of serial position was examined considering only consonants and consonant errors. The stimulus sets evaluated in this analysis consisted of words that contained between 2 and 5 consonants (1 and 6-consonant words were excluded) and geminate consonants were "counted" as single elements[1] (n=694 words for GSI and 691 for CRI). For this reason, in all subsequent analyses we will use the term "grapheme" rather than "letter". Both GSI and CRI produced few complex errors (where the response deviated from the target by more than one letter), and those complex errors were always interpretable. Therefore, we included all errors (both simple and complex) produced by each individual. To combine stimuli of different lengths, we used the normalization method proposed by Machtynger and Shallice (2009) collapsing all of the data into 4 positions (A–D) or what Machtynger and Shallice call "regions". Given that only consonant accuracy is of interest (for this and all subsequent analyses) only consonants are considered in the normalization process. This allows us to clearly observe the effect of serial position on consonant accuracy.

For GSI, the error percentages for consonants across the four normalized positions were 1, 16, 32 and 43, respectively (see Figure 3a). Thus, GSI showed a generally monotonically increasing error function – with the probability of an error increasing with the distance of a consonant from the beginning of the word. For CRI, the error percentages for consonants from the first to the fourth position were 6, 15, 20 and 11 (see Figure 3b). CRI made more errors on consonants in medial positions than on those in initial and final positions, producing a bow-shaped error function.

This analysis establishes that despite the fact that GSI and CRI were similar in terms of exhibiting the hallmark symptoms of O-WM deficit, as well as with regard to their remarkably selective difficulties with consonants, they exhibited starkly different serial position effects. These serial position curves, although restricted to consonant errors due to the nature of their deficits, are otherwise comparable to those reported in the literature and whose origins have been debated. Therefore, on the basis of their serial position curves, GSI is a candidate for an abnormal-decay deficit, while CRI is a candidate for an abnormal-interference deficit, although in both cases, the deficits are restricted to consonants. As

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[1] Evidence from a number of dysgraphic individuals reported in the literature indicates double (geminate) letters are represented by a single letter with separate representation of doubling information. For example, patient LB (Caramazza and Miceli, 1990) never made errors involving only one of the geminate consonants (pa*ll*a -> p*l*a*l*a) (see also, Miceli, Benvegnù, Capasso, & Caramazza, 1995; Schiller et al., 2001; Tainturier & Caramazza, 1996; for a review, see Miceli & Capasso, 2006). GSI and CRI 's spelling errors were consistent with these reports. In fact, substitutions and transposition errors occurred on both letters of a geminate and never involved only one of the two letters.

discussed in the Introduction, the restriction of the deficits to the category of consonants allows us to test three specific predictions (Table 1) that follow from the hypothesis that GSI and CRI suffer from abnormal-decay and abnormal-interference deficits, respectively.

EXPERIMENTAL INVESTIGATION

Analysis1a. Length effect: The effect of varying consonant length while keeping grapheme length constant

Temporal stability and representational distinctiveness deficits can be distinguished by whether the increased forgetting that occurs with increasing stimulus length is a function of the number of graphemes or the number of consonants in the letter string. As a first step in examining this prediction, we considered words from the spelling to dictation task that contained 4 to 11 graphemes and 2 to 5 consonants. We considered the number of graphemes/consonants in the target spelling of the word rather than the number of graphemes/consonants in the produced response. We note that both GSI and CRI produced spelling errors that included consonant omissions and although omission errors are expected with O-WM impairment, it is also possible that at least some of these errors arose prior to O-WM. In that case, fewer consonants than we have assumed would have actually been processed at the level of O-WM, introducing a potential source of noise in the analyses.

We calculated response accuracy (incorrect consonants/total consonants) for each word length for a corpus of 718 words for GSI and 720 words for CRI. Results, indicate that both individuals exhibited a significant length effect, regardless of whether accuracy was measured in terms of the number of graphemes (GSI: χ^2 (4) = 69.96; p<.0001; CRI: (χ^2(4) = 45.33; p<.0001), or the number of consonants (GSI: χ^2 (2)= 48.41; p<.0001; CRI: χ^2(2)= 41.55; p<.0001).

However, this result is not surprising, as both had an O-WM deficit and the number of consonants closely correlates with the number of graphemes. In order to disambiguate the effects of consonant and grapheme length, we carried out a second analysis in which we compared the accuracy of consonants holding number of graphemes constant while varying number of consonants. For example, we compared percent consonant errors on 7-grapheme words with 3 vs. 4 consonants (*società* vs. *scatola*). This allowed us to determine if length measured in terms of the number of consonants affected performance. Overall, we examined words with 5–8 graphemes and 2–5 consonants (GSI n=612 words; CRI n=619 words). The results of this analysis for GSI and CRI are presented in Table 6.

As reported in Table 6, results indicate that the total number of consonants in a word did not affect GSI's consonant accuracy at any grapheme length. In contrast, for CRI, the number of consonants affected consonant accuracy such that at every grapheme length, consonant accuracy was significantly lower on words with more consonants, despite the fact that they were matched for number of graphemes. These results are clearly consistent with the prediction (Table 1) that the number of consonants (but not graphemes) should affect consonant accuracy in an abnormal interference deficit (CRI), but not in an abnormal decay deficit (GSI).

Analysis 1b. Length effect: Number of consonant vs. number of graphemes (Regression and Montecarlo evaluations)

The previous analysis provided a strong test of the role of consonant number; however, to directly contrast whether the total number of consonants or number of graphemes in a word better accounts for consonant errors, a more comprehensive analysis of GSI and CRI's consonant errors was carried out using logistic regression (GSI n=718 words; CRI n=720 words).

Grapheme and consonant length were highly correlated (.84 for GSI, .87 for CRI); this high degree of co-linearity precluded examining both factors within a single regression analysis (Gordon, 1968). Many approaches have been proposed for dealing with co-linearity in regression analyses; the simplest is to run the regression model with only one of the related independent variables (e.g., Cohen, Cohen, West & Aiken, 2003). We took this approach here, running two separate logistic regression models, each with a single length regressor. In the Consonant model, the length regressor was the length of the target word in number of consonants while for the Grapheme model, the length regressor was the length of the target word in number of graphemes. We then evaluated which model better accounted for the pattern of errors produced by each participant, using a Cox & Snell pseudo-r^2.[2] A better fit for the Consonant model would constitute evidence that errors depend on number of consonants in a word, while a better fit for the Grapheme model would constitute evidence that errors depend on the number of graphemes in a word.

The results of this analysis confirmed the results reported in the previous section. For CRI the Consonant model was a better predictor of consonant accuracy than the Grapheme model (Consonant Model, pseudo-r^2= .027; Grapheme Model, pseudo-r^2= .009). Conversely, for GSI, the Grapheme model was a better predictor of consonant accuracy than the Consonant model (Grapheme Model, Cox & Snell pseudo-r^2 = .017; Consonant Model pseudo-r^2= .014).

While these regression results are consistent with the results of Analysis 1a, the differences in fit are small, and without additional information (providing a measure of variance) it is impossible to gauge whether the differences in fit are significant. To evaluate the significance, a resampling procedure was used whereby the two models were evaluated on numerous randomly selected subsets of the data. This allowed us to determine the degree to which the model fits obtained for the complete data sets, were consistently observed on different subsets of the data. The resampling procedure was carried out as follows for each subject. On each run of the Monte Carlo resampling analysis, 500 consonants were randomly selected from the subject's complete response set, with the requirement that 50% of the consonants in the random selection had been produced correctly and 50% had been produced incorrectly. For example, CRI spelled the word "*comincia* [s/he starts]" as COMICIA. In one run of the Montecarlo analysis, the (correctly produced) C at the onset of the word and the (incorrectly produced) N may have been randomly selected, while the (correctly produced) M was not included. On some other iteration of the analysis, the N and M from "comincia" may have been included in the analysis while the initial C was not. For each random subset of data, two logistic regression analyses were run, the Grapheme and the Consonant models. These analyses were identical to those carried out over the complete data set, except now they were carried out only over a subset of the data. For each subset of data, a Cox & Snell pseudo r^2 measure of fit was obtained for both the Grapheme and the Consonant model. The program then simply tallied which of the two models had a larger Cox & Snell pseudo r^2 for each data-subset. That is, the program determined which of the two models better predicted consonant accuracy on each subset of data. This procedure was repeated 10,000 times. In other words, the program created 10,000 sub-samples of the data each with 500 data points and for each sample compared the fit of the two logistic regression models. For the 10,000 random samples, the program calculated the proportion of samples for which the Grapheme model or the Consonant model fit the data better. If the observed differences in fit between the Consonant and Grapheme model for CRI and GSI are

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[2] While Cox & Snell pseudo-r^2 values cannot be interpreted as the proportion of variance explained as in a linear regression, they can be used to evaluate multiple models predicting the same outcome on the same dataset, with the higher pseudo r^2 value indicating the model that better predicts the outcome (e.g., Freese & Long, 2006).

significant, then, for each individual, the same model should consistently fit the data better over these randomly selected subsets of the data.

The results for CRI were unmistakable. For all 10,000 subsamples of the data, the Consonant model predicted consonant accuracy better than the Grapheme model, allowing us to be confident that the likelihood of a consonant error depended on target length measured in terms of the number of consonants rather than the number of graphemes. On this basis, we can reject the null hypothesis that the Consonant and Grapheme models fit the data equally well for CRI ($p<.001$).

For GSI, the Grapheme model was a better predictor of consonant accuracy than the Consonant model on 79% of the 10,000 subsamples of the data. While we cannot reject the null hypothesis (at a $p<.05$) that the Consonant and Grapheme models fit the data equally well for GSI from this analysis, it is, nonetheless, evident that the Grapheme model performed better than did the Consonant model. Therefore, these results are consistent with the previous analysis showing that for GSI spelling accuracy was not significantly influenced by the number of consonants. It is worth considering one reason why this analysis may not have clearly adjudicated between grapheme and consonant length. One possibility is that for a consonant-specific, abnormal decay deficit we expect consonant accuracy to be influenced by the position of a consonant with respect to all other letters in the words. That is, consonants earlier in the string will be produced more accurately than consonants later in the string. However, there was no guarantee that, in the stimulus set GSI was administered, consonant position was similarly distributed across positions in words with different numbers of graphemes. For example, if consonants in words with 7-graphemes occurred more often in the first half of the word than they did in 3 letter words, this would diminish the strength with which grapheme length would predict consonant accuracy. To elucidate this question, in the next section, we report on Analysis 2, in which we directly examine the effect on consonant accuracy of the position of a consonant with respect to all of the graphemes in a word.

Analysis 2. Serial position: Grapheme position or consonant position?

The results thus far have revealed contrasting patterns for GSI and CRI with regard to both serial position curves and length effects. CRI exhibited increased error rates in the middle of words and the total number of consonants in the words significantly affected spelling accuracy. In contrast, GSI made more consonant errors at the ends of words and his spelling accuracy was influenced by the number of graphemes in a string. As indicated in Table 1, the two-deficit hypothesis also makes predictions regarding the effect on consonant accuracy of the serial position of a consonant with respect to the other graphemes in a word. Specifically, for GSI, consonant accuracy should be determined by the position of each consonant with respect to all other graphemes in the word (grapheme position), while for CRI, consonant position with respect to other graphemes should be largely irrelevant. For example, GSI should spell the second consonant of a word more accurately when it appears in the second grapheme position (e.g., t in *sTadio*) than when it appears in the third grapheme position (e.g., t in *paTria*). For CRI, consonants that appear in the same consonant position should be spelled comparably, regardless of their grapheme positions (e.g., t in *sTadio* and in *paTria* should be spelled comparably).

For this analysis we measured spelling accuracy for consonants that were in the same consonant position but in different grapheme positions, considering consonant positions 2, 3 and 4 at different grapheme positions (2–7). The word corpus for GSI included 612 words, for CRI it included 619 words. The results, depicted in Figure 4, are very clear. As predicted, GSI produced higher error rates on consonants matched for consonant position but with greater grapheme position (more errors for the second-position consonant T when it appeared in the third grapheme position in *paTria* than in the second grapheme position in *sTadio).* This effect was found for all consonant positions examined: 2nd position consonants ($\chi^2(1)= 6.35$, $p < .05$); 3rd position consonants ($\chi^2(1)= 17.3$, $p < .0001$) and 4th position consonants ($\chi^2(1)= 30.5$, $p<.0001$). By contrast, for CRI each of these comparisons was non-significant, indicating that grapheme position was largely irrelevant: 2nd position consonants: $\chi^2(1)= 0.01$, p = ns; 3rd position consonant: $\chi^2(1)= 0.01$, p = ns and 4th position consonant: $\chi^2(1)= 0.56$, p = ns).

Analysis 3. Serial position curves: Interaction with number of consonants in a word?

A further prediction of the two-deficit hypothesis is that for an abnormal-decay deficit the total number of consonants in a word should not influence performance at a given serial position, whereas for an abnormal-interference deficit the number of consonants in a word is always relevant. This is because, for an abnormal-interference deficit, the greater the number of consonants, the greater the overall interference and, therefore, the greater the impact on consonant accuracy. Therefore, at every consonant position, the total number of consonants in a string should have an effect on performance (although this interacts with the normal bow-shape crowding effect such that the effects may be more severe for some positions than others).

To examine this prediction we considered whether consonant accuracy differed for consonants that occupied the same consonant position but that differed in the total number of consonants in the word they came from. For example, we considered accuracy on the second consonant in words that contained a total of two, three, four or five consonants (e.g., t in sTuoia, sTadio, sTazione, sTudente).

The stimulus set for this analysis consisted of 694 words for GSI and 691 for CRI (the same corpora used for the analyses of the serial order). The results are displayed in Figure 5. For GSI, it is very clear that accuracy at each position was uninfluenced by the total number of consonants in the target word. For example, he produced a similar rate of errors for consonants in the second consonant position, regardless of the whether the word contained a total two, three, four or five consonants (2nd consonant: $\chi^2(3)=2.25$, p=ns; 3rd consonant: $\chi^2(2)=0.04$, p=ns; 4th consonant: ($\chi^2(1)= 0.33$, p=ns). Further, one can see that for GSI the monotonic serial position curves are identical in slope, regardless of the number of consonants in the word.

This is what would be expected for an abnormal-decay deficit for which distance (time to decay) is the determining variable. Conversely, CRI's spelling errors in the different consonant position increased as the total number of consonants in the target word increased. For example, for the second consonant position, CRI's error rates were 9%, 12%, 21% and 29% for words with a total of 2, 3, 4 and 5 consonants, respectively. There was a significant effect of consonant length at: 2nd position ($\chi^2(3)=19.11$, $p<.001$); 3rd position $\chi^2(2)= 22.16$, $p<.0001$; and 4th position: $\chi^2(1)= 5.34$, $p<.05$; only at the first position, where few errors were produced, the effect was not significant. Further, the bow-shaped accuracy function is apparent at all lengths (except for 2-consonant words), but, importantly, the peak of the function was strongly influenced by the number of consonants in the words. This is quite unlike what was seen for GSI.

GENERAL DISCUSSION

One of the primary questions in working memory research is: What causes forgetting in working memory? Answering this question provides a means to understanding the internal structures and functions of working memory systems. We have suggested, consistent with various proposals in the literature, that WM systems require functions that ensure (among other things) what we have referred to as the temporal stability and the representational distinctiveness of the elements manipulated by a WM system. Failures of these functions will lead to abnormal decay and interference, respectively. In this report we have provided evidence that these two functions operate in orthographic WM (O-WM) and can be separately disrupted by brain damage.

Evidence for this claim comes from the analysis of the spelling performance of two individuals, GSI and CRI who, as a result of strokes, suffered from acquired dysgraphia that affected their spelling ability by specifically disrupting O-WM. Furthermore, their O-WM deficits were largely limited to consonants. While the two individuals were alike in this regard, they differed in the nature of their serial position curves, with GSI exhibiting a monotonically increasing error function and CRI a bow-shaped error function.

Our hypothesis was that the monotonically increasing error rate function resulted from a consonant-specific, abnormal-decay deficit, while the bow-shaped error rate function resulted from a consonant-specific, abnormal-interference deficit. We developed three sets of contrasting predictions (listed in Table 1) that followed from the assumptions we made regarding these two different deficit types. Specifically, we assumed that in a consonant-specific, abnormal decay deficit, consonant accuracy should be affected by the total number of letters to be produced because decay is affected by the distance (in time or elements produced) from the beginning of the word, regardless of whether the elements are consonants or vowels. For a consonant-specific, abnormal-interference deficit, we assumed that consonant accuracy should primarily be affected by the number of consonants to be produced because it is only consonants that increase interference. The three primary findings of this research confirm the specific predictions that we derived from these assumptions: (1) For the abnormal-decay deficit, consonant accuracy was determined by the number of letters in words and not by the number of consonants in words; for the abnormal-interference deficit, the opposite was found to be the case; (2) For the abnormal-decay deficit, consonant accuracy was determined by the position of a consonant relative to all other letters in the word, while its position relative to other consonants was irrelevant; in contrast, for the abnormal-interference deficit, the position of a consonant relative to other letters in a word did not affect performance; and (3) For the abnormal-decay deficit, the total number of consonants in a word did not affect performance at any position in a word; in contrast, for the abnormal-interference deficit, accuracy at a given serial position was affected by the number of consonants in the word, such that letters in words with more consonants were more error-prone than letters in words with fewer consonants.

Implications for understanding the internal structures and functions of O-WM

Relationship to other claims in the O-WM literature—The interpretation we have proposed of the bow-shaped serial position effect differs from the explanation offered by Schiller et al. (2001). Schiller and colleagues argued that the error pattern arises because of reduced activation of the target word in the orthographic lexicon, rather than due to an impairment to O-WM itself. Although plausible, there is no strong or independent reason to assume that the errors resulted from reduced lexical activation, rather than from disruption at the level of O-WM. Problematic for the claim, in fact, is the finding that CRI showed a bow-shaped serial position curve not only for words, but also for pseudowords (error percentages for consonants in pseudowords across the four normalized positions were 17, 32, 36, and 22, respectively) (see Figure 3). Furthermore, in the only case for which the pattern of error distribution for words and pseudowords was reported in literature (Caramazza & Miceli, 1990), similar bow-shaped curves were produced for both.

Computational models of the graphemic buffer—Houghton, Glasspool and colleagues (Houghton, Glasspool & Shallice, 1994; Glasspool & Houghton, 2005) have developed computational models of the O-WM (the graphemic buffer) that make use of an architecture referred to as “competitive queuing” (CQ). These models were developed in response to the challenge of developing computationally explicit account of the representation and control of the serially ordered aspects of spelling behavior. This class of models has been applied to various output domains in addition to spelling, as it assumed that the computational challenges of serial production are not limited to spelling but also occur, for example, in spoken word production.

Without going into too much detail, there are a couple of points that are worth making regarding the relationship between the findings we report and the functions of the CQ models. The first is that the CQ models make a distinction between what Glasspool and Houghton (2005) refer to as the “activating” mechanism and the “competitive selection” mechanism. This distinction bears some similarity to the distinctions discussed above between activation and selection, that were referred to by Rapp and Kong (2002) and also by Kan et al. (2006) in the context of spelling and that have also been drawn by others in the broader context of WM research (e.g., Owen, Evans & Petrides, 1996).

However, the specific mapping of temporal stability/decay and representational distinctiveness/interference onto these components of the computational model are less straightforward. Within the CQ models of the graphemic buffer, establishing representational distinctiveness is an important function. Furthermore, disruption to the model affects representational distinctiveness and produces striking bow-shaped accuracy functions. It is less clear, however, whether and how temporal stability is instantiated in the model. Decay is not an explicit component of the model given that activation decrease is accomplished via active inhibitory processes. Nonetheless, one can imagine that the model should be able to be disrupted so as to generate an increasing error function. There is a mechanism (the E-node) that provides activation to each letter position by virtue of the letter’s distance from the end of the word (and a symmetrical mechanism for letters based on the distance from the beginning of the word, the I-node). Disruption of the activity of the E-node is likely to generate an increasing error function (see Ward & Romani, 1998 for further discussion). However, it is unclear if this disruption would also generate the other specific behaviors associated with what we have referred to as an abnormal-decay deficit. Furthermore, while the model does allow for the distinction between consonants and vowels, it may be a challenge for decay and interference deficits to be restricted to either C’s or V’s.

In any case, the findings we report here have an important role to play in providing further constraints on the important contributions to theory development and testing that is played by computational models such as these.

Relationship of this study to the broader literature on WM

Investigations of O-WM and of WM in other domains have proceeded with almost complete independence of one another. However, this is not because O-WM research has relied almost entirely on data from acquired impairments, as the literature on verbal WM has also drawn heavily from research on individuals with verbal working memory deficits (Baddeley, 1992). The causes are, therefore, more likely to be related to the view that orthography, in general, and perhaps spelling, in particular, are evolutionarily recent skills, whose study may not be relevant to the study of the evolutionarily more basic WM systems, such as verbal and spatial WM. If correct, this reasoning is somewhat, surprising, as it is most plausible that orthographic processing is either parasitic on these older skills or that, in the course of literacy acquisition, orthography-specific mechanisms were modeled on these older systems (Dehaene and Cohen, 2007; Farah, 2010).

The finding that abnormal-decay and abnormal-interference may very well play a key role in understanding the failures of O-WM, underscores the likely shared relationship between the various domains of WM. As reviewed in the Introduction, the need to ensure temporal stability and representational distinctiveness has been posited in the WM literature, although the debate has focused on whether or not decay and interference effects constitute independent mechanisms of forgetting in WM. The findings from the research reported here contribute to this debate in that they provide evidence that both decay and interference must be posited to explain the detailed aspects of the spelling errors produced by these individuals. Also relevant is the evidence indicating that the functions that prevent abnormal decay and interference may be sufficiently independent of one another that they may be selectively disrupted by brain damage.

Anatomical-clinical correlates in GSI and CRI, and the neuroanatomy of O-WM components

Working memory has been extensively investigated in cognitive neuroscience. Studies in dysgraphic individuals with O-WM impairment have frequently reported frontal and parietal damage (for a recent review and original data in acute stroke, see Cloutman et al, 2009). Studies in monkeys (e.g., Chafee & Goldman-Rakic, 2000) and neuroimaging investigations of the neural correlates of human WM using linguistic and non-linguistic visual stimuli (e.g., Smith & Jonides, 1998; Marshuetz, Reuter-Lorenz, Smith, Jonides & Noll, 2006) also documented the involvement of a fronto-parietal neural network. A recent fMRI study of cognitively unimpaired participants, specifically tapping O-WM, demonstrated activations in the left superior frontal sulcus and in the left intraparietal sulcus (Rapp & Dufor, in press). Lesion data in GSI and CRI are consistent with these observations (Figure 2). Damage in GSI affected the entire frontal lobe and extended posteriorly to the parietal lobe, including the superior parietal lobule on both banks of the intraparietal sulcus. CRI had two large but more circumscribed lesions, one in the frontal lobe (that did not extend to the superior frontal sulcus) and one in the parietal lobe that included the intraparietal sulcus. These observations further support the hypothesis that a left fronto-parietal network is critical for O-WM.

From the cognitive perspective, however, two behavioral features set these two O-WM damage cases apart from previously reported individuals and from each other, namely, the selective impairment for consonants (shared by GSI and CRI), and the contrasting damage to temporal stability (case GSI) and representational distinctiveness (case CRI). The neural underpinnings of these two features are much more difficult to discuss, due to the paucity of relevant data.

Available lesion data on the consonant-vowel distinction are inconsistent. Of the two individuals with selective vowel deficits for whom lesion information is available, one suffered from subcortical damage to the left frontal lobe (case CW, Cubelli, 1991), the other from a subcortical lesion in the posterior portion of the left temporal lobe (case LiB, Cotelli et al, 2003). In the two cases reported on here, brain damage affected the left frontal and parietal lobes. Further, no focal lesions were detected in the case of JH (Kay & Hanley, 1994), who had selective damage for consonants. Thus, the current data, do not seem provide clearly distinguishable neural correlates for the two types of functional damage. Neuroimaging data are just as inconsistent. In an fMRI study, subjects read aloud, or evaluated the lexical status of, words and nonwords constructed by transposing or substituting consonants or vowels from real words (Carreiras & Price, 2008). Greater activation was observed in response to vowel changes during reading aloud in the right middle temporal gyrus, and in response to consonant changes during lexical decision in the right middle frontal gyrus. In an ERP study, also using visual lexical decision on words and on similarly constructed pseudowords, bilateral N400 effects were observed for consonants in anterior-middle regions, and for vowels in middle-posterior regions (Carreiras, Vergara, Perea, 2007).

As regards the stability/distinctiveness contrast, ours is the first report of such dissociation. The two subjects have very large, but mostly overlapping lesions, the main difference being that the post-central, supramarginal and (in part) angular gyri are spared in CRI. It would be tempting, therefore, to attribute normal temporal stability to sparing of these structures, and loss of representational distinctiveness to frontal and/or parietal damage. However, on the same account, one would expect the massive suprasylvian damage in GSI to be associated with damage to both distinctiveness and stability, which is not the case. Clearly, further observations from both normal and brain-damaged subjects are needed in order to provide reasonable accounts for the neural underpinnings of the consonant-vowel distinction and for the dissociability of temporal stability and representational distinctiveness.

Conclusions

We have presented evidence that the monotonically increasing and the bow-shaped error functions that have been observed subsequent to damage to orthographic working memory can be explained by assuming disruption to different working memory functions. Based on detailed analyses of the spelling performance of two individuals with consonant-specific orthographic WM deficits, we have proposed that the monotonically increasing error function can be attributed to abnormally rapid decay caused by a disruption to the WM function responsible for maintaining temporal stability. In contrast, we have argued that the bow-shaped error function can be attributed to abnormal interference among representations, caused by a failure to maintain representational distinctiveness. These findings shed light on the internal complexity of orthographic working memory and provide links between the dysgraphia literature on graphemic buffer deficits and the broader literature on the causes of forgetting in working memory more generally.

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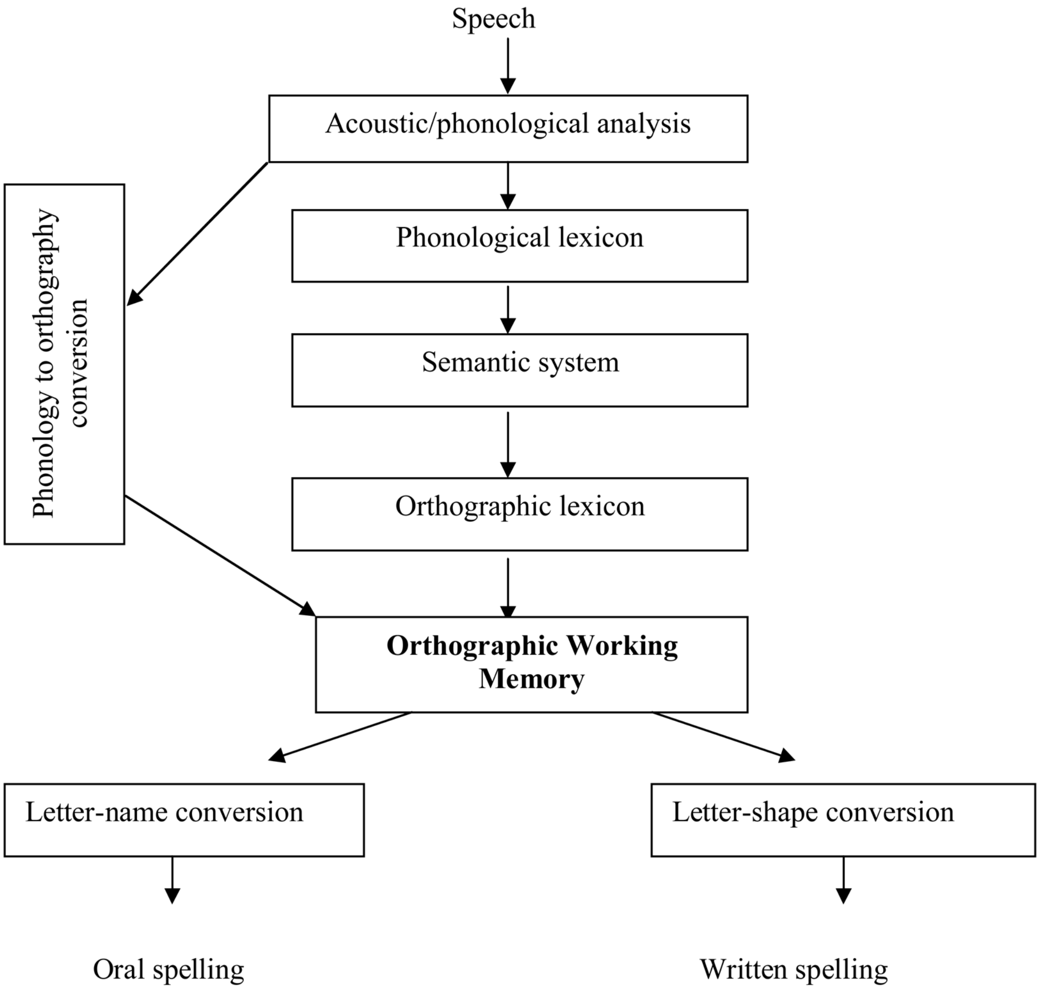

Figure 1.
Schematic representation of the functional architecture of the spelling system.

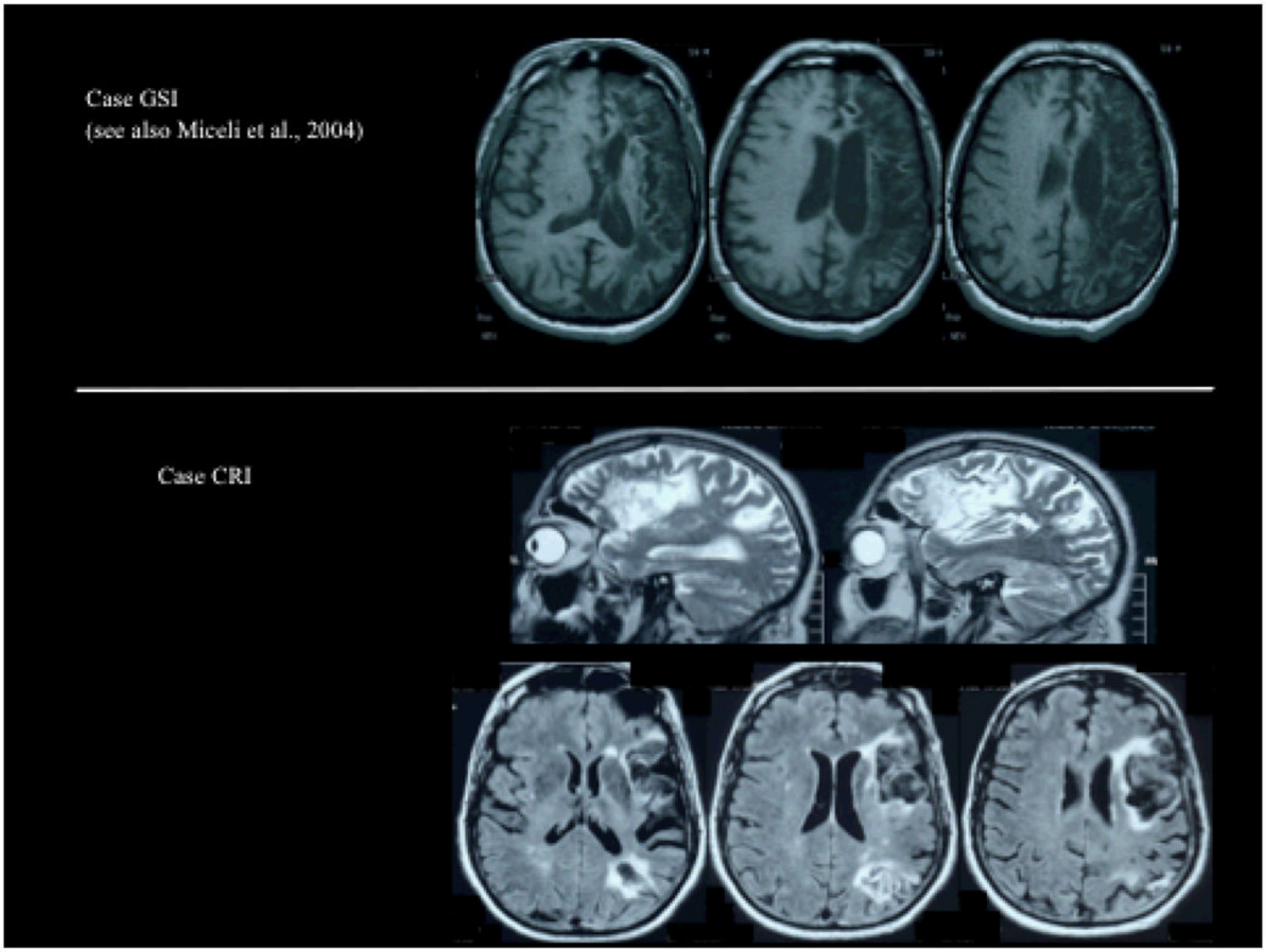

Figure 2.
Representative MRI images for GSI (top) and CRI (bottom). Note that, for CRI, the lesion spared the post-central, supramarginal and (in part) angular gyri. In contrast, GSI suffered sever damage to the frontal and parietal lobes, without intervening spared tissue (see Discussion).

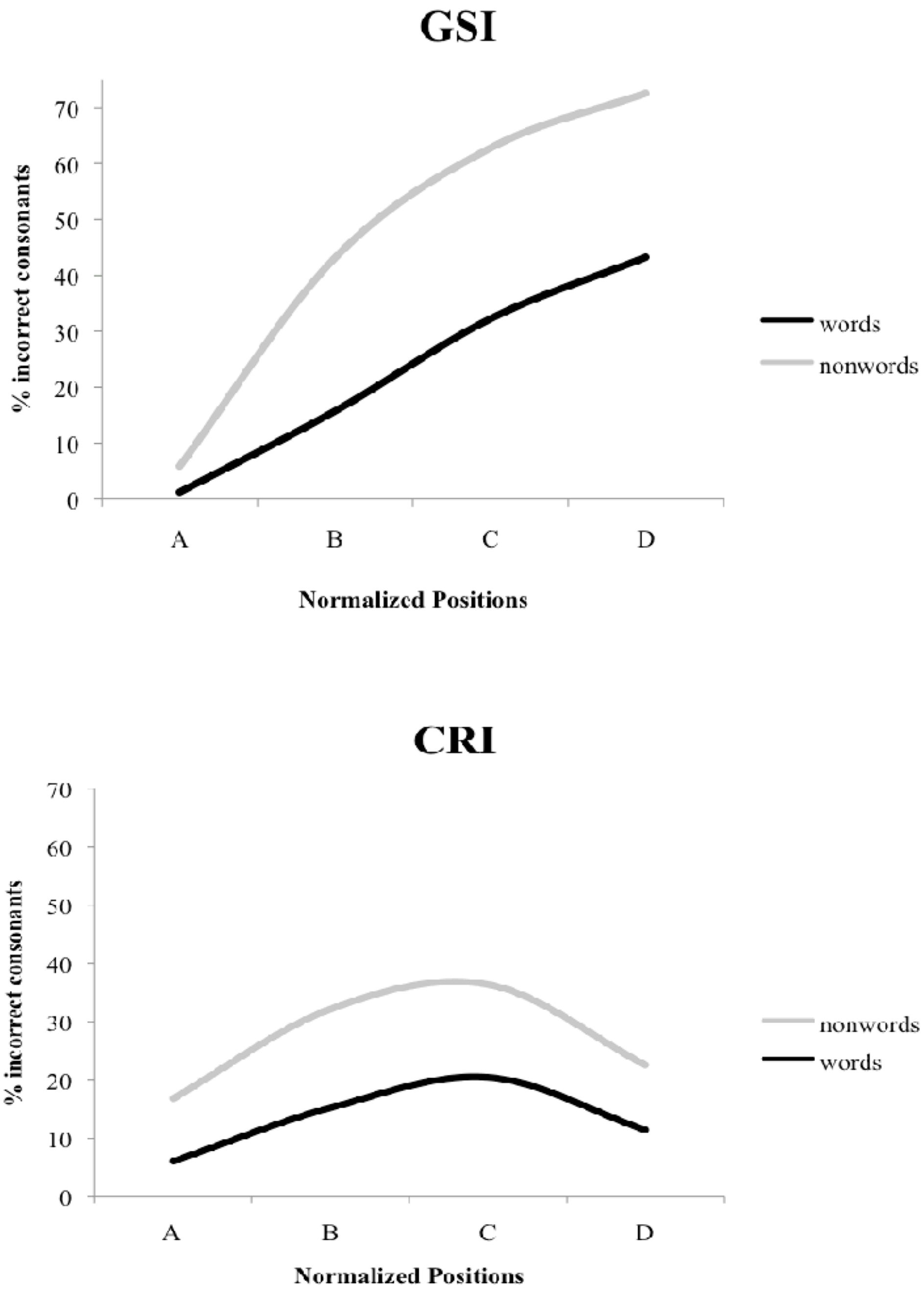

Figure 3.

Percent incorrect consonants as a function of the "normalized" positions for GSI (3a) and CRI (3b). Consonant positions in words (and pseudowords) with 2–5 consonants are normalized to four consonant positions on the basis of the scheme developed by Macthynger and Shallice (2009).

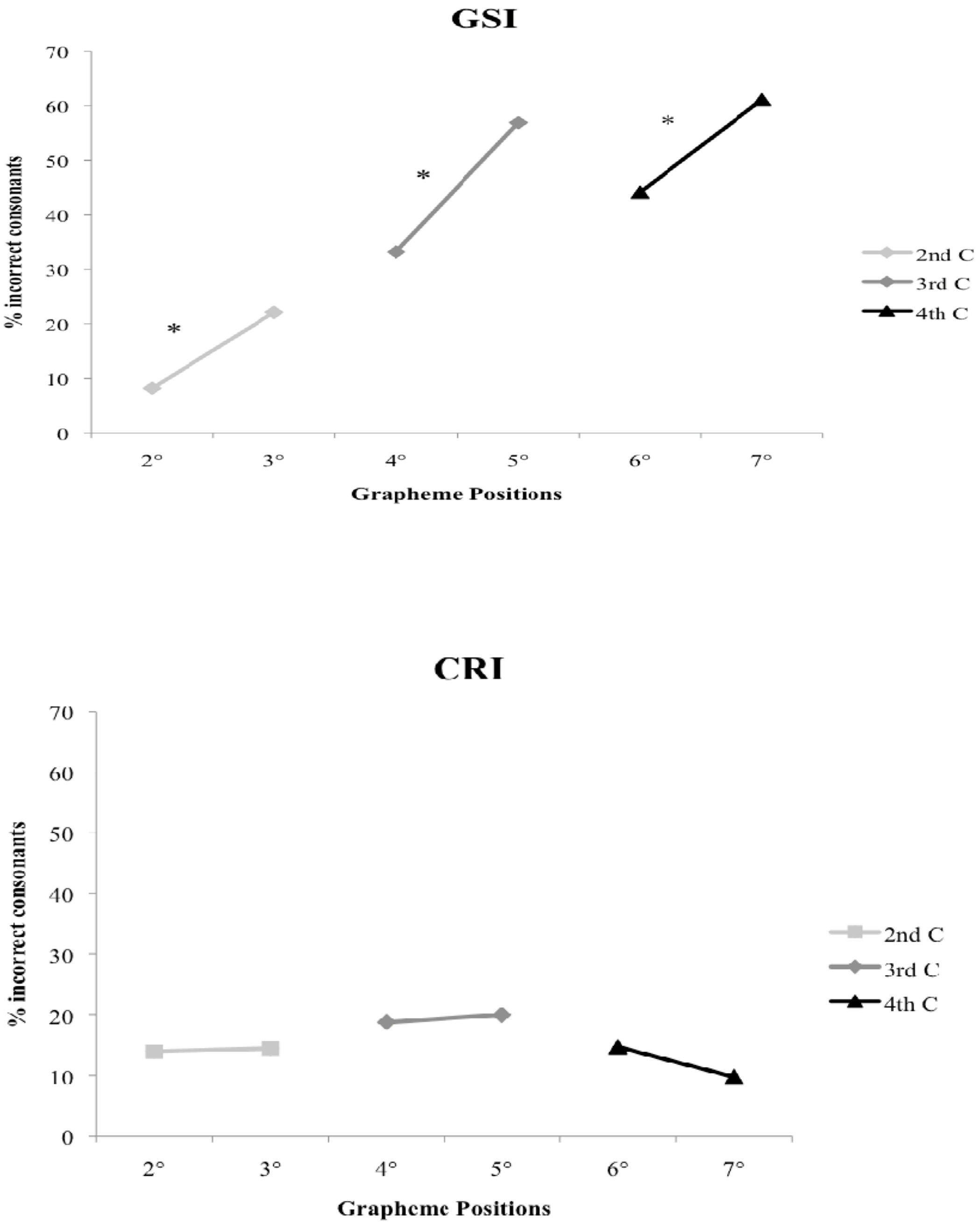

Figure 4.

Evaluation of the effect of grapheme position on consonant error rates. For consonant positions 2, 3, and 4 (2nd cons, 3rd cons, 4th cons) accuracy was compared for two grapheme positions. Results are presented for GSI (4a) and for CRI (4b). All comparisons were statistically significant for GSI, none were for CRI (see text for more details).

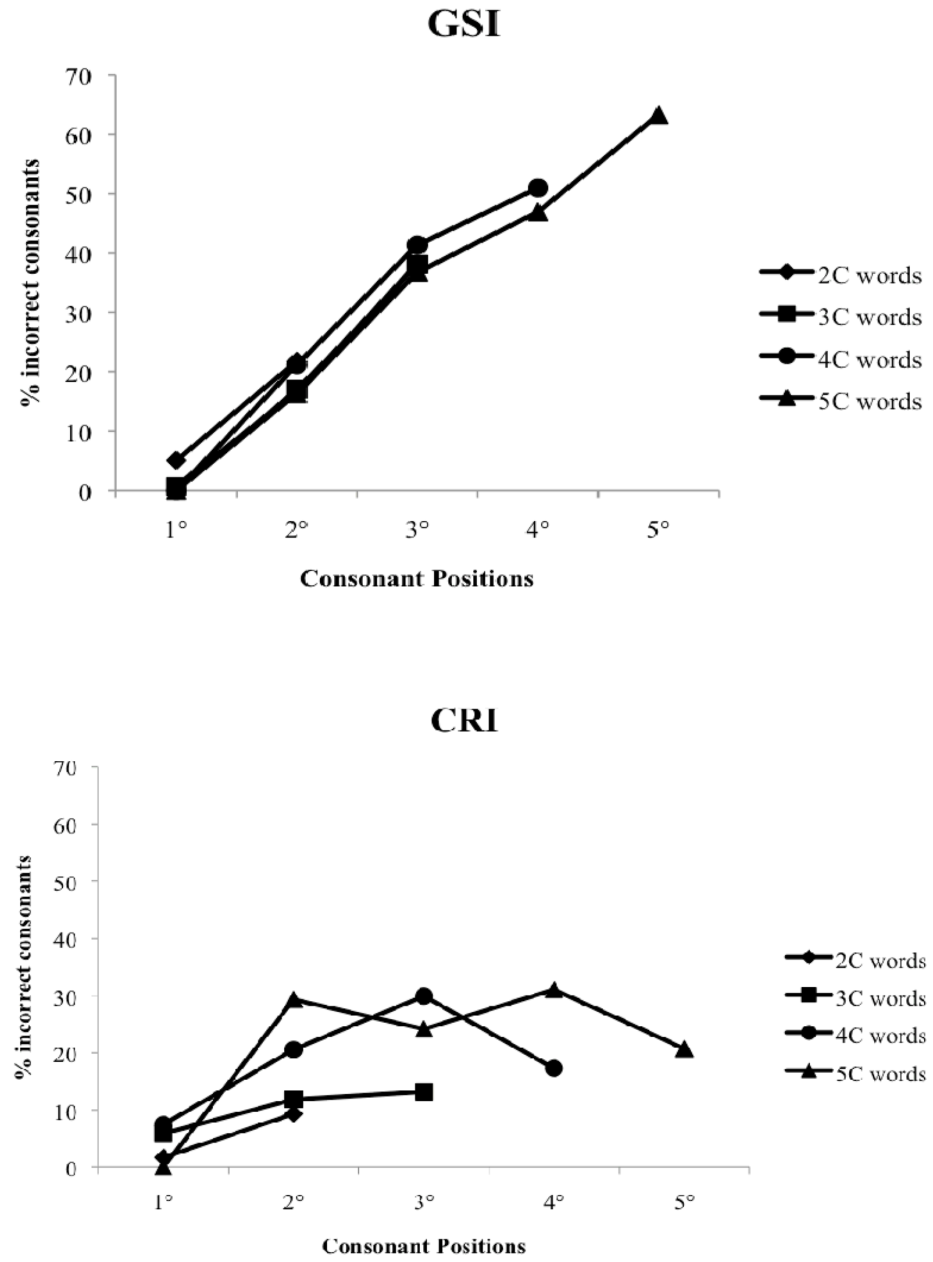

Figure 5.

Evaluation of the effect of the total number of consonants in a word on consonant accuracy at each serial position. For each consonant position there is a comparison of words containing different numbers of consonants: words with 2, 3, 4 and 5 consonants (2 cons words, 3 cons words, etc.) were considered. Results for GSI (5a) and CRI (5b).

Table 1

Predictions in the event of consonant-specific, abnormal-decay versus abnormal-interference deficits in orthographic working memory.

	Abnormal Decay	**Abnormal Interference**
Serial position curve	MONOTONIC	BOW-SHAPED
Length effect determined by the number of	GRAPHEMES	CONSONANTS
Effect of letter vs. consonant position on consonant accuracy	PRESENT	ABSENT
Effect of total number of consonants on serial position curve	ABSENT	PRESENT

Table 2

Percent incorrect responses (number of incorrect items/total number of items) produced by GSI and CRI on the BADA (Miceli, Laudanna, Burani, Capasso, 1994).

	GSI	**CRI**
Phoneme discrimination	7 (4/60)	3 (2/60)
Auditory-visual matching	2 (1/60)	10 (6/60)
Pseudo-word transcoding tasks		
Repetition	3 (1/36)	6 (2/36)
Writing to dictation	28 (7/25)	48 (12/25)
Delayed copy	17 (1/6)	17 (1/6)
Reading aloud	4 (2/45)	13 (6/45)
Lexical decision		
Auditory	1 (1/80)	2 (2/80)
Visual	1 (1/80)	6 (5/80)
Word transcoding tasks		
Repetition	4 (2/45)	4 (2/45)
Writing to dictation	20 (9/46)	35 (16/46)
Delayed copy	40 (4/10)	10 (1/10)
Reading aloud	3 (3/92)	2 (2/92)
Auditory word-picture match		
Nouns	2 (1/40)	5 (2/40)
Verbs	5 (1/20)	5 (1/20)
Visual word-picture match		
Nouns	0 (0/40)	5 (2/40)
Verbs	10 (2/20)	15 (3/20)
Spoken naming		
Nouns	3 (1/30)	28 (8/30)
Verbs	18 (5/28)	32 (9/28)
Written naming		
Nouns	18 (4/22)	54 (12/22)
Verbs	27 (6/22)	59 (13/22)
Spoken naming to definition		
Nouns	6 (1/16)	25 (4/16)
Grammatically judgments		
Auditory	4 (2/48)	6 (3/48)
Visual	0 (0/24)	25 (6/24)
Sentence transcoding tasks		
Repetition	10 (2/20)	0 (0/20)
Reading aloud	0 (0/6)	0 (0/6)
Sentence-picture matching		
Auditory	8 (5/60)	15 (9/60)
Visual	6 (3/45)	31 (14/45)

Table 3

Percent incorrect responses produced in word spelling to dictation (number incorrect/total items)

	GSI	**CRI**
Frequency		
High frequency words	57 (23/40)	20 (8/40)
Low frequency words	52 (21/40)	27 (11/40)
Abstractness/Concreteness		
Abstract words	60 (12/20)	15 (3/20)
Concrete words	55 (11/20)	20 (4/20)
Grammatical class		
Nouns	50 (10/20)	10 (2/20)
Adjectives	50 (10/20)	25 (5/20)
Verbs	75 (15/20)	30 (6/20)
Functors	50 (10/20)	30 (6/20)
Length		
4–5 letters	7 (102/1407)	6 (77/1278)
6–7 letters	13 (214/1677)	9 (155/1796)
8 and more letters	17 (226/1290)	12 (170/1391)

Table 4

Percent incorrect responses on consonants (C) and vowels (V) within words and pseudowords, for different spelling tasks (number of incorrect letters/total letters).

	GSI		CRI	
	Incorrect C	**Incorrect V**	**Incorrect C**	**Incorrect V**
Words Dictation	23 (532/2324)	0.5 (10/2128)	14 (338/2393)	3 (64/2181)
Pseudowords Dictation	45 (98/217)	0.5 (1/195)	18 (50/276)	3 (8/244)
Written Picture Naming	21 (62/292)	0.7 (2/265)	9 (55/608)	2 (12/595)
Total	24 (692/2833)	0.5 (13/2588)	13 (443/3277)	3 (84/3020)

Table 5

Percentage of consonants (C) and vowels (V) in the corpus of stimulus items, compared to the percent errors on consonants and vowels produced in spelling the words to dictation.

	C number / total letters	C errors/total errors	V number / total letters	V errors/total errors
GSI	52.2 (2324/4452)	98 (532/542)	47.8 (2128/4452)	2 (10/542)
CRI	52.3 (2393/4574)	84 (338/402)	47.7 (2181/4574)	16 (64/402)

Table 6

Comparison of percent incorrect consonants for words matched in total number of graphemes but differing in total number of consonants. For words of each grapheme length (5–8) there is a comparison of consonant accuracy for words of two different consonant lengths. Results are presented for GSI and for CRI. All contrasts between consonant number for each grapheme length are statistically significant for CRI but not for GSI.

GSI	**2-consonant**	**3-consonant**	**4-consonant**	**5-consonant**	**chi-square analysis**
5-grapheme	13 (16/128)	15 (74/480)			χ^2 (1) =0.47 p = .493
6-grapheme		23 (69/294)	21 (27/128)		χ^2 (1) = 0.17 p =.6801
7-grapheme		18 (17/96)	27 (86/320)		χ^2(1) = 2.86 p =.0908
8-grapheme			34 (113/334)	35 (52/150)	χ^2(1) = 0.01 p =.9203
CRI					
5-grapheme	6 (8/134)	13 (58/450)			χ^2(1) =4.08 $p<.05$
6-grapheme		9 (30/345)	29 (30/104)		χ^2 (1) = 26.31 $p<.001$
7-grapheme		7 (7/96)	18 (62/348)		χ^2(1) =5.57 $p<.05$
8-grapheme			16 (55/352)	26 (39/150)	χ^2 (1) = 6.77 $p<.01$