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PhD Thesis

Orthographic Representations and Working Memory Properties in the Spelling Process: A Neuropsychological Analysis

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General Abstract

The present thesis investigates the graphemic stage of the spelling process. Aim of thesis is to study the sub-processes occurring at the orthographic working memory level and the interaction between graphemic representations and working memory that holds these representations active during spelling. Chapter 1, after a brief description of the two-routes spelling model adopted in this research, deals with, presenting neuropsychological evidences, some of the most important issues about the relations between the different levels of elaboration that are engaged in the spelling process. Final part of this chapter is dedicated to the review of the neuropsychological researches regarding the structural organization and the processing of the orthographic representation.

Chapter 2 reports the cases of GSI and CRI, two dysgraphic subjects with a selective deficit for consonants and a graphemic buffer disorder (GBD), whose spelling patterns are consistent with the hypothesis that their deficits affect different properties of orthographic working memory: temporal stability for GSI and representational distinctiveness for CRI. Their performance on spelling task demonstrate two things: first, GBD is not a homogeneous deficit because different sub-processes, involved in graphemic buffering, can be selectively affected by cerebral damage; second, different patterns of GSI and CRI arise from interaction of consonant representation and WM properties, both impaired in these subjects.

Chapter 3 reports the case of a third dysgraphic subject, PPO, with a selective disorder for consonants but whose spelling picture was not identifiable as a clear GBD. Spelling pattern of this subject, quite different from those of both subjects of Chapter 2, demonstrates that the internal structure of orthographic representation, holding at working memory level, can be selectively impaired in

the absence of working memory deficit. Moreover, PPO's results on spelling task confirm the role of temporal stability and representational distinctiveness in the spelling and the interaction between representations and WM.

Finally, Chapter 4 summarizes all the presented results and discusses the implications.

Chapter 1

The spelling process

Introduction

The study of writing, of how it is possible, through what mechanisms it works, and what abilities it involves, is an important contribution to the understanding of human cognition.

Writing, unlike spoken language, is not an innate ability of the human being but is learned with education. So for many years writing was only used by a limited number of individuals and today too anyone takes much longer to speak than to write. Thus we understand why for a long time interest in writing was limited.

In the neurological sphere too, writing disorders were classified in relation to other deficits. Agraphia with aphasia, agraphia with alexia, pure agraphia, agraphia with apraxia and spatial agraphia were the first taxonomic classifications of dysgraphia (Benson, 1979). In the 1980s, with the development of cognitive neuropsychology (Caramazza, 1984, 1986), the study of subjects with cerebral damage led to the emergence of new detailed theories on the normal cognitive system.

Most of our knowledge of the cognitive mechanisms of the spelling system and the orthographic representations comes from research with brain-damaged individuals. The logic used in these studies is the following: the pattern displayed by the patients in a specific task expresses the underlying functional lesion of one or more components (or the relation between the components) of cognitive systems that support that task. The behaviour of the patient “constitutes empirical support for a model of spelling, if the observed pattern of spelling impairment is explicable by specifying a functional lesion to the postulated model” (Caramazza, Miceli, Villa & Romani, 1987).

Thus the performance of dysgraphic individuals constituted the primary source of evidence on the organization of the writing system and contributed to the development of the model normally assumed in many researches on spelling. This model (analogously to the reading model) proposes different levels of processing of orthographic representation: semantic, lexical, sublexical, orthographic/segmental.

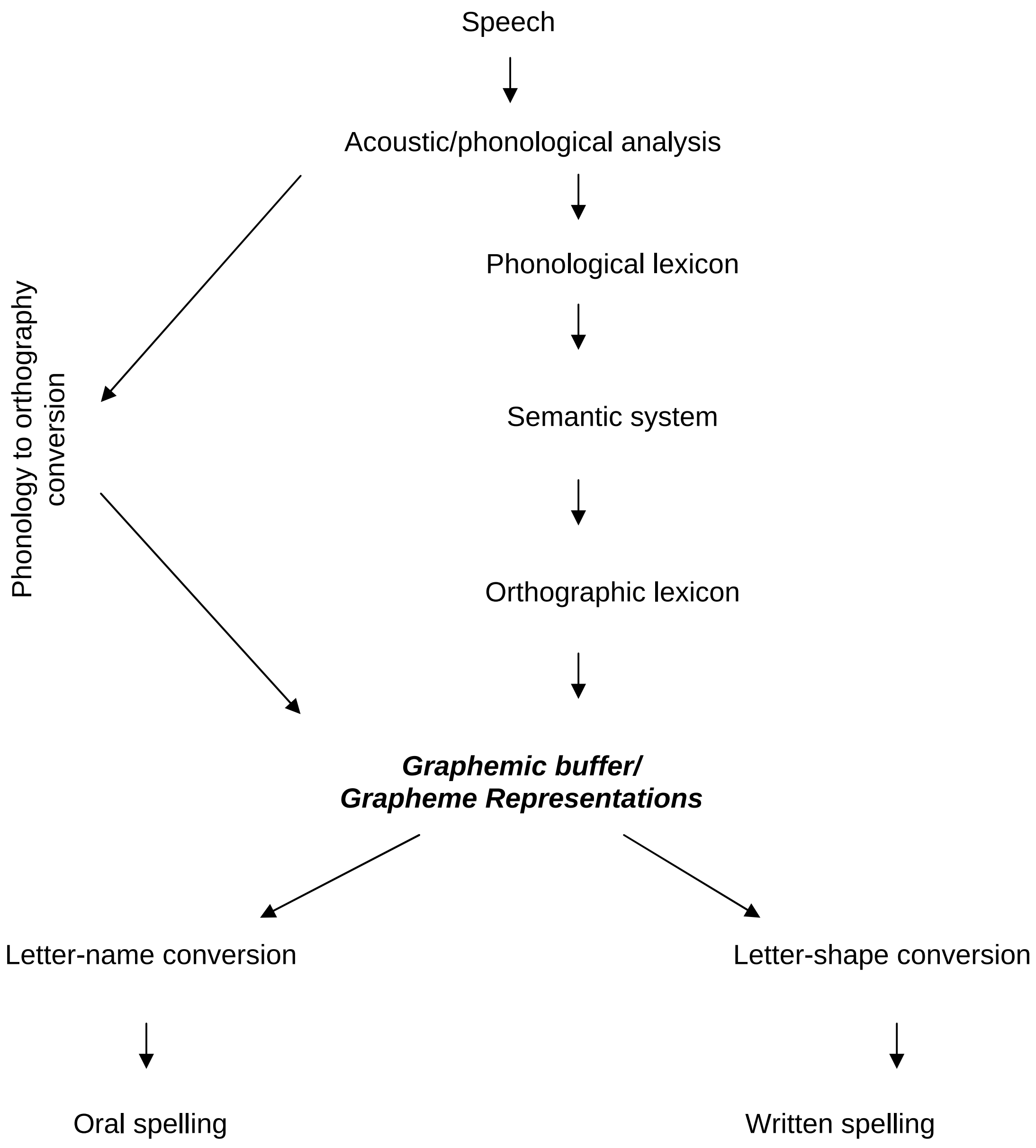
1.1 The spelling process

The two-routes model proposes two separate procedures for writing new and known words. Figure 1 describes the processes that are active during the spelling of a word introduced through the auditory pathway.

First of all, acoustic-phonological processes convert sounds into a phonological representation. If the word is familiar (e.g., *table*), the phonological input lexicon activates the semantic-lexical system, which provides the meaning associated with the word. The semantic representation serves as a basis for the output orthographic lexicon, the long-term memory for the orthographic form of familiar words, in order to choose and produce a lexical orthographic representation associated with the meaning (t-a-b-l-e). The existence of a third non-semantic lexical pathway has been hypothesized (Patterson, 1986), which, bypassing the semantic system, directly connects the phonological and orthographic lexicon (but for evidence contrary to this hypothesis, see Hillis & Caramazza, 1991).

If instead the word that we hear is a word that we do not know or a pseudo-word, it is the sublexical conversion procedures that are activated. In this case the phonological form represents the input for the phoneme-grapheme conversion system, which produces a reasonable spelling of the stimulus phonemes, using the information stored on the relationship between sounds and letters.

Figure 1. Schematic representation of the functional architecture of the spelling (adapted by Tainturier & Rapp, 2003)



Following the model in Figure 1 we see that the lexical and sublexical pathways converge on the graphemic buffer, a working memory system whose role is to keep the orthographic representation sent by the two upper processes active, until each grapheme (the abstract form of the letter) has been turned into a specific form (in the written spelling) or into a specific name (in the oral spelling).

Since a word can be written in very different ways, it is believed that the orthographic representation stored in the buffer does not have a precise form but is rather an abstract representation, independent of a specific format.

After the level of the buffer a differentiation takes place between the processes required for written and oral spelling. In written spelling, for each letter the allographic system conversion specifies the case (upper/lower), the character (italics, capital, etc.) and subsequently the form of the letters. Lastly, the motor processes produce the movements required to produce the letters in the specific desired form. In oral spelling the abstract orthographic form of the letters is transformed into the phonological form of the letters and into the oral articulatory movements required for producing it.

Numerous studies have shown that each component of the spelling system can selectively be impaired by cerebral damage (for a review, see Rapp and Gotsch, 2001). The different forms of dysgraphia that have been reported in the literature are referable to weakening of one or more parts of the spelling process just described. These deficits confirm the independence of each level of processing but do not exclude their possible interaction (e.g., between lexical and sublexical system). We will now look more closely at the fundamental components constituting the spelling process, and for these we will trace out a general picture of the behavioural pattern in the case of functional damage.

1.1.1 The orthographic lexicon

The *orthographic output lexicon* is the long-term memory containing the orthographic representations of the words that we have learned during our lives. It is recruited in the writing of familiar words; it is related to the semantic system that as a rule activates it in response either to an auditory stimulus (writing under dictation) or to a figure (denomination) or simply when we want to write a word whose meaning we have in our minds. When the orthographic lexicon is impaired (Baxter & Warrington, 1987; Beauvois & Derouesne, 1981; Hatfield & Patterson, 1983; Parkin, 1993; Weekes & Coltheart, 1996), the subject can make semantic errors because the target word does not reach the level of activation required for production, and in its place a word is produced with which it shares some characteristics (e.g., *lion* instead of *tiger* or *table* instead of *chair*) and which has reached the necessary level of activation.

Another type of error that characterizes impairment of the orthographic lexicon is phonologically plausible error (PPE). As a rule these errors are made when the subject is given an auditory stimulus, as in writing under dictation. Since the orthographic lexical form of the word is not available because of damage to the orthographic lexicon, in order to write subjects rely on sublexical conversion procedures. PPEs originate from transformation of the phonological form of the target word into its corresponding orthographic form. The result is a string of graphemes that, though phonologically suitable, does not correspond to the correct spelling of the word (for example writing *yot* instead of *yacht*). Normally PPEs are sensitive to the frequency of the phoneme-grapheme mapping of a specific language, that is to say the frequency with which a sound is turned into graphemes.

1.1.2 The sublexical system

The *phoneme-grapheme conversion system* can only be studied in writing under dictation, in which a string of sounds must be transformed into a corresponding orthographic string. It is employed in writing words that the subject has never heard before or in writing pseudo-words (e.g., *zood*). It can also be used for accurately writing words that have a regular spelling (e.g., *cat*). It is believed that this system is separated into two processes: phonological parsing, which organizes representation into smaller units (single phonemes or syllables), and the real conversion process, which turns every phoneme into a reasonable graphemic form. In languages like Italian, in which at a segmental level the relations between writing and pronunciation are almost entirely transparent, the sublexical system could also be used for writing known words correctly. Afterwards we will mention the interaction between the lexical system and the sublexical system in a transparent language like Italian.

When phoneme-grapheme conversion procedures do not work because of brain damage (Baxter & Warrington, 1985; Bub & Kertesz, 1982; Shallice, 1981), the subject will prove to have difficulty about writing new words or pseudo-words but should preserve the ability to write familiar words. In non-transparent languages like English and French, the phoneme-grapheme conversion system contains the necessary information on all the possible ways in which a phoneme can be written. As a rule the phoneme-grapheme conversion system is the one used with the greatest frequency in such a language.

The orthographic lexicon and the phoneme-grapheme conversion procedures can be impaired independently, but also simultaneously. When both systems are affected by a neurological accident (Baxter & Warrington, 1985;

Beaton, Guest, & Ved, 1997; Bub & Kertesz, 1982; Caramazza & Hillis, 1991; Cipolotti & Warrington, 1996; Hillis, Rapp, & Caramazza, 1999; Rapp, Benzing, & Caramazza, 1997), the subject will not succeed in writing non-words, will not show sensitivity to the frequency of phoneme-grapheme mapping and will produce semantic errors and lexical substitutions when he/she writes words.

1.1.3 The graphemic buffer (or orthographic working memory)

The product of lexical and sublexical processing converges on the graphemic buffer, the working memory of the writing system. As we are talking about a sequential task, in which letters are written one after another, the abstract orthographic representation of the word has to remain active until it has been entirely written. It is therefore necessary to hypothesize a working memory system inside the spelling process because of the computational incommensurability between the representations produced by the lexicon (whose order of greatness is the word) and the representations with which the post-buffer systems have to work (whose order of greatness is the letter). The graphemic buffer, like every other element of the spelling process, can selectively be compromised by cerebral damage. The clinical picture shown by subjects with this deficit (Caramazza, Miceli, Villa, & Romani, 1987; Jonsdottir, Shallice, & Wise, 1996; McCloskey, Badecker, Goodman-Schulman, & Aliminosa, 1994; Miceli, Capasso, Benvegnù, & Caramazza, 2004; Tainturier & Rapp, 2004) is compatible with the role and the position that the buffer has in the writing process. The performance will be comparable regardless of the input modality (dictation, denomination, spontaneous writing) and the output modality (written spelling, oral spelling, typing); no lexical, frequency or grammatical effects will be present and the errors will be of a segmental type (substitutions, omissions, transpositions, insertions); lastly, the performance will be very much characterized by reduced accuracy in writing longer words. The orthographic working memory (WM) and its deficits will be dealt with at length in the rest of the thesis, since they constitute its main focus.

1.1.4 Post-buffer processes

While the buffer deals with keeping the representation of the word active, the subsequent processes transform the abstract form of the representation into a specific form (written spelling) or into a specific sound (oral spelling). The distinction between modality-specific mechanisms, devoted to written spelling and oral spelling, is based on double dissociations found in neuropsychological patients: some subjects have selective deficits for one of these modalities and not for the other.

Post-buffer deficits concern selective difficulty about recovering the names that correspond to graphemes (Bub & Kertesz, 1982; Kinsbourne & Warrington, 1965), and the production of the written form of words (Baxter & Warrington, 1986; De Bastiani & Barry, 1989; Goodman & Caramazza, 1986; Rapp & Caramazza, 1997; Miozzo & De Bastiani, 2002). In the latter case the subject can have difficulty about assigning the character (italics, block capitals) and the case (upper, lower) and/or about assigning the form to the letters.

Though in the spelling process each component has a specific role and can be selectively affected by cerebral damage, the various levels of the system present complex interactivity. In the next section some proof justifying adoption of the two-route spelling model will presented; further, we will briefly deal with some of the most important issues regarding the relations between the different phases of processing of graphemic representation in the writing process.

Does a relationship exist between the sublexical phoneme-grapheme conversion system and the orthographic lexicon? How is lexical information activated during the writing process? What is the role of the phonological lexicon? How do the phonological lexicon, the orthographic lexicon and the sublexical procedures interact? What is the function of this interaction?

For each of these questions, we will furnish neuropsychological evidence reported in the literature on the spelling process.

1.2 Independence of orthographic lexicon and phoneme-grapheme conversion system

The two-routes model in Figure 1 assumes that different processes are involved in writing new and familiar words. The evidence for the independence of these two processes comes from the observation that one pathway can be selectively compromised by neurological damage and not the other.

RG (Beauvois & Derouesne, 1981) is a French-speaking patient whose writing errors can be related to damage to the lexical pathway and specifically to the orthographic lexicon output. The patient’s errors are all phonologically plausible and they show the effect of phoneme-grapheme mapping: the performance is good enough on words containing high-probability PG mapping, while it worsens on words with low-probability PG mapping. This picture is also compatible with the use of the sublexical system in writing words, because of failure to recover the spelling of a word in the orthographic lexicon. Moreover, the integrity of the sublexical system is confirmed by perfect performance in writing of non-words under dictation (for other similar cases, see Baxter & Warrington, 1987; Behrmann & Bub, 1992; Goodman-Shulman & Caramazza, 1987; Hatfield & Patterson, 1983; Weekes & Coltheart, 1996).

The opposite picture, difficulty in writing non-words and preserved ability to write familiar words, is shown by PR (Shallice, 1981). This patient has good writing of words and spelling not influenced by frequency or by PG mapping probability. By contrast, performance on non-words is greatly compromised, suggesting as the locus of the deficit the sublexical system that converts phonemes into graphemes (for other similar cases, see Bub & Kertesz, 1982; Goodman-Shulman & Caramazza, 1987; Roeltgen, Rothi, & Heilman, 1986).

The complementary dissociation shown by these patients demonstrates the separability of the lexical and sublexical mechanisms involved in spelling and confirms that the writing of words and non-words is entrusted to different processes, which can be selectively affected by neurological damage.

1.3 Interaction between orthographic lexicon and sublexical system

Despite what has just been said, independence of lexical and sublexical mechanisms does not rule out the possibility of interaction between them. Considerable evidence exists, based on studies carried out with dysgraphic subjects (Folk, Rapp, & Goldrick, 2002; Hillis & Caramazza, 1991; Hillis, Rapp, & Caramazza, 1999; Rapp, Epstein & Tainturier, 2002) and with normal subjects (Barry & De Bastiani, 1997; Barry & Seymour, 1988; Campbell, 1983; Folk and Rapp, 2004), that lexical and sublexical processes may interact in spelling. On one side the writing of known words, mainly conducted via the lexical pathway, may be integrated by sublexical information; on the other, the lexical system may intervene on the sublexical system in the writing of pseudo-words.

One neuropsychological indication that has suggested an interaction between sublexical and lexical mechanisms is the case of JJ (Hillis & Caramazza, 1991). This subject has a deficit in the semantic-lexical system, while the phoneme-grapheme conversion procedures are intact. If familiar words were *only* written via the lexical pathway (which is damaged in JJ), then semantic errors should be produced in all tasks involving writing of familiar words; instead, JJ makes semantic errors in written picture naming but not in writing-to-dictation.

It has been hypothesized that in naming the figure, for example, of a *pear*, this subject activates an impoverished semantic representation of the word, which in turn activates in the orthographic lexicon a series of candidates with which it shares some semantic characteristics (pear, apple, orange, etc.). The most active word, at times correct, at times semantically correlated with the target, "will win" the competition and will be selected. In writing under dictation, to the semantic input is added the phonological input (/pɛr/), which is converted into a graphemic string that, though not correct from the orthographic point of view (*pair*), is useful however for constraining the selection of the target word in the orthographic lexicon. For this reason in written picture naming, in which the figure activates a lexical mechanism that is damaged, JJ makes semantic errors; instead, in writing-to-dictation, in which the auditory stimulus also produces a phonological representation of the target, participation of the sublexical system avoids the production of semantic errors. The authors maintain that the sublexical and lexical systems *sum* their information in order to eliminate the semantic errors in the writing of words.

Folk, Rapp, & Goldrick (2002) have suggested that the role of the sublexical system is to reinforce, and therefore benefit in the competition for lexical selection, the representation of the target word and the graphemes that constitute it. Rapp, Epstein & Tainturier (2002) have proposed two possible mechanisms allowing interaction between lexical and sublexical processes: 1) fill in the gap, in which *first* the lexical system produces an incomplete orthographic representation, and *afterwards* the sublexical system furnishes a reasonable content for the gaps; 2) simultaneous activation, in which the lexical and sublexical systems are *simultaneously* engaged in recovery of the orthographic string from the phonological input, and simultaneously activate the graphemes of the target word. The information from the sublexical system and from the lexicon would then converge at a graphemic level and, thanks to a feedback mechanism, the information thus integrated would return to the orthographic lexicon to participate in the process of lexical selection.

1.4 Interaction between lexical and sublexical systems in the Italian language

The evidence reported on the spelling system is largely based on studies carried out with English-speaking subjects, who in order to write rely mainly on the lexical system. What happens to the interaction just described between lexical and sublexical mechanisms in languages with transparent spelling like Italian, in which most of the words can be written simply using the non-lexical pathway? An answer to this question comes from the study by Laiacona, Capitani, Zonca, Scola, Saletta and Luzzatti (2009), who analyzed twelve cases of *mixed dysgraphia*, a clinical picture in which regular words are written better than ambiguous ones and pseudo-words (21% of aphasic Italians present these characteristics). In Italian, ambiguous words are those that contain segments transcribable in more than one orthographic form, but whose lexical form it is necessary to know in order to write them correctly (e.g., the words *cuoco* and *quota*); pseudo-words (e.g., *ralo* and *niffa*), as in languages with opaque spelling, can only be written via the non-lexical pathway; regular words (e.g. *dito* and *filtro*) can be correctly written using both pathways.

In normal English-speaking subjects the lexical activation source prevails over the sublexical one; in Italian-speaking subjects the opposite could happen, because of the different role that the sublexical system has in writing. In order to study the interaction between the lexicon and sublexical conversion mechanisms, Laiacona and coworkers use a mathematical method to calculate the probability of a regular word being written correctly. The authors hypothesize that in mixed dysgraphia the residual abilities of the lexical pathway and sublexical mechanisms simultaneously process regular words, operating separately and independently (*cooperation* hypothesis). Thus regular words have a higher probability of being produced correctly. It is also possible that the two systems may reinforce their respective efficiency, raising the probability of success above the sum of the two separate probabilities (*interaction* hypothesis).

In order to verify the cooperation and interaction hypotheses with differentiation between the lexical and sublexical pathways, for each patient the authors quantify, on a probabilistic basic, the separate contribution of the residual lexical and sublexical resources in the spelling of regular words. The capacity of the lexical pathway can be estimated on the basis of the real success rate on irregular words; the efficiency of the sublexical pathway is instead estimated starting from the real accuracy percentage on non-words. If the success rate observed on regular words is significantly higher than that calculated on the basis of the single probabilities, then it will be possible to accept the interaction hypothesis.

Among the twelve cases studied by Laiacona and coworkers in four subjects the success rate on regular words is higher than expected. In one case this difference is not significant, so that it is possible to hypothesize a relationship of cooperation; in the other three cases the mixed dysgraphia can be explained with the interaction between the residual resources of the lexical and sublexical pathways.

1.5 Independence and interaction of phonological and orthographic lexicon

An issue that has received great attention in researches on written language concerns activation of lexical information in writing, that is to say how we recover the orthographic form of the words that we have to write. The schematic representation of the writing process in Figure 1 shows that orthographic information in the lexicon is directly activated by the semantic system. However, in order to reach this conclusion it was necessary to exclude alternative hypotheses, among which the hypothesis of *phonological mediation* (Brown, 1972; Frith, 1979; Luria, 1966; Hotopf, 1980; Van Orden, Johnston, & Hale, 1988) according to which in order to write, for example, the word *cat* it is necessary to access first the phonology of the word and only afterwards recover its spelling.

This hypothesis was proposed quite precociously in researches on writing, probably because of the obvious fact that we learn first to speak and then to write, and that above all we learn spelling starting from phonology. Recent researches confute these hypotheses, demonstrating the autonomy of orthographic forms with respect to phonological ones and suggesting that the orthographic lexicon can be directly activated by the semantic system. To return to the previous example, when I want to write *cat* it is sufficient for the semantic system to directly activate the representation of the word in the orthographic lexicon.

Neuropsychological evidence contradicts the *phonological mediation* hypothesis. In this connection, some subjects with impairment of the semantic-lexical system only make semantic errors in one modality (oral or written). This pattern cannot be explained with obligatory phonological activation mediating between the semantic system and the orthographic lexicon. Indeed, if the phonological mediation hypothesis was true, subjects that make semantic errors in oral production should also necessarily make them in written production, and subjects that do not make semantic errors in spoken production should not make them in writing either.

The case of RGB (Caramazza & Hillis, 1990) provides a good example of the fact that orthographic lexical forms are independent of phonological ones (for other relevant cases, see Caramazza & Hillis, 1990; Hillis, Rapp, & Caramazza, 1999).

The good results in comprehension tasks suggest that RGB’s semantic system is intact. However, he produces semantic errors in oral denomination and in reading aloud. For example, he denominates the figure of a *kangaroo* as *raccoon* and reads the word *kangaroo* as *giraffe*. RGB’s deficit therefore derives from difficulty in activating the correct phonological forms in the output phonological lexicon.

In contrast with the phonological mediation hypothesis, RGB's written production proves to be intact. He almost entirely produces correct responses both in written picture naming and in writing-to-dictation, and among his few errors there are no semantic substitutions. This pattern, impaired oral production and preserved written production, cannot be explained in an architecture in which access to orthographic forms is mediated by activation of the corresponding lexical phonological forms; RGB's results can instead be explained by hypothesizing *direct* activation of the orthographic lexicon by the semantic system.

Hence it is reasonable to assume that representations in the orthographic lexicon may be directly activated by the semantic system and independently of phonological representations.

However, the fact that phonological information is not necessary for writing does not rule out the possibility of it interacting with orthographic information. Indeed, selection of a word in the orthographic lexicon may be constrained by activation of a word in the phonological lexicon and vice versa. This interaction would be realized through sublexical conversion mechanisms.

1.6 Role of sublexical procedures in lexical interaction

Recent studies (Alario, Schiller, Domoto-Reilly, & Caramazza, 2003; Beaton, Guest, & Ved, 1997; Miceli & Capasso, 1997; Miceli, Capasso & Caramazza, 1999; Rapp, et al., 1997) suggest a two-way relationship between the orthographic lexicon and the phonological lexicon through sublexical conversion mechanisms.

The results of some dysgraphic subjects in the double naming task and in transcoding tests demonstrate an association between the state of the sublexical system and performance in the double naming task (a task that consists in producing an oral response and a written one to the same stimulus, consecutively). Since it makes it possible to verify whether the same figure activates the same lexical representations in the phonological and orthographic lexicon, this task is useful for understanding what type of relationship exists between phonological and orthographic lexicon.

What can be observed is that the probability of these subjects producing the same lexical response to the double naming task is linked to availability of their sublexical mechanisms.

WMA (Miceli, Benvegnù, Capasso, & Caramazza, 1997), PW (Rapp, et al., 1997) and WB (Alario, et al., 2003) produce semantic errors in comprehension tasks (except PW, who has a deficit at the lexical but not the semantic level) and naming tasks. Further, as can be deduced from the tests on reading and writing pseudo-words, their phoneme-grapheme and grapheme-phoneme conversion mechanisms are both impaired (see Table 1a). When submitted to the double naming task, all the subjects give inconsistent responses (a correct response and a semantic error or two different semantic errors).

These three dysgraphic subjects have both semantic-lexical system and conversion sublexical procedures impaired and produce inconsistent responses under the two conditions of the double naming task (see Table 1b).

PGE, GIM (Miceli and Capasso, 1997) and EA (Alario, et al., 2003) show similar performance in comprehension and naming tasks (they make semantic errors in both, suggesting a deficit of the semantic and lexical components) but, unlike the three subjects referred to above, they read and write non-words well enough (Table 1a). The crucial fact is that their responses to the double naming tasks are virtually all consistent (double semantic error, or double correct response; Table 1b).

Table 1a. Percentage of accuracy in transcoding, comprehension and picture naming tasks for seven dysgraphic subjects (see text).

Table 1b. Percentage of inconsistent responses (one correct response and one semantic error, or two different semantic errors) in two double naming task conditions.

A

	PW	WMA	WB	PGE	GIM	EA	ECA
Pseudowords reading aloud	0	13	0	100	100	64	86
Pseudowords writing-to dictation	0	0	0	100	92	23	10
Auditory word-picture match	95	79	92	55	82	91	86
Visual word-picture match	-	60	-	58	91	-	90
Spoken naming	72	60	43	25	48	65	80
Wtitten naming	46	44	28	21	36	63	85

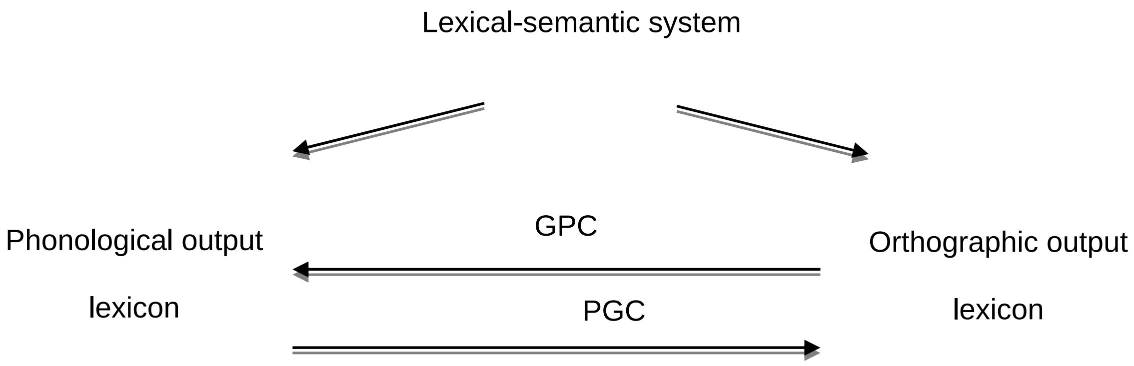
B

Double naming task say-then-write	7	35	0	1	31	0	15
Double naming task write-then-say	33	40	0	1	26	1	0

It appears evident that for all the cases referred to above it is the state of the sublexical system that constrains selection of consistent responses. Impaired conversion mechanisms are accompanied by inconsistent responses to the double naming task, and intact conversion mechanisms are associated with production of consistent responses.

What do these results suggest in relation to the writing process? On one side they suggest that orthographic and phonological representations are autonomous, and on the other that they can interact through sublexical conversion mechanisms. When we have to write the name of a figure, an orthographic representation is activated by the semantic system and also partly by the corresponding phonological representation (in turn activated by the semantic system). Phoneme-grapheme conversion procedures would convert the phonological representation into an orthographic string; in this way all available information converges on the orthographic representation of the target word, increasing its activation.

Figure 2. Relations between semantic system, orthographic and phonological lexicon, grapheme-phoneme (GPC) and phoneme-grapheme (PGC) conversion procedures (adapted by Miceli & Capasso, 2006).



1.7 Orthographic working memory

In the previous sections the relations between different elements of the spelling process were explored. On the one hand, since can be selectively affected by cerebral damage, the different elaboration levels are autonomous; on the other hand, probably to compensate an impaired functional status, they interact. Thus, semantic system, phonological and orthographic lexicon and sublexical conversion procedures integrate their information to ensure a correct written production.

The product of their elaboration reaches a memory system, responsible of the temporary hold of graphemic representation during the successive conversion processes.

1.7.1 Orthographic working memory and graphemic buffer disorder

Caramazza, Miceli and Villa (1986) argued that an orthographic WM is required in the functional architecture of the spelling process because of the computational incommensurability between the representations of orthographic sequences, either retrieved from long-term memory (orthographic lexicon) or assembled by sublexical conversion procedures, and the more peripheral components of the spelling process, like grapheme-to-letter shape conversion in written spelling or grapheme-to-letter name conversion in oral spelling, which operate on a single element at a time. Given the difference in unit size (sequences versus single elements), an intermediate working memory component is required to ensure that sequence representations remain active during the serial selection of elements.

Empirical evidence for this orthographic working memory system comes from detailed analyses of spelling performance by individuals who, as a result of acquired neurological damage, are affected by Graphemic Buffer Disorder (henceforth GBD). The essential behavioral features of GBD can be predicted on the basis of the putative role of orthographic WM in the spelling process (see Figure 1).

In the event of damage to orthographic WM, spelling performance should be comparable across spelling tasks, regardless of input (written picture naming, writing-to-dictation, delayed copy, spontaneous writing) or output modality (written or oral spelling). In addition, because the orthographic WM is a postlexical stage of processing, response accuracy should be unaffected by lexicality (familiar vs novel words), frequency, or grammatical class. In contrast, 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, because orthographic WM is a short-term memory process of limited capacity. Finally, since the orthographic WM is shared by all the task that require the activation of an orthographic string, GBD should result in segmental errors, as letter substitutions, (e.g., *tavolo* -> *tabolo*), omissions (e.g., *tavolo* -> *taolo*), additions (e.g., *tavolo* -> *taviolo*), transposition (e.g., *tavolo* -> *talovo*), rather than lexical errors (semantic, morphological, other word errors) or phonological plausible errors. A number of cases with these characteristics have been reported (Blanken, Schafer, Tucha, & Lange, 1999; Cantagallo & Bonazzi, 1996; Cotelli, Aboutalebi, Zorzi, & Cappa, 2003; Cubelli, 1991; Jónsdottír, Shallice, & Wise, 1996; Kan et al., 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, see also Caramazza & Miceli, 1990). In addition to supporting the orthographic working memory component of the spelling system, individuals with GBD have been used to investigate the structure of orthographic representations. Most of our knowledge about the structure of orthographic representation held in the buffer come from the LB's spelling analyses.

1.7.2 Orthographic working memory and orthographic representation

Initially, it was proposed a linear structure of orthographic representation: in a string of letter to-be-written only identity and order of the graphemes are specified (Caramazza, et al., 1987). Further and more detailed analyses on LB's performance disconfirmed the linear hypothesis. In fact, the orthographic representations are internally more complex and nonlinear. In conjunction with identity and order, other factors affect the spelling performance: the geminate feature, the graphosyllabic structure and the consonant/vowel status of a grapheme. Besides LB, these hallmarks have been found in other brain-damaged individuals with GBD.

Geminate. Evidence on double letters (geminate) suggests that they behave as spelling units. Comparing the performance on items with same length and orthographic structure - but with a cluster of two consonants or a geminate in the same position (pa*dr*e vs pa*ll*a) - LB spelled better the geminates consonants in comparison to the clusters consonants. In addition, the errors on the geminates reveal that the double letters behave as a unit: he never made errors involving only one of the geminate consonants (palla -> plala). This observation led Caramazza and Miceli to propose that information regarding doubling is also independent from letter identity information. Subsequently, the same results have been found in other dysgraphic subjects (Miceli, Benvegnù, Capasso, & Caramazza, 1995; Schiller et al., 2001; Tainturier & Caramazza, 1996). For example, patient FM (Tainturier & Caramazza, 1996) preserved information about geminate, even when his responses were extremely distorted (hammer -> harron; giraffe -> gafficate).

Graphosyllabic structure. Syllabic organization of a word may be represented in the graphemic structure. Thus, for example the word *tavolo* may have an internal structure consisting of three syllables (syllable 1: *ta*; syllable 2: *vo*; syllable 3: *lo*). Concerning the influence of graphosyllabic structure, we have evidence again by LB. The performance on words of the same length should be identical, regardless of their orthographic structure, if the only constraints of the graphemic representation were identity and order. Instead LB spelled correctly 73% of item with simple-CV structure (like *tavolo*) and only 52% of item with complex-CV structure (like *albero*). Furthermore, types of errors were very different for the two classes of stimuli: omissions occurred in complex-CV words (i.e, albero -> abero) whereas errors on simple-CV words were mainly substitutions (tavolo -> tabolo). The evidence of this factor is not yet completely clear, since in some subjects did find an effect of orthographic structure (TH and PB, Schiller, Greenhall, Shelton & Caramazza, 2001; Schonaeur & Denes, 1994) but not in other subjects (JH, Kay & Hanley, 1994; AS, Jónsdottír, Shallice & Wise, 1996; BA, Ward & Romani, 2000).

Consonant/Vowels Status. Two types of evidence confirm that the CV status of a grapheme is a crucial feature of orthographic knowledge.

First, in the literature there is a number of reports showing that substituted letters preserve the CV status of the target (see Table 2). This means that a consonant was substituted with another consonant (table -> *tagle*) and a vowel with another vowel (table -> *toble*). If CV status of graphemes was not an essential part of orthographic representation, then the error substitutions should be random, that is a consonant may be substituted at times with a vowel, other times with a consonant, and vice versa. Data reported in Table 2 demonstrate that this is not the case. When the graphemic buffer is stressed the information about the identity may be lost but the information about the CV status could be preserved: this may be the reason of the high rate of substitutions that respects the CV status.

The second evidence demonstrating special status of CV is that some dysgraphic subjects present with a selective inability to spell consonants or vowels. If in the orthographic representation consonants and vowels are not distinguished, then spelling errors should affect both in a comparable way. Naturally, deficits for consonants and vowels were observed in several GBD cases (Caramazza, et al., 1987; Jonsdottir, et al., 1996; McCloskey, et al., 1994; Schiller, at al., 2001), but in literature there are cases of selective impairment for consonants (JH, Kay & Hanley, 1994; GSI, Miceli, Capasso, Benvegnù & Caramazza, 2004) and cases of selective impairment for vowels (CF and CW, Cubelli, 1991; LiB, Cotelli et al., 2003).

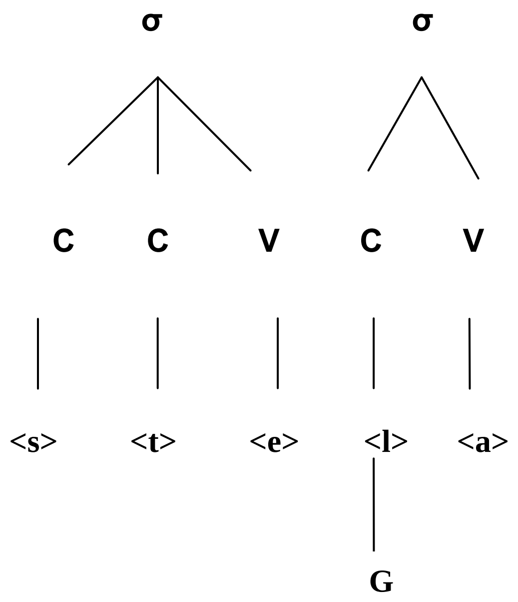
Table 2. CV preservation rates of patients with impairment at the level of the graphemic buffer (adapted by Miceli & Capasso, 2006)

Subjects	N of substitutions in the error corpus	% of errors preserving CV status
LB (Caramazza & Miceli, 1990)	520	99.8
CW (Cubelli, 1991)	340	99.0
JH (Kay & Hanley, 1994)	253	93
HE (McCloskey et al., 1994)	207	95
AS (Jónsdottír et al., 1996)	121	85
BA (Ward & Romani, 1998)	138	88
TH (Schiller et al., 2001)	291	86
LiB (Cotelli et al., 2003)	283	100
GSI (Miceli et al., 2004)	46	100

This can be considered further evidence of the CV structure constraint (see Miceli & Capasso, 2006 for review and Buchwald and Rapp, 2006 for evidence that CV status is specifically orthographic and not phonological).

In summary, the analysis of errors in GBD patients provided evidence consistent with the view that orthographic representations are multidimensional objects, that specify the C/V-status, identity and quantity of each grapheme, possibly along with graphosyllabic structure and they can be represented as in Figure 3.

Figure 3: Organization of the orthographic representation maintained in the buffer (adopted by Caramazza and Miceli, 1990).



As already mentioned, several additional GBD cases have provided converging evidence for this proposal. Of particular interest for this current study is the claim that orthographic representations distinguish consonants and vowels. In fact, three case of GBD with a selective deficit for consonants will be reported in the following chapters. This will allow differentiating the effects of damage to different WM properties and clarifying the interaction between orthographic representations and WM system.

1.7.3 Orthographic working memory: serial order effects

While the observation that individuals can suffer GBD as a consequence of stroke supports the role of orthographic working memory in the spelling system, differences in performance among individuals with GBD suggest that orthographic working memory can be impaired in different ways. Clear across subjects differences emerged when analyzing the distribution of spelling errors across letter positions. In published reports of subjects with graphemic buffer disorder, spelling errors are not randomly distributed across letter positions, but rather fall into two basic patterns. In the first pattern, errors predominate in central positions, thus yielding a bow-shaped distribution (eg, Buchwald & Rapp, 2010; Caramazza & Miceli, 1990, Jónsdottír, Shallice & Wise, 1996, McCloskey et al., 1994, Tainturier & Rapp, 2004): the beginning and the end of the string are relatively spared, and errors peak at central positions. The second pattern is characterized by errors increasing monotonically from initial to final position in the written string (eg, Katz, 1991; Ward & Romani, 1998; Schiller, et al., 2001; Miceli et al., 2004).

These different error distributions probably are a result of damage to different components of the orthographic working memory system. Several interpretations of these error curves were proposed in literature. For example, Schiller and colleagues (2001) suggest that the bow-shaped curve arises because lower-than-normal level of activation of the string, that render the letters in stimulus-central positions more error-prone under normal conditions, and this may be accentuated following damage to the orthographic lexicon. Instead, originally Wing & Baddeley (1980) proposed that bow-shaped curve was due to the lateral interference effect between neighboring letters in the graphemic buffer. The monotonic error function, on the other hand, has been attributed to the rapid decay of the orthographic representation at the working memory level (Katz, 1991; Schiller et al., 2001), or of letter retrieval at the lexical level (Ward & Romani, 1998).

Some authors (Cipolotti, Bird, Glasspool, & Shallice, 2004; Sage & Ellis, 2004) have hypothesized an involvement of the higher levels that, affecting the buffer functioning, would be responsible of the two curves. For example, bow-shaped curve of patient BH (Sage & Ellis, 2004) was interpreted as an artefact due to the exclusion of complex errors in the serial order analyses (but see Buchwald & Rapp, 2010, for a different interpretation); inserting also these types of error (that for BH consisted mostly of more than one omission at the end of the string) BH's curve would be a monotonic function. Sage and Ellis explained monotonic curve as insufficient activation supplied to the graphemes constituting the words from the semantic system or the orthographic output lexicon, rather than as rapid decay of representation at the buffer level (Schiller, et al., 2001).

An alternative approach trying to explain underlying mechanism of the serial order in spelling rejects the notion of graphemic buffer and is based on a connectionist model: the competitive queueing (CQ) (Shallice, Glasspool, & Houghton, 1995). This model comprises three layers of nodes: control node, letter node and a competitive filter. Control layer has two nodes: Initial node connects more strongly with the initial letters in the word and progressively less with the following letters; End node connects more strongly with the final letters. Letter layer has 26 letter nodes and a special node for producing geminate letters.

Serial order in this model is codified by temporal frame of activation in the two control nodes and by strength of connections betweens control node and letter node. The competitive filter selects more active graphemes from the letter node.

Once produced, a grapheme is inhibited so that next letter in the string could be produced. In this model bow-shaped is simulated adding noise to competitive filter; monotonic curve is produced weakening the activation level of the control node E. In order to simulate dysgraphic behavior, the model subsequently assumed an explicit distinction between consonants and vowels (Glasspool & Houghton, 2005).

However, apart from the adopted approach, the serial order effect constitutes a double open matter. One question concerns the lexical (Ward & Romani, 2004; Sage & Ellis, 2004; Schiller et al., 2001) or segmental (Katz, 1991; Miceli et, al., 2004; Schiller et al., 2001; Wing & Baddeley, 1980) origin of the two curves; the other pertains to the proposed mechanisms producing the bow-shaped and the monotonic curves: interference, incomplete or weak activation, or rapid decay.

Aim of the thesis

The overall aim of the present thesis was to expand the current knowledge of the grapheme-level representations in the spelling process. In particular, we aimed to investigate further the sub-processes involved in graphemic buffering and the relation between representation and WM in the spelling in order to explain the variability emerging by literature (see paragraph above). In fact, even though individuals with GBD share specific behavioral features, i.e., 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 it is enough to justify the conclusion that "the term GBD is no more than a convenient label for a pattern of behaviors by a group of subjects and does not reflect a homogeneous cognitive deficit" (Miceli & Capasso, 2006; p. 126).

What happens when orthographic representation, elaborated from higher levels, reach the memory system holding temporarily the representation, before the intervention of serial processes that will convert abstract letters in format-specific representations? What properties take part in? It is possible to detect different sub-processes within orthographic WM?

A cognitive neuropsychology paradigm was adopted. Apart from spelling error analyses in subjects with WM impairment, it will infer the normal structure of graphemic representation and of orthographic working memory (Caramazza, 1984, 1986).

Thesis outline

In the second chapter, two GBD cases with a specific deficit for the consonants are presented. The performance of these subjects are analyzed under the hypothesis that their deficits affect different properties of orthographic WM. Spelling task analyses concern 1) the positions in which errors were made, 2) the accuracy in function of the number of graphemes (consonants and vowels) and consonants in a word, and 3) the interaction between position and length. These data show that the graphemic buffer disorder is not a homogeneous deficit and the orthographic WM could be divided in sub-processes; furthermore since the subjects of this study have a selective deficit for consonants, their different patterns can be explained as the result of the interaction between consonant representation and different WM properties.

Chapter three contains the description of a third dysgraphic subject with a selective disorder for consonants but whose spelling picture was not identifiable as a clear GBD. Spelling performance of this subject consents to demonstrate that the structure of graphemic representation (in this case, the graphemes marked as consonants) can be selectively affect by functional/cerebral damage, in the absence of working memory deficit. Moreover, his results on spelling tasks are a confirmation of the role of temporal stability and representational distinctiveness in the spelling and of the interaction between representation and WM.

Finally, chapter four presents a summary of the results emerged from the data presented in this thesis, with a discussion of their theoretical implication with respect to the existing literature on graphemic buffer disorder, orthographic working memory and graphemic representation.

Chapter 2

The properties of orthographic working memory: temporal stability and representational distinctiveness

Introduction

Working memory (WM) systems, maintaining representations activated that must undergo further processing, have been proposed in many cognitive domains (Anderson, Reder, & Lebiere, 1996; Just & Carpenter, 1992; Martin, 1993; Morton & Morris, 1995; Papagno, Valentine, & Baddeley, 1991; for a review, see Miyake & Shah, 1999). In this thesis, we will address the working memory system that has been posited in the context of the spelling system. According to current theory, spelling relies on a limited-capacity, short-term memory system that keeps orthographic representations active in the course of spelling the individual letters of the word. However, recent evidence from individuals with acquired dysgraphia has suggested that this orthographic WM system may be composed of separable subcomponents (Kan, Biran, Thompson-Schill, & Chatterjee, 2006; Rapp & Kong, 2002). We analyzed the performance of two subjects with orthographic WM damage, and used their patterns of performance to argue that orthographic WM has at least two distinct properties, *temporal stability* and *representational distinctiveness*. These properties are responsible for the correct selection and production of the elements in an orthographic string, and can be independently disrupted by neurological damage.

Contrasting performance of two individuals with graphemic buffer disorder (GBD) elucidates how different deficits can produce the length effect, the hallmark of GBD, and the contrasting serial position effects observed in various GBD cases (see Chapter 1, paragraph 1.7.3).

2.1 Temporal Stability and Representational Distinctiveness

If it is accepted that different forms of impairment at the orthographic WM stage can yield a performance profile compatible with the diagnosis of GBD, detailed qualitative analyses of the performance of GBD subjects might help clarify the role of the components that contribute to this processing stage.

Intuitively, correct spelling requires a temporally stable and distinctive, well-specified representation of the graphemes comprising the to-be-spelled string. In other words, it is reasonable to assume that a representation has to remain active for successive processes to be carried out flawlessly (more specifically, for serially converting the abstract representation into letter shape or letter names and executing the appropriate motor action); in addition, since during production each grapheme must be selected, the graphemes comprising the to-be-spelled string have to be represented distinctly from each other.

The analysis of spelling performance in subjects with putative GBD suggests that different components are involved at the level of the orthographic working memory.

We claim here that the processes operating at the orthographic WM level are responsible for the *temporal stability* and *representational distinctiveness* of the elements (graphemes) that comprise the target string. Under normal conditions, these two properties are necessary for the elements of the representation to be selected and passed on to later processes flawlessly and in the correct order. Temporal stability ensures that the orthographic string, be it retrieved from long-term memory or assembled by phoneme-grapheme conversion procedures, remains active during serial selection and production. 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.

Individuals with orthographic working memory impairments could have disruptions to either of these two features. Both impairments should result in the observed length effect – more segmental errors will be produced in response to longer words than to shorter words. However, the length effect is caused by different mechanisms in the two cases and, as we will show later on, under certain conditions these length effects can be qualitatively different. Moreover, we argue that these deficits predict the different serial position effects observed in individuals with GBD. In the event of disruption to temporal stability (e.g., abnormally rapid decay of information in working memory), since longer words have to 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 words. Since the likelihood that an element is under-activated increases with the distance of each grapheme from the beginning of the string, a monotonic error distribution should be observed with a disruption to temporal stability.

In contrast, in the case of reduced representational distinctiveness, the length effect arises because sequences with more graphemes will "crowd" the representational space more than sequences with fewer graphemes, and therefore graphemes in longer words are more likely to be confused than elements in shorter words. This disruption is also predicted to give rise to a bow-shaped serial position effect. Reducing the representational distinctiveness will exaggerate the normal effect of crowding in central positions (relative to the peripheral positions), due to the interference that occurs between adjacent letters at the buffer level (Wing & Baddeley, 1980). As a result, graphemes in central positions will be more prone to error than graphemes in the peripheral positions.

In this chapter, we describe two individuals with disruption of the orthographic working memory. These individuals both present with selective damage to consonants, which will allow us to better distinguish their underlying deficits. While their spelling performance is similar in many regards, we will argue that, in one case, performance is consistent with a disruption to the temporal stability of consonants, whereas in the other case, performance is consistent with a disruption to the representational distinctiveness of consonants. An investigation of the performance of these two individuals allows us to argue that stability and distinctiveness are indeed distinct functions of the orthographic working memory.

2.1.1 Effect of damage to representational distinctiveness and to temporal stability in subjects with selective impairment for consonants: predictions

As indicated earlier, there is ample evidence that consonants and vowels are represented with sufficient independence that brain injury can disrupt the processing of one more than the other (Kay & Hanley, 1994, Miceli et al., 2004; Cubelli, 1991, Cotelli et al., 2003). Furthermore, if we are correct in assuming that brain damage may result in selective disorders of either temporal stability or representational distinctiveness, some consonant-selective deficits should also selectively affect one or the other property of the graphemic buffer. In the case of selective impairment to consonant representations, contrasting predictions concerning the serial position effect, the length effect and the interaction between accuracy by position and length can be made in the case of damage to temporal stability or representational distinctiveness. These predictions will now be expounded.

In the case of a consonant-specific representational distinctiveness deficit, the representational space for consonants is reduced. A bow-shaped serial position effect is predicted, as crowding in the consonantal space will reducing the distinctiveness of individual consonants, but especially of those in central positions. In terms of length effects, the critical prediction is that the number of consonants, rather than the overall number of letters, should help to determine letter accuracy. For example, words matched in number of consonants but differing in total letters should be spelled with comparable accuracy; and, words matched in number of letters but differing in number of consonants should yield different error rates. This prediction arises because the extent of crowding will be determined by the number of consonants in the word, and not by the number of letters.

A final prediction concerns the interaction between position and length. Word length (in consonants) should affect accuracy on letters matched for position (in consonants). As an example we can consider the words *figlia* (daughter) and *tromba* (trumpet). They have the same number of letters, but because *figlia* has 3 consonants, whereas *tromba* has 4, the consonantal space is more crowded in *tromba*. Consequently, the *g* in *figlia* will be spelled more accurately than the *r* in *tromba*, even though both consonants are in the second consonant position.

Different predictions can be made in the case of a temporal stability deficit selectively affecting consonants. Since all the letters in a word must be selected serially for production, the total number of letters (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. Thus, a temporal stability deficit will produce higher error rates for consonants with "increasing" serial position, resulting in an error rate function that increases with the absolute position of the consonant in the target string. As regards the effects of length, consonant accuracy in a subject with abnormally fast temporal decay should be affected by the total number of letters in the string – the more letters in the string and the more time elapses during production, the more likely a consonant will be under-activated. This prediction is in clear contrast with the expectations in the case of a representational distinctiveness deficit, which predicts that consonant accuracy is determined by the number of consonants in the word.

A different prediction concerning the interaction between position and length can be derived from the temporal stability deficit. Different accuracies for consonants in the same consonant position but in a different absolute position are predicted. For example, in this case the *g* in *figlia* should be spelled less accurately than the *r* in *tromba* because, even though both appear in the second consonant position, *r* is in second and *g* is in third (absolute) letter position, and therefore should be more affected by abnormally fast decay.

In sum, contrasting predictions can be derived in the event of damage to either the temporal stability or the representational distinctiveness dimension of the orthographic WM (see Table 1).

These differences are magnified in cases of individuals with selective impairments to consonants (though the logic would apply to individuals with selective impairments to vowels as well). If these predictions were to be borne out by the pattern of performance of our two subjects, data would provide evidence consistent with the proposed role of temporal stability and representational distinctiveness in the orthographic working memory.

Table 1. Predictions in the event of damage to consonant temporal stability and consonant representational distinctiveness.

	Temporal Stability	**Representational Distinctiveness**
Serial Position Curve	MONOTONIC	BOW-SHAPED
Length Effect	GRAPHEMES	CONSONANTS
Effect of Absolute Grapheme Position	PRESENT	ABSENT
Effect of number of Consonants on Specific Position	ABSENT	PRESENT

Before presenting experimental data demonstrating that the subjects in this study are both affected by different deficits at the orthographic WM level, the neuropsychological background and general spelling abilities of these subjects will be reported. In this project frequency, grammatical class, abstractness and length effects were calculated by analyzing performance in terms of letters, instead of words. Buchwald and Rapp (2010) claimed that in order to determine the locus of impairment within the spelling system, letter accuracy rather than word accuracy should be considered. In the event of a deficit that does not concern the graphemic buffer, the error rate per letter should be constant, although the probability of making an error on longer words is greater than on shorter words. In contrast, because the buffer is a limited-resource system, in the event of graphemic buffer disorder the probability that a letter is spelled incorrectly increases for longer words. Using this assessment of spelling performance, we were more confident in determining the locus of impairment within the spelling system for dysgraphic subjects reported in this work.

2.2 CASE GSI. Neuropsychological background

GSI, a 60-year old, right-handed university professor of physics, 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 present in the left posterior-inferior parietal lobe.

An extensive report on GSI's language abilities is already available (Miceli et al., 2004) but his neuropsychological evaluation obtained with the BADA (*Batteria per l'Analisi dei Deficit Afasici,* Miceli, Laudanna, Burani & Capasso, 1994), a screening battery for aphasia, will be provided here (see Table 2).

The phoneme discrimination task was close to normal. Repetition and reading aloud were slightly below normal for words, and mildly but clearly pathological for pseudo-words. 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).

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 > fun_o; *pennello*, brush > penne_o). Auditory and visual sentence-picture matching tasks were 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 is characterized by agrammatical production due to errors on verb agreement, omission of functors and of main verbs and use of general verbs. How GSI described his daily activities is reported below:

...La attina presto faccio...la colazione e...successivamente la...lavo e vesto poi vado alla terapia... motoria...poi alla ....quella...logopedista, poi ho...vedo la televisione ho...faccio la settimana enigmistica fino all`ora di pranzo. Dopo..quando finisco col pranzo riposo fino alle tre e mezza, poi a quel punto faccio l`aerosol e il the coi biscotti. A quel punto o viene Leandro per fare l`altra ter.. motoria o guardo la televisione. Verso le sette faccio la cena poi a letto faccio la televisione...fino alle dieci e mezzo di sera, poi vado a dormire. Sabato e domenica invece faccio il computer Paola.

Table 2. Incorrect responses produced by GSI on the subtests of the BADA (adapted by Miceli et al., 2004).

Phoneme discrimination	4/120 (3%)
Auditory-visual matching	2/120 (2%)
Pseudo-word transcoding tasks	
Repetition	9/72 (12%)
Writing to dictation	16/45 (35%)
Delayed copy	1/6 (17%)
Reading aloud	7/90 (8%)
Lexical decision	
Auditory	3/160 (2%)
Visual	3/160 (2%)
Word transcoding tasks	
Repetition	4/90 (4%)
Writing to dictation	9/46 (20%)
Delayed copy	4/10 (40%)
Reading aloud	3/184 (2%)
Auditory word-picture match	
Nouns	2/80 (2%)
Verbs	2/40 (5%)
Visual word-picture match	
Nouns	1/80 (1%)
Verbs	5/40 (12%)
Spoken naming	
Nouns	10/60 (18%)
Verbs	17/56 (30%)
Written naming	
Nouns	15/44 (34%)
Verbs	19/44 (48%)
Spoken naming to definition	
Nouns	4/32 (12%)

Grammatically judgments	
Auditory	7/96 (7%)
Visual	5/48 (10%)
Sentence transcoding tasks	
Repetition	6/40 (15%)
Reading aloud	0/12
Sentence-picture matching	
Auditory	7/120 (6%)
Visual	5/90 (6%)

2.2.1 General spelling abilities

Looking at Table 2, a particular difficulty of GSI for spelling tasks is detected. A dysgraphia battery was administered to GSI in order to better check his spelling abilities.

In the writing-to-dictation task, five lists of words were administered. Stimuli were matched in order to evaluate the effects of abstractness/concreteness, grammatical class, length, frequency, orthographic structure, morphological structure and the ability to spell phonologically opaque segments. Pseudowords were divided into two lists, controlled for length and morphological decomposability. Pictures used for written naming were controlled for length and frequency of the target name/verb.

To summarize the spelling data obtained by GSI, he was asked to spell-to-dictation 731 words, containing 4374 letters overall. He misspelled 376/731

(51.4%) words and 542/4374 (12.4%) letters. He also spelled incorrectly 66/80 pseudowords (82%) and 99/412 (24%) letters. Note that if words and pseudowords were matched for length and orthographic structure, their difference was not significant (incorrect words: 56/89, or 63%; incorrect pseudowords: 13/21, or 62%; χ^2 (1)= 0.02; p= n.s.).

Table 3 shows the different types of error produced by GSI in dictation: he made very few lexical substitutions, no morphological or semantic errors, and only 5 PPEs. The great majority of his errors were segmental (96% of the total errors).

Table 3. Subject GSI. Types of error in word writing-to-dictation. PPEs (phonological plausible errors); Morph (morphological); Sem (semantic), Word errors (lexical); nonwords errors (segmental).

Total errors		**PPEs**	**Morph**	**Sem**	**Word Errors**	**Nonwords errors**
	%	1	0	0	2	96
376	**N**	5	0	0	8	363

Table 4. Subject GSI. Segmental errors produced in different spelling tasks. Percentages are in parenthesis.

	Substitutions	**Omissions**	**Transpositions**	**Insertions**

Word Dictation	46/542 (8)	424/542 (78)	69/542 (13)	3/542 (0.5)
Pseudoword Dictation	38/99 (38)	53/99 (53)	8/99 (8)	0/99 (0)
Written Picture Naming	9/64 (14)	40/64 (63)	13/64 (20)	2/64 (3)

Table 4 shows segmental error distribution in different spelling tasks. Across these tasks, omissions were the most frequent error type, followed by transpositions, substitutions and insertions. Only in pseudoword dictation was the proportion of substitutions and transpositions reversed: substitutions increased, whereas transpositions decreased.

Performance in spelling-to-dictation tasks was influenced by length (χ^2 (2)= 65.63; p<.0001) but not by lexicality (χ^2 (1)= 0.02; p= n.s.) or lexical variables, like frequency (χ^2 (1)= 0.05; p= n.s.), grammatical class (χ^2 (3)= 3.35; p= n.s.), concreteness/abstractness (χ^2 (1)= 0.00; p= n.s.) (see Table 5). Furthermore, the same results were reproduced in oral spelling. GSI spelled orally 111 words, matched for frequency, grammatical class and length. Although this task is unusual for Italian individuals, GSI performed in a comparable way written and oral spelling. In fact, error rate was unaffected by grammatical class (χ^2 (1)= 1.18; p= n.s.) and frequency (χ^2 (1)= 0.20; p= n.s.) but was significantly influenced by length (χ^2 (2)= 11.69; p =.002) (see Table 6). [1]

Table 5. Subject GSI. Summary of incorrect responses produced in word spelling to dictation (n=718) (adapted by Miceli et al., 2004).

Frequency	
High frequency word	23/40 (57%)
Low frequency word	21/40 (52%)
Abstractness/Concreteness	
Abstract words	12/20 (60%)
Concrete words	11/20 (55%)
Grammatical class	
Nouns	10/20 (50%)
Adjectives	10/20 (50%)
Verbs	15/20 (75%)
Functors	10/20 (50%)
Length	
4-5 letters	102/1407 (7%)
6-7 letters	214/1677 (13%)
8 and more letters	226/1290 (17%)

Table 6. Subject GSI. Error rate in oral spelling task (n=111).

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[1] It is probable that GSI's high educational level (he was a university physics professor) allowed to him to carry out the oral spelling, which normally is not used by Italian individuals.

Frequency	
High frequency words	18/40 (45%)
Low frequency words	15/40 (38%)
Grammatical class	
Nouns	16/53 (30%)
Verbs	22/52 (42%)
Length	
4-5 letters	8/199 (4%)
6-7 letters	20/323 (6%)
8 letters	20/152 (13%)

The main feature of GSI's dysgraphia was a complete dissociation between impaired consonants and spared vowels. Table 7 shows the error rate on consonants and vowels in different spelling tasks. It was very evident that errors selectively affected consonants: he misspelled 692/2833 (24%) consonants and only 13/2588 (0.5%) vowels. This means that, across the tasks, 98% of errors occurred on consonants and 2% occurred on vowels.

When GSI spelled a consonant, he left blank spaces (for example, *ultimo,* last -> *ul_i_o*) and he commented that the blank spaces had to be filled with a consonant but that he did not remember which one. Furthermore, GSI attempted to fill the blank space at times successfully (*ul_i_o* -> *ulti_o*), and other times writing incorrect letters (*chiarire*, to clarify -> *chia_ire* -> *chiavire*).

Table 7. Subject GSI. Error rate on consonants and vowels in different spelling tasks (number of incorrect consonants/total consonants and number of incorrect vowels/total vowels are considered). Percentages are in parenthesis.

	Incorrect consonants	**Incorrect vowels**
Words Dictation (n=718)	532/2324 (23)	10/2128 (0.5)
Pseudowords Dictation (n=80)	98/217 (45)	1/195 (0.5)
Written Picture Naming (n=97)	62/292 (21)	2/265 (0.7)
Total	692/2833 (24)	13/2588 (0.5)

GSI's locus of impairment

The data in Tables 3-6 show that GSI presents the typical pattern associated with impairment to the graphemic buffer. Since he makes very few lexical substitutions and no morphological or semantic errors and most of his errors are segmental (Tables 3 and 4), a lexical-semantic deficit can be ruled out; furthermore, he exhibits no effect of frequency, concreteness or grammatical class on spelling accuracy, but shows a significant effect of letter length (Table 5), features usually linked to a disorder of the orthographic WM; finally a post-buffer deficit is unlikely because GSI yields comparable errors in oral and written spelling (Table 6) and he has a selective disorder for consonants (Table 7).

2.3 CASE CRI. Neuropsychological background

CRI is a 70-year-old, right-handed clerk. In July 2001 he suffered a left middle cerebral artery stroke, disrupting 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.

Spelling and language data were collected between October 2001 and March 2002. The results on the BADA (Miceli, et al., 1994) are summarized in Table 8.

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 a segmentally related word response (*tomba*, tomb > *tromba*, trumpet) and a possible morphological error (*volpe*, fox > *volpi*, foxes). CRI produced more errors in tasks that required the ability to process visual input than in tasks involving auditory stimulus presentation. For example, his 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 mostly resulted in 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. Auditory and visual word-picture matching was slightly below normal for nouns, and mildly impaired for verbs. Auditory and visual sentence-picture matching tasks were 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 articulatory precision were normal. The amount of information conveyed was normal, but with some anomic pauses, especially with verbs (in these cases the target lexical verb was substituted by a semantically related verb). Sentence structure was simplified. A sample of CRI's spontaneous speech is reported below:

Dunque posso dire che la mattina mi alzo, e …prendo…vado a vedere i nipotini che poi vanno a scuola... Poi e…cosa faccio poi? …cosa faccio?…e…faccio sempre un paio di telefonate, faccio un paio di al al par…a qualche parente che abita un po' lontano e…anche a degli amici…samamaente mi chiamano. Poi... faccio la colazione, questo lo faccio prima e non dopo, poi compro…a…mia sorella chiede sempre qualche cosa da comprare per lei, poi…ogni volta che torno su, torno a casa, "ho dimenticato questo" allora via, riparti, e…passo pure il tempo così. Poi ...l'ora di pranzo… poi aspetto i bam…bambini che tornano dalla scuola. Poi …che cosa faccio più? …un sacco di cose le f…ah! leggo i…le parole incrociate. Alcune me vengono proprio be…ci devo molto pensare su invece prima le facevo correttamente invece adesso devo pensare su le cose che devo fare….

Table 8. Incorrect responses produced by CRI on the subtests of the BADA.

Phoneme discrimination	2/60 (3%)
Auditory-visual matching	6/60 (10%)
Pseudo-word transcoding tasks	
Repetition	2/36 (6%)

Writing to dictation	6/45 (13%)
Delayed copy	1/6 (17%)
Reading aloud	6/45 (13%)
Lexical decision	
Auditory	2/80 (2%)
Visual	5/80 (6%)
Word transcoding tasks	
Repetition	2/45 (4%)
Writing to dictation	16/46 (35%)
Delayed copy	1/10 (10%)
Reading aloud	2/92 (2%)
Auditory word-picture match	
Nouns	2/40 (5%)
Verbs	1/20 /5%)
Visual word-picture match	
Nouns	2/40 (5%)
Verbs	3/20 (15%)
Spoken naming	
Nouns	8/30 (28%)
Verbs	9/28 (32%)
Written naming	
Nouns	12/22 (54%)
Verbs	13/22 (59%)
Spoken naming to definition	
Nouns	4/16 (25%)
Grammatically judgments	
Auditory	3/48 (6%)
Visual	6/24 (25%)

Sentence transcoding tasks	
Repetition	0/20
Reading aloud	0/6
Sentence-picture matching	
Auditory	9/60 (15%)
Visual	14/45 (31%)

2.3.1 General spelling abilities

Results on the BADA showed that writing was the most impaired task for CRI. He performed spelling tasks that allowed an extensive evaluation of his spelling-to-dictation abilities, as well as of written picture naming.

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 (χ^2 (1)= 3.09; p= n.s.).

Table 9 shows that errors normally associated with impairment to the orthographic lexicon, which involve selecting the wrong orthographic lexeme, as in other word errors (e.g., *stagione*, season -> *salone*, salon), semantic errors (e.g., *stagione* -> *inverno*, winter) and morphological errors (*stagione* -> *stagioni*, seasons), are not the majority in CRI's spelling, nor are the phonologically plausible errors (*scienza*, science -> scenza) that arise from the use of the phonology-orthography conversion system to generate a response. Across the word errors, almost all result from a single letter error (*brutto*, ugly, -> *butto*, I throw; *stacca*, she removes, -> *sacca*, bag; *corpo*, body, -> *corso*, course) that could arise from a segmental level failure. The percentage of segmental errors (84%) within of CRI's total errors is consistent with this proposal (see Table 9).

Table 9. Subject CRI. Types of error in word writing-to-dictation.

Total errors		**PPE**	**Morph**	**Sem**	**Word Errors**	**Nonwords errors**
	%	4	3	0	9	84
287	**N**	12	9	0	26	240

These 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). Same error types were observed in spelling to dictation both words and pseudowords, and in written picture naming (see Table 10). The spelling-to-dictation performance is summarized in Table 11.

Table 10. Subject CRI. Different segmental errors produced in the Dysgraphia Battery. Percentages are in parenthesis.

	Substitutions	**Omissions**	**Transpositions**	**Insertions**
Words Dictation	172/402 (43)	168/402 (42)	55/402 (14)	7/402 (2)
Pseudowords Dictation	28/58 (48)	20/58 (34)	8/58 (14)	2/58 (3)
Written Picture Naming	39/67 (58)	15/67 (22)	11/67 (16)	2/67 (3)

Table 11. Subject CRI. Summary of incorrect responses (letters) produced in word spelling to dictation (n=720)

Frequency	
High frequency word	34/508 (7%)
Low frequency word	34/500 (7%)
Abstractness/Concreteness	

Abstract words	10/194 (4%)
Concrete words	7/194 (5%)
Grammatical class	
Nouns	11/248 (4%)
Adjectives	17/262 (6%)
Verbs	23/256 (9%)
Functors	17/242 (7%)
Length	
4-5 letters	72/1278 (6%)
6-7 letters	155/1796 (9%)
8 and more letters	170/1391 (12%)

Accuracy was uninfluenced by the concreteness of the stimulus ($\chi^2(1)=0.55$; p=ns), or by the frequency of usage ($\chi^2(1)=0$; p=ns) or grammatical class ($\chi^2(3)=4.2$; p=ns) but was significantly affected by length ($\chi^2(2)=35.93$; $p<.0001$). Since normally Italian individuals do not use oral spelling, CRI was not able to carry out this task.

A remarkable feature of this subject's spelling was the contrasting error distribution across consonants and vowels. This difference was consistent across tasks (see Table 12). On the whole, CRI wrote incorrectly 527/6297 (8%) letters. He misspelled 443/3277 (13%) consonants and 84/3020 (3%) vowels ($\chi^2(1)=231.94$; $p<.0001$). In other words, 84% of his spelling errors affected consonants, and 16% vowels. Therefore, he can be added to the other two subjects reported on (Kay and Hanley, 1994; Miceli et al., 2004) showing a disproportionate difficulty in spelling consonants.

Table 12. Subject CRI. Error rate on consonants and vowels in different spelling tasks (number of incorrect consonants/total consonants; number of incorrect vowels/total vowels). Percentages are in parentheses.

	Incorrect consonants	**Incorrect vowels**
Words Dictation (n=720)	338/2393 (14)	64/2181 (3)
Pseudowords Dictation (n=80)	50/276 (18)	8/244 (3)
Written Picture Naming (n=188)	55/608 (9)	12/595 (2)
Total	443/3277 (13)	84/3020 (3)

CRI's locus of impairment

Tables 9 to 11 show that CRI's spelling pattern was affected by a graphemic buffer disorder. In fact, in spelling-to-dictation 84% of the total errors were substitutions, omissions and transpositions of single or double letters, and the low rate of lexical errors (26/287, 9%) probably arises from chance substitutions, omissions and transpositions (Tables 9-10). Furthermore, no lexical variable, i.e. frequency, concreteness or grammatical class, influenced CRI's spelling accuracy, which instead was significantly affected by the length of the stimulus (Table 11).

Finally, a post-graphemic disorder can be excluded, since a confusion matrix (see Appendix) of CRI's consonant errors revealed that the probability of substituting the target consonant with another consonant does not depend on visual or motor similarity (Rapp & Caramazza, 1997). Moreover, a deficit to the allographic conversion procedures appears to be unlikely, given the specificity of the disorder for consonants.

2.4 GSI and CRI: selective deficits for consonants?

Ward & Romani (2000) argued that careful evaluation of chance is required in order to evaluate whether there is a specific and significant deficit for CV encoding. Therefore, additional analyses were carried out over GSI and CRI's spelling performance to determine if they did in fact show a selective deficit for consonants. Simply using the proportion of consonants and vowels in the orthography of a specific language (in the case of Italian: 16/21 consonants or 76%; 5/21 vowels or 24%) is unsatisfactory, as some letters occur more frequently than others. A more appropriate test is to determine whether the distribution of consonant and vowel errors in the corpus of words spelled by each patient is significantly different than distribution of consonant and vowels among the correct spellings of those words. For each individual the total number of consonants and vowels in the corpus of words (GSI: n= 718; CRI: n= 720) was compared with the total number of errors on consonants and vowels.

Table 13. Subjects GSI and CRI: performance in writing to dictation. Distribution of consonants and vowels in the corpus, compared to the distribution of the errors on consonants and vowels (percentages are in parenthesis).

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

The data reported in Table 13 confirm that GSI and CRI suffer from a selective deficit for consonants: a significant difference was found between the distribution of consonants and vowels among the errors and those of the correct spelling (GSI: χ^2 (1)= 414.57; p<.0001; CRI: χ^2 (1)= 149.27; p<.0001). For both subjects, a larger proportion of errors was on consonants and a smaller proportion on vowels than would be expected from the distributions within the whole corpus of words.

In the next section, the data for GSI and CRI as regards to a) the serial position effect, b) the length effect and c) the effects of absolute grapheme position and length (by number of consonants) on accuracy in specific consonant positions are presented. The contrasting results of these analyses demonstrate that, although both subjects can be considered as bona fide GBD cases, their deficits affect different components of the orthographic working memory system: GSI's deficit affects temporal stability while CRI’s deficit affects representational distinctiveness.

2.5 Serial position effect

The distribution of spelling errors on consonants was evaluated using the method proposed by Machtynger and Shallice (2009). Given the highly selective spelling deficit of the subjects, we only considered errors on consonants. We focused on stimuli that contained between 2 and 5 consonants, and normalized error distribution across 4 positions, or what Machtynger and Shallice call “regions”. In other words, we treated words from 2 to 5 consonants as 4-consonant words because, on the basis of the method proposed by Machtynger and Shallice, it is preferable to normalize across number of letters with more elements. Thus, we normalized errors across 4 positions (rather than, say, across 3 or 5 positions) because 4-consonant words were the most represented in the corpora spelled by GSI and CRI.

On the method used by Machtynger and Shallice, for each string, each position (or region) is divided into a number of cells equal to the number of positions across which error distribution must be normalized (four cells in our case). Thus, the 2 consonants in the word *cane,* dog, to be normalized in four regions, are assigned 4 cells each (8 cells). Subsequently, errors are assigned to all the cells that correspond to the error position; in the previous example, an error on the first consonant c will be scored as 2/4 of an error in the first position and 2/4 of an error in the second position, and an error on the second consonant n will be scored as 2/4 of an error in the third position and 2/4 of an error in the fourth position (see Table 14).

Table 14. Machtynger's method, modified. Words were divided on the basis of the number of consonants. Take as an example a word with three consonants, like insieme (together). If an error occurs on the first consonant, 3/4 of the errors are assigned to position A, and 1/4 to position B. If the error occurs on the second consonant, 2/4 of the errors are counted in position B, and 2/4 in position C. Finally, if the error occurs on the third consonant, 1/4 is scored in position C and 3/4 in position D.

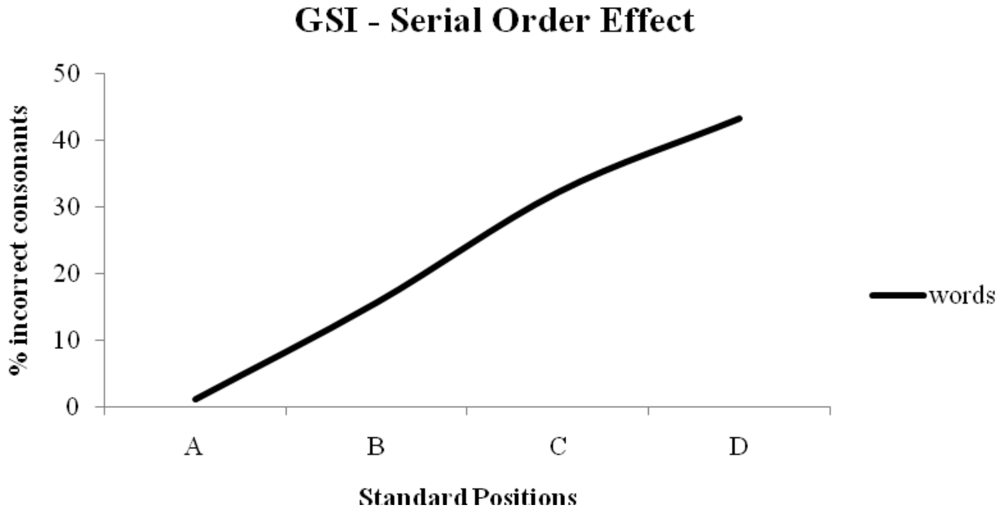
	A	**B**	**C**	**D**
Length 2 cons	1 1	1 1	2 2	2 2
Length 3 cons	1 1 1	1 2 2	2 2 3	3 3 3
Length 4 cons	1 1 1 1	2 2 2 2	3 3 3 3	4 4 4 4
Length 5 cons	1 1 1 1 2	2 2 2 3 3	3 3 4 4 4	4 5 5 5 5

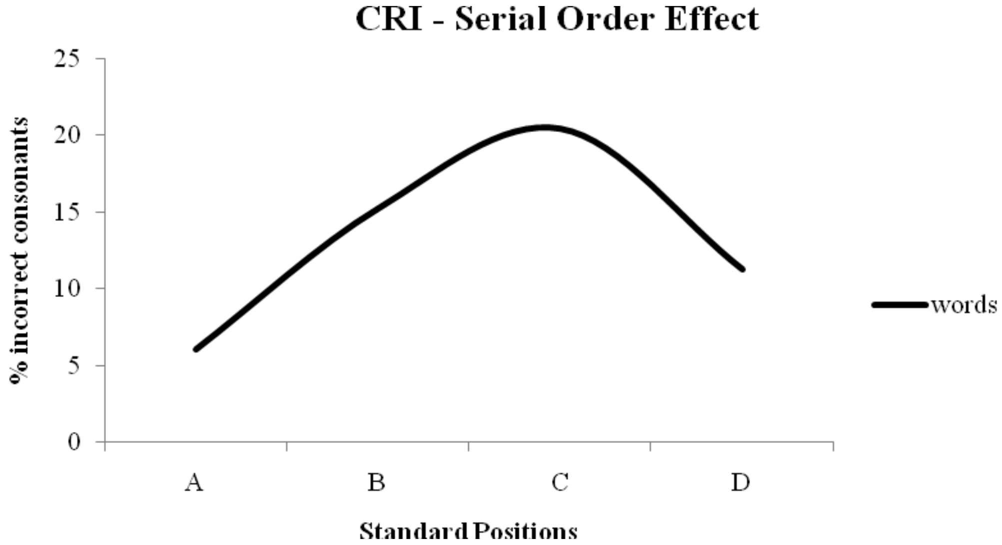
Both GSI and CRI produced few complex errors (where the response deviate from the target by more than one letter), and those complex errors were always interpretable. Therefore, we calculated the serial order effect by combining all of the errors (both simple and complex) produced by each subject (for example, one substitution and one omission) (for a discussion see Sage & Ellis, 2004 but also Buchwald & Rapp, 2010).

For GSI, the error percentages on consonants across the four normalized positions were 1, 16, 32 and 43, respectively (see Figure 1a). GSI showed a monotonic error function – errors increased with the distance of the consonant from the beginning of the word. As already mentioned, error distribution in this subject is similar to that observed in other dysgraphic individuals, whose error rates increase monotonically from the beginning to the end of the word, but with a substantial difference: in GSI the curve corresponds to the distribution of errors on consonants, not on graphemes.

For CRI, the error percentages from the first to the fourth position were 6, 15, 21 and 11 (see Figure 1b). This subject made more errors on the consonants in medial positions. This pattern is similar to the bow-shaped serial position curves reported for other GBD individuals, though again we are only showing the distribution of errors on consonants, not on all graphemes.

Figure 1. Spelling accuracy as a function of the serial letter position for GSI (a) and CRI (b). Different letter lengths are normalized to four positions on the basis of the scheme developed by Macthynger and Shallice (2009).





2.6 Length effect

Temporal stability and representational distinctiveness deficits can be distinguished by whether the length effect is a function of the number of graphemes or the number of consonants. In order to evaluate the two contrasting possibilities, we considered words that contained from 4 to 11 graphemes (geminate consonants were considered as single letters) and calculated response accuracy (incorrect letters/total letters) for each length in the spelling-to-dictation task. A similar analysis was performed on words that contained from 2 to 5 consonants (incorrect consonants/total consonants). The corpus contained 718 words for GSI and 720 words for CRI.

Figures 2 and 3 demonstrate the effects of length in the performance of GSI and CRI. Graphs 2a and 3a show the proportion of letters (consonants and vowels) produced incorrectly by GSI and CRI as a function of the number of graphemes in the stimulus; Figures 2b and 3b show the proportion of incorrect consonants produced by the two subjects as a function of the number of consonants in the stimulus. Furthermore, Tables 15 through 18 report the error rate on words of different length, on which Figures 2 and 3 are based.

Both subjects presented with a significant length effect, regardless of whether accuracy was measured with reference to the number of graphemes (GSI: χ^2 (4)= 69.96; p<.0001; CRI: (χ^2(4)= 45.33; p<.0001), or to the number of consonants (GSI: χ^2 (2)= 48.41; p<.0001; CRI: χ^2(2)= 41.55; p<.0001). In other words, GSI and CRI made more errors in words with more graphemes and in words with more consonants. This result is not surprising, as the number of consonants closely correlates with the number of graphemes.

Table 15 Subject GSI. Incidence of incorrect responses in word spelling-to-dictation as a function of grapheme length.

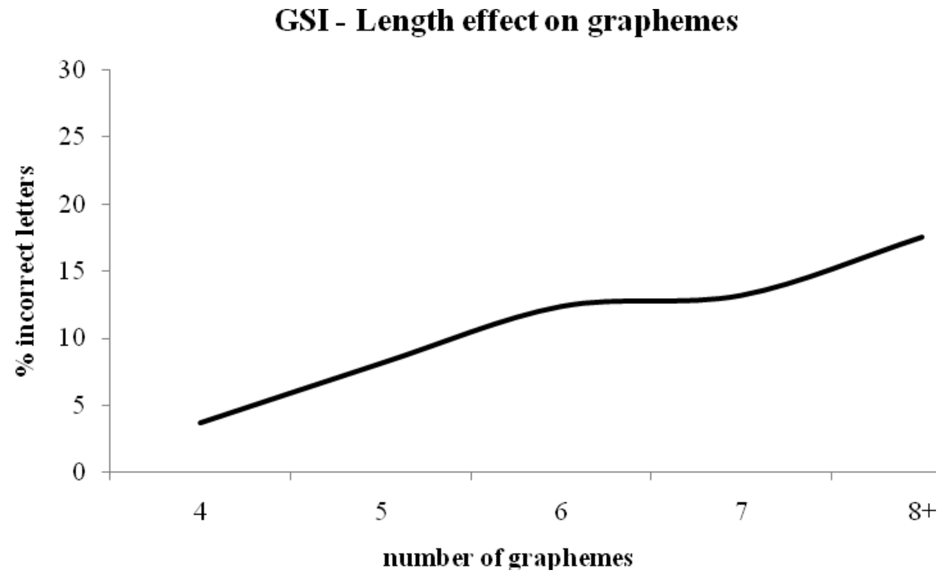
Graph length	# words	# letters	# incorrect letters	%
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

6	143	858	106	12
7	117	819	108	13
8+	162	1290	226	18

Table 16. Subject GSI. Incidence of incorrect responses in word spelling-to-dictation as a function of consonant length.

Cons length	**# words**	**# consonants**	**# incorrect consonants**	**%**
2	138	276	37	13
3	299	897	168	19
4-5	208	1077	317	29

Figure 2. Subject GSI. Incidence of incorrect letters in words of different grapheme length (a) and incidence of incorrect consonants in words of different consonant length (b).



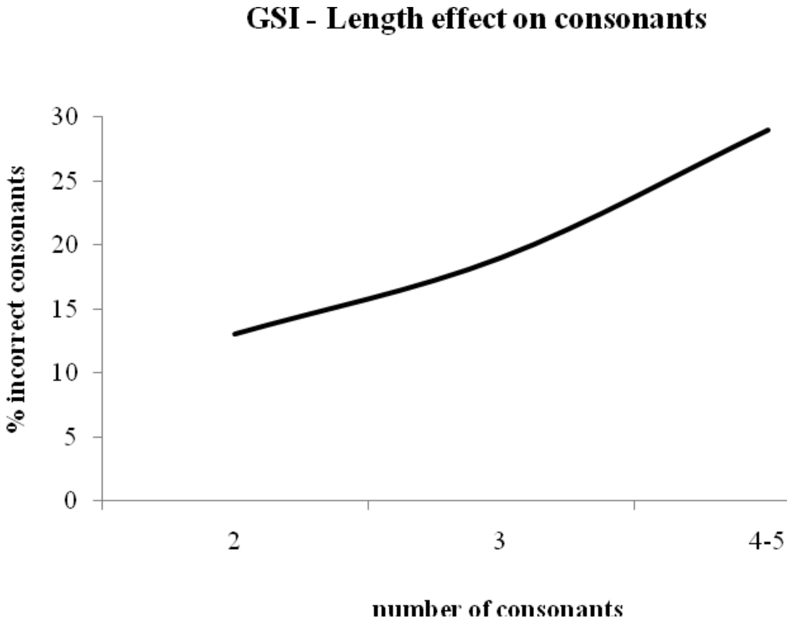


Table 17. Subject CRI. Incidence of incorrect responses in word spelling-to-dictation as a function of grapheme length

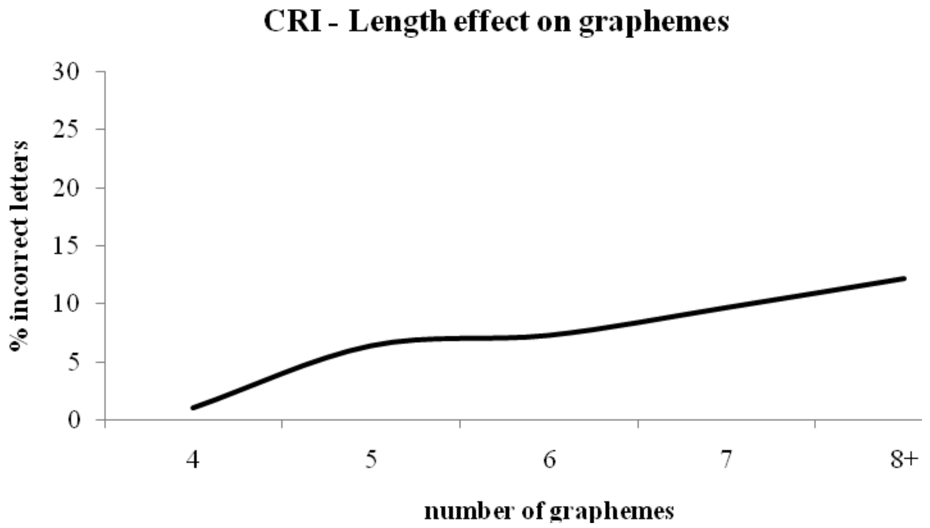
graph length	# words	# letters	# incorrect letters	%
4	47	188	2	1

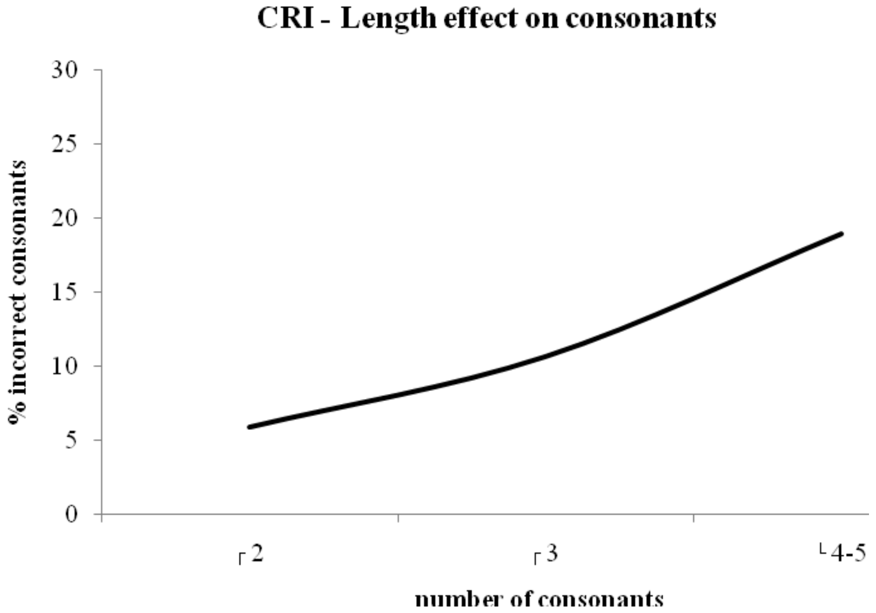
5	218	1090	70	6
6	157	942	69	7
7	122	854	83	10
8+	174	1391	170	12

Table 18. Subject CRI. Incidence of incorrect responses in word spelling-to-dictation as a function of consonant length

Conson length	# words	# consonants	# incorrect consonants	%
2	119	238	14	6
3	304	912	97	11
4-5	549	989	187	19

Figure 3. Subject CRI. Incidence of incorrect letters in words of different grapheme length (a) and incidence of incorrect consonants in words of different consonant length (b).





In order to disambiguate the effects of consonant and of grapheme length, we analyzed accuracy on words with the same number of graphemes but a different number of consonants, and vice versa. For example, we contrasted the performance on 7-grapheme words with 3 vs. 4 consonants (*società*, society vs.

scatola, box) and the performance on 4-consonant words made up of 6, 7 and 8 graphemes (*scelta*, choice vs. *cuscino*, pillow vs. *fantasia*, fantasy)[2]. Given that both subjects made errors mainly on consonants (98% of total errors for GSI, 84% for CRI), accuracy was measured by calculating the number of errors on consonants/number of total consonants present in each word group. The results for GSI and CRI are presented in Figures 4a and 4b, respectively.

GSI showed a significant tendency to spell less accurately words with the same number of consonants but a larger number of graphemes (Figure 4a). To consider the sample of words with 4 consonants, GSI incorrectly spelled 21% (27/128) of consonants in 6-grapheme words, 27% (86/320) in 7-grapheme words and 34% (113/334) in 8-grapheme words ($\chi^2(2)= 8.39$; $p<.015$). The number of consonants did not affect GSI's spelling performance on 5-grapheme words (16/128 or 13% of errors in 2-consonant words, 74/480 or 15% of errors in 3-consonant words; χ^2 (1)= 0.47; p= ns), on 6-grapheme words (69/294 or 23% of errors in 3-consonant words, 27/128 or 21% of errors in 4-consonant words; χ^2 (1)= 0.17; p= ns) and on 7-grapheme words (17/96 or 18% of errors in 3-consonant words, 86/320 or 27% of errors in 4-consonant words; $\chi^2(1)= 2.86$; p= ns).

Figure 4. Error rate on consonants in words with different number of graphemes and consonants, for GSI (a) and for CRI (b). Note that, for each length, words with more consonants but with the same number of graphemes are spelled less accurately by CRI, but not by GSI.

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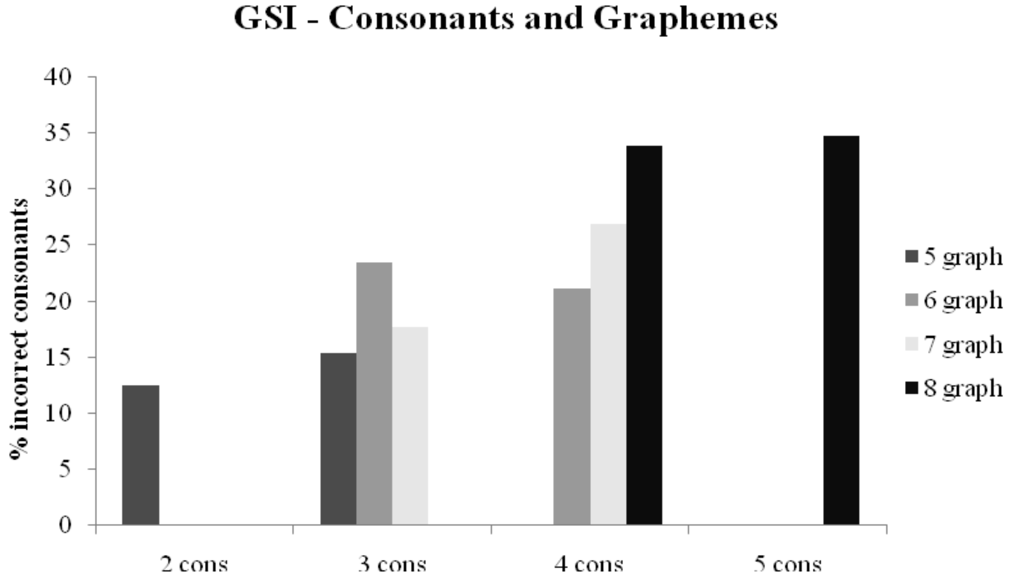
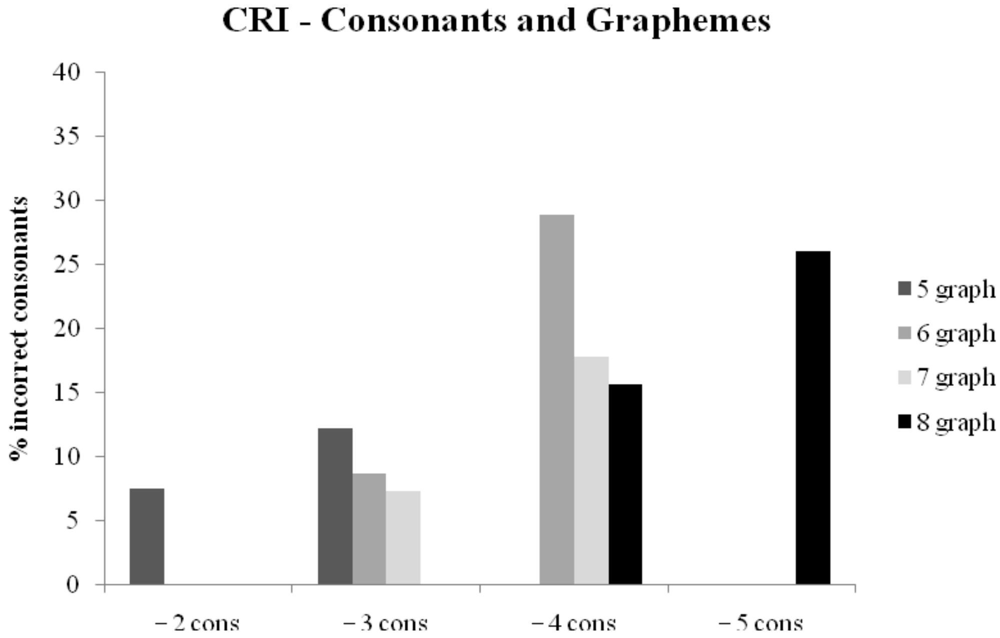
[2] Given the relatively small number of stimuli, we were unable to match words for syllabic structure.



GSI - Consonants and Graphemes



CRI - Consonants and Graphemes

In contrast, for CRI, the number of consonants rather than the number of graphemes affected this subject’s performance (Figure 4b). Indeed, across different grapheme lengths, performance was significantly less accurate on words with more consonants but with the same number of graphemes. For example, in 6-grapheme, 3-consonant words CRI incorrectly spelled 30/345 (9%) consonants, whereas in 6-grapheme, 4-consonant words he incorrectly spelled 30/104 (29%)

(χ^2 (1)= 26.31, p<.0001). In the same group of words GSI spelled 69/294 (23%) and 27/128 (21%) consonants (χ^2(1)= 0.17, p= n.s.), respectively.

This contrast between the two patients was also observed in performance on 8-grapheme words. CRI incorrectly spelled 55/352 (16%) consonants in 4-consonant words and 39/150 (26%) in 5-consonant words (χ^2 (1)= 6.77, p<.009), whereas GSI's performance on the two groups of items was almost identical, as he incorrectly spelled 113/334 (34%) consonants in 4-consonant words and 52/150 (35%) in 5-consonant words (χ^2(1)= 0.01, p=n.s.).

2.6.1 Regression analyses and Monte Carlo simulation

The previous analyses were based on a subset of the errors (5-8 grapheme words and 2-5-consonant words) produced by GSI and CRI. To confirm that the results from the previous set of analyses held constant across all incorrect responses, a more comprehensive analysis of GSI and CRI's consonant errors was carried out using logistic regression.

For each subject, we used two different models, the Consonant model and the Letter model, to predict the likelihood that each consonant would be produced incorrectly. Both models contained a single length regressor. In the consonant model, the length regressor was the length of the target word in number of consonants. In the letter model, the length regressor was the length of the target word in number of letters.

For each patient, we determined which of the two models provides the best fit for the data. This analysis confirmed the results reported in the previous section. For GSI, the Letter model was a better predictor of consonant accuracy than the Consonant model (Letter Model, r^2= .017; Consonant Model r^2= .014).

Conversely, for CRI the Consonant model was a better predictor of consonant accuracy than the Letter model (Consonant Model, r^2= .027; Letter Model, r^2= .009). In the latter subject, the likelihood that a consonant was going to be produced in error was predicted more accurately by the number of consonants than by the number of graphemes in the target. The statistical reliability of these differences was verified using a Monte Carlo resampling procedure for each subject.

In each run of the Monte Carlo analysis, 500 consonants were randomly selected, with the requirement that 50% of the consonants in the random selection were produced correctly and 50% were produced incorrectly[3]. The Letter and the Consonant models were each applied to that random subset of data, and a program tabulated which model provided the better fit. This procedure was repeated 10,000 times. In other words, the program created 10,000 random samples, and for each sample compared the fit of the two logistic regression models. Out of the 10,000 random samples, the program calculated the proportion in which the Letter model or the Consonant model fit the data better.

The results for CRI were unmistakable. In all 10,000 random subsamples of the data, the Consonant model predicted consonant accuracy better than the Letter model. For this subject, we can confidently conclude that the likelihood that he would produce a consonant in error depended on target length in number of consonants rather than in number of letters. For GSI, the Letter model was a better predictor of consonant accuracy than the Consonant model on 79% of the 10,000

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[3] This method, stratified sampling, in which an equal number of samples from each stratum (here correct and incorrect consonants) is considered as an expected reference level, is a common statistical technique when using logistic regression (see Anderson, 1972 for discussion of the merits of this technique).

analysis runs, thus indicating that the Letter model typically performs better than the Consonant model, though not overwhelmingly so. These results support our previous conclusion, that spelling accuracy was influenced by the number of graphemes in GSI, and by the number of consonants in CRI.

To sum up our results so far, GSI and CRI showed contrasting patterns as regards both serial order and length effects. GSI made more errors at the end of the word and his spelling accuracy was constrained by the number of graphemes in the string. This pattern of performance is consistent with a temporal stability deficit, because in this case activation of the orthographic representation rapidly decays as a function of the absolute distance (time elapsed or number of letters produced) from the beginning of the word. Conversely, CRI error crowding in the middle of the string and the number of consonants in the words constrained spelling accuracy. This second pattern of performance can be explained as the consequence of reduced representational distinctiveness, since the representational space of consonants is more crowded in words with more consonants.

The spelling performances of GSI and CRI are consistent with the view that two different properties characterize the orthographic working memory level: stability and distinctiveness.

2.7 Effects of consonant length and absolute position on accuracy by consonant position

The analyses of the length effect conducted so far suggest that the number of graphemes and the number of consonants in a word play a different role in the spelling performance of our two subjects. Even though in both cases errors concern consonants exclusively (GSI) or predominantly (CRI), spelling accuracy deteriorates with the number of graphemes in the to-be-written string for GSI, but with the number of consonants for CRI.

We further analyzed the spelling performance in our subjects by calculating the effects of length (in either number of graphemes or number of consonants) on accuracy for consonants that occupy specific positions in the target string. If GSI suffers from a temporal stability deficit, information about consonants should rapidly decay as a function of the number of graphemes in the to-be-spelled string. Therefore, spelling accuracy on consonants that occupy the same (relative) consonant position but a different absolute position should differ. For example, GSI should spell the second consonant of a word more accurately when it appears in second absolute position (e.g., *t* in stadio, stadium) than when it appears in third absolute position (e.g., *t* in patria, home country). In contrast, his performance when spelling consonants in a given position should not be affected by the number of consonants in the target. Thus, he should spell with similar accuracy the second consonant in words that contain two or three consonants (e.g., *t* in stadio, stadium, and in stuoia, mat).

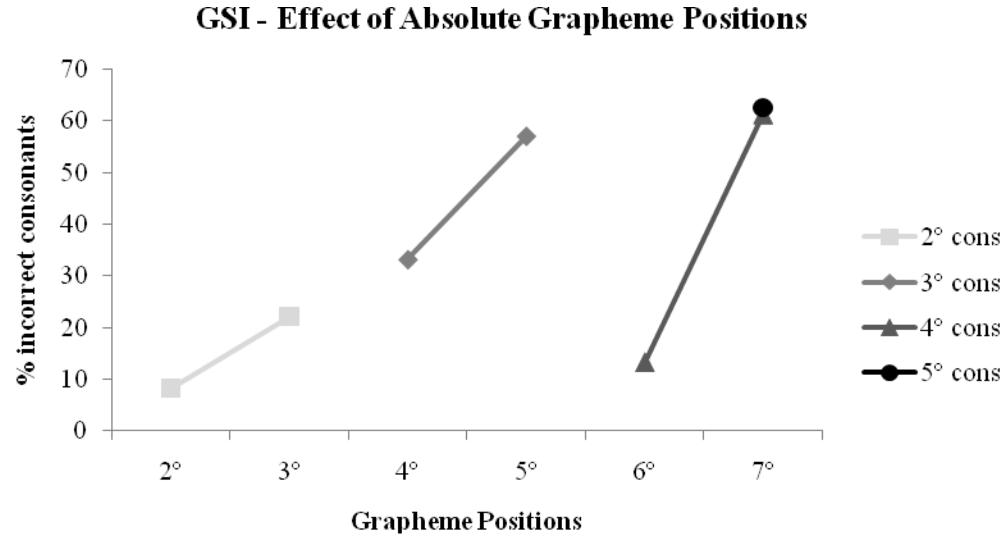
The opposite pattern is predicted for CRI. If his spelling difficulties are due to decreased distinctiveness between consonants, his performance should be constrained by the number of consonants – more consonants would result in greater crowding and hence in more misspellings. Consequently, he should spell consonants in the same consonant position with different accuracy, depending on the total number of consonants in the to-be-written word. For example, he should spell the second consonant more accurately in words that contain two consonants (e.g., *t* in *stuoia*, mat) than in words that contain three consonants (*t* in *stadio*, stadium). By contrast, he should spell with similar accuracy consonants that appear in the same relative position but in a different absolute position within a word (e.g., t in *stadio*, stadium, and t in *patria*, home country).

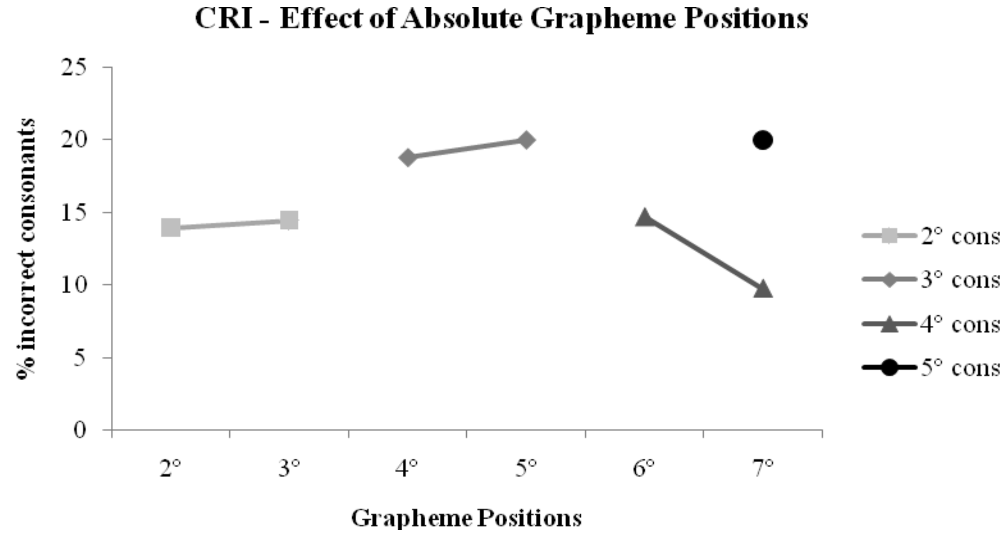
To clarify this issue, two analyses were conducted. The first measured the accuracy in spelling consonants that are in the same consonant position but in a different absolute position (for example, accuracy on second consonants that occupy the second, third and fourth absolute positions). Therefore, each consonant position corresponds to one position in terms of consonants and one position in terms of graphemes. For words of the same length (from 5 to 8 graphemes), the proportion of errors on consonants was calculated by dividing the number of errors on consonants by the number of consonants in each position.

The corpus spelled by GSI and CRI contains words with many different orthographic structures (for example, for each length, the corpus collected from GSI includes between 15 and 35 different orthographic structures). Therefore, in order to obtain a more stable measure of the absolute position effect on specific consonant positions, for each word length only the orthographic structures most represented in the corpus (that is, most numerous) were considered in each subject. For example, in the corpus of 5-grapheme words collected from GSI the following orthographic structures were considered: CVCCV (*padre*, father), n=106; CVVCV (*ruolo*, role), n=33; CCVCV (*creta*, clay), n=31; CCVGV (*prezzo*, price), n=19.

The results (Figure 5a) are very clear. As predicted, GSI spelled less accurately the t in *patria* than the t in *stadio*. In fact, even though both letters are in the second consonant position, t in patria is in third absolute position and t in stadio is in second absolute position ($\chi^2(1)= 6.35$, $p=.011$). Also, this pattern was replicated for each consonant position (3rd consonant: $\chi^2(1)= 17.3$, $p<.0001$; 4th consonant: $\chi^2(1)= 30.5$, $p<.0001$), and for each group of words (5, 6, 7 and 8 graphemes). By contrast, the error distribution for CRI is random (2nd consonant: $\chi^2(1)= 0.01$, p=ns; 3rd consonant: $\chi^2(1)= 0.01$, p=ns; 4th consonant: $\chi^2(1)= 0.56$, p=ns) (see Figure 5b).

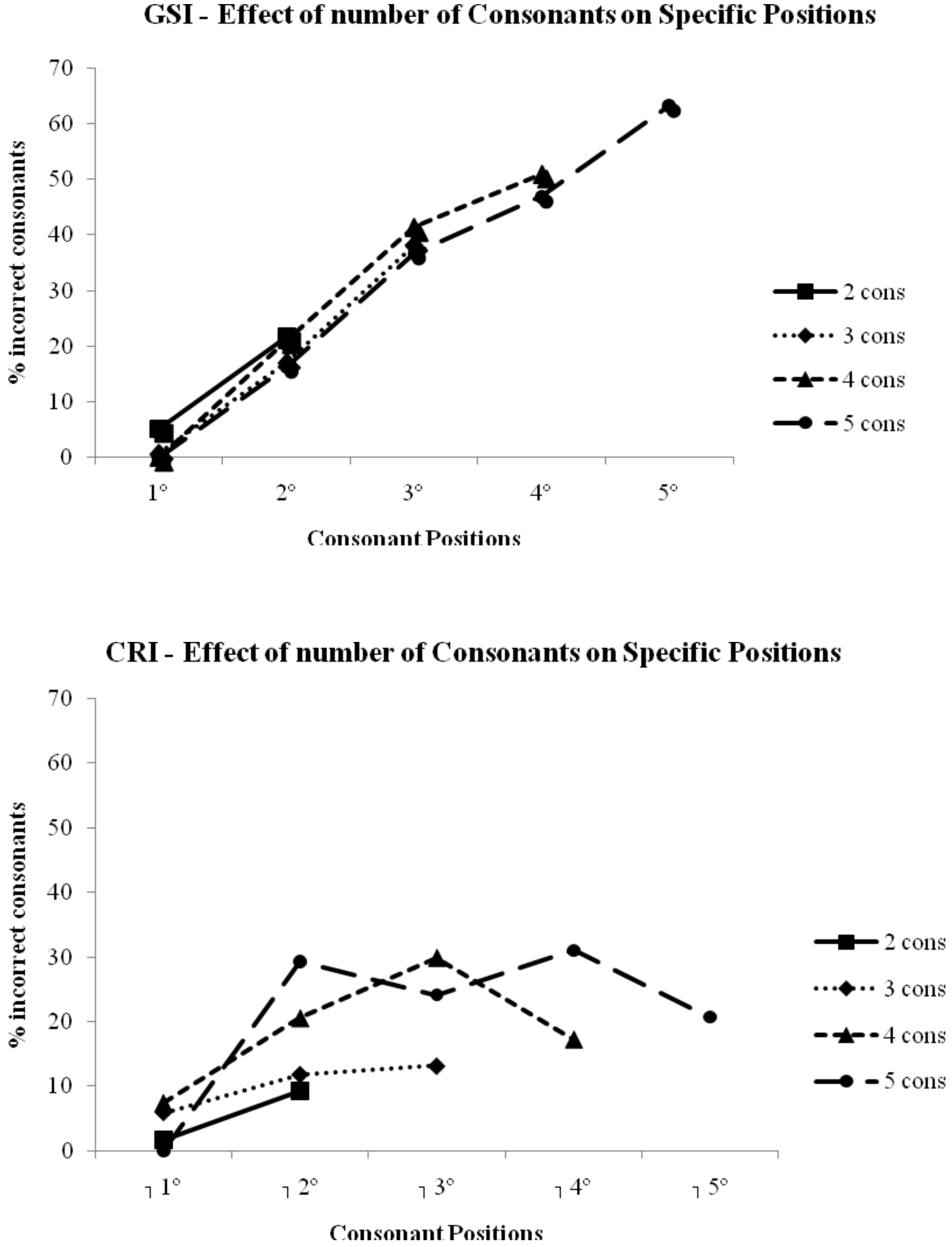
Figure 5. Error rates on consonants that appear in the same consonant (relative) position but in different letter (absolute) position for GSI (a) and for CRI (b). Words that contain from 5 to 8 graphemes are considered. For each length, analyses focused on the orthographic structures most represented in the corpus.


GSI - Effect of Absolute Grapheme Positions
% incorrect consonants
70
60
50
40
30
20
10
0
2°
3°
4°
5°
6°
7°
Grapheme Positions
2° cons
3° cons
4° cons
5° cons


CRI - Effect of Absolute Grapheme Positions
% incorrect consonants
25
20
15
10
5
0
2°
3°
4°
5°
6°
7°
Grapheme Positions
2° cons
3° cons
4° cons
5° cons

The second analysis evaluated the length effect on consonants appearing in specific positions, in words containing different numbers of consonants (from 2 to 5). Accuracy for each position was obtained by scoring the errors that occurred in each consonant position, in each group of words. We compared the error rate on consonants occupying the same position for words containing a different number of consonants. The results confirmed the predictions stated earlier (Figure 6). It is very clear that for GSI accuracy did not depend on the number of consonants in the target word: he produced a similar number of errors on each consonant position, irrespective of whether the word contained 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 (Figure 6a). By contrast, the same analysis clearly documented that consonant spelling accuracy in CRI (Figure 6b) depended on the number of consonants in the word. For example, spelling accuracy in second consonant position decreased with an increasing number of consonants in the target word. In fact, CRI incorrectly spelled the second consonant 9%, 12%, 21% and 29% of the times in words with 2, 3, 4 and 5 consonants, respectively. Error rates on the second consonant were significantly different depending on word length in consonants ($\chi^2(3)=19.11$, p=.0003). The results were the same on the third consonant: $\chi^2(2)= 22.16$, $p<.0001$; and on the fourth consonant: $\chi^2(1)= 5.34$, p=.020.

Figure 6. Consonant error distribution in different relative (consonant) positions, as a function of consonants number in the word for GSI (a) and CRI (b). Words with 2, 3, 4 or 5 consonants were considered. Errors occurring in each consonant position, in each group of words were scored.


GSI - Effect of number of Consonants on Specific Positions

CRI - Effect of number of Consonants on Specific Positions

2.8 Discussion

In the Introduction, we suggested that the orthographic WM can be broken down into at least two distinct subcomponents: the temporal stability of the orthographic representations retrieved from the lexicon (for words) or assembled by sublexical conversion procedures (for pseudowords), and the representational distinctiveness of the elements (graphemes) that comprise the target orthographic representation. Temporal stability would ensure that the elements of the orthographic string remain active in the course of serial selection and production of graphemes. Representational distinctiveness would keep each grapheme of the to-be-written string distinct from the others, so that it can be appropriately selected for production. Under normal conditions, therefore, the two dimensions jointly ensure that, at each point in time, the element of the orthographic representation that needs to be spelled is active and fully distinguished from its neighbors.

Evidence for this distinction came from the analysis of two dysgraphic individuals, GSI and CRI. Both presented with a common core of dysgraphic features: their spelling accuracy was unaffected by lexical-semantic dimensions but it was constrained by length; their errors were graphemic in nature and selectively involved consonants. This pattern of performance was consistent with damage to the orthographic WM level, associated with a selective disorder for consonants.

However, more detailed analyses demonstrated substantial differences between these two subjects. Their contrasting performance reported on here suggested considering the possibility that they suffer from distinct disorders, both affecting properties of the orthographic WM. In the first place, they showed different serial position effects: errors increased monotonically from the beginning of the word for GSI, but clustered in medial positions for CRI (see Figures 1a and 1b). Secondly, different factors affected spelling accuracy in the two subjects: GSI made more consonant errors in words with more graphemes, whereas for CRI accuracy on consonants was affected by length in number of consonants (see Figures 4a and 4b). Finally, analyses that evaluated performance accuracy on consonants in the same grapheme (absolute) position and consonants in the same consonant (relative) position for words of different lengths yielded contrasting results (Figures 5 and 6) in the two subjects. For GSI, accuracy on writing consonants that appeared in the same relative position (e.g., the second consonant of the target string) was constrained by the absolute position of that consonant in the string (i.e., by whether it was the second, third, fourth, etc. grapheme in the target). In contrast, for CRI the error rate on the same consonant was influenced by the number of consonants in the string (i.e., by whether the target contains three, four, five, etc. consonants), and regardless of its absolute (graphemic) position. These results provided converging evidence that GSI's deficit can be accounted for by reduced temporal stability and CRI's deficit by low representational distinctiveness. Furthermore, their patterns were consistent with the predictions, summarized in Table 1, in the event of damage to consonant temporal stability and consonant representational distinctiveness.

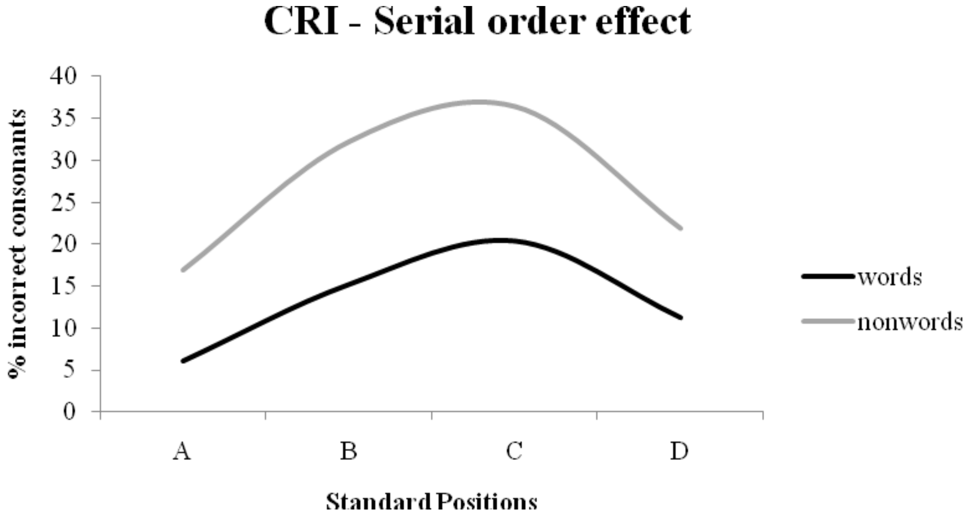
The interpretation proposed here of the bow-shaped serial position effect differs from the explanation offered by Schiller et al. (2001). They argued that the error pattern arises because of reduced activation of the target word in the lexicon, rather than an impairment of the GB itself. One of the reasons for this claim was that the bow-shaped curve of these subjects resembles the distribution of misspellings observed in normal subjects writing a university entrance exam under time pressure (Wing & Baddeley, 1980). The analogy is questionable, however, as control subjects produced these errors on words that they presumably knew and would have produced correctly if writing at a more leisurely pace. In other words, there is no strong reason to assume that these errors result from reduced lexical activation, rather than from dysfunction at the graphemic buffer level.

Interestingly, CRI showed a bow-shaped serial position curve not only for words, but also for pseudowords (error percentages on consonants across the four normalized positions were 17, 32, 36 and 22, respectively), which undermined the claim that the effect was lexical in nature (see Figure 7). Furthermore, in the only case for which the pattern of error distribution for words and pseudowords was reported in the literature (Caramazza & Miceli, 1990), similar bow-shaped curves were produced too.

Given the similarity between the two curves, errors on both words and pseudowords were likely to arise from the impairment of one and the same property of the orthographic WM (representational distinctiveness), rather than from damage to distinct levels of processing (reduced activation of lexical representations for words, and orthographic WM damage for pseudowords).

In the theoretical framework we are proposing, then, data from CRI were consistent with the view that a bow-shaped error distribution can also originate from damage to the orthographic WM system. The curve was caused by abnormal crowding of the elements (in this case, consonants) of the orthographic representation, especially those appearing in central positions.

Figure 7. Subject CRI. Error rate on words and pseudowords as a function of position in a letter string. Different letter lengths are normalized to four positions on the basis of the scheme developed by Macthynger and Shallice (2009).



By dividing orthographic working memory into temporal stability and representational distinctiveness, we could explain the differences in overall distribution of consonant errors in our two dysgraphic subjects. The results were crystal clear for CRI. For example, in Monte Carlo analyses his performance was more accurately accounted for by the Consonant length than by the Grapheme length model in 100% of cases. The results for GSI were less clear-cut, as the Grapheme length model provided a better fit than the Consonant model only in 80% of cases. Two different explanations can be entertained for this observation. The first relies on a possible role of consonant clusters. Miceli et al. (2004)

showed an effect (albeit non-significant) of CV structure in GSI: he misspelled the third consonant in the fourth absolute position for 16.3% of the singletons (*trono*, throne) and 46.8% of the clusters (*carne*, meat) (p. 116). Unfortunately, the corpus collected from this subject was too small to allow statistical comparisons on subsets of words of the same graphemic length, matched for syllabic structure. Therefore, interactions of absolute consonant position and syllabic structure in this subject remain a possibility. As an alternative, GSI might suffer from two distinct disorders, both disproportionately affecting consonants: a marked deficit of temporal stability and a mild disorder of representational distinctiveness, which in some instances might prevail over temporal decay, increasing the subject's difficulty spelling consonants in non-initial positions. Be this as it may, qualitative and quantitative aspects of performance in this subject (the monotonic error increase; the length effect being constrained by the number of graphemes; the effect of absolute consonant position on consonant accuracy) were clearly compatible with damage to temporal stability.

2.8.1 Interaction between structure and processing

The serial order effects observed in these two subjects demonstrated very clearly the interaction between the structure of orthographic representations and the WM that processes them. Since these subjects produced only (GSI) or overwhelmingly more (CRI) errors on consonants than on vowels, all the analyses reported here were conducted on consonants. Therefore, each graph (Figures 1-7) attested to the interaction between damage to a structural property of orthographic representations (damage to consonants) and damage to WM properties that operate on these representations (temporal stability in GSI; representational distinctiveness in CRI). An interaction between serial order position and grapheme type was already documented in GSI (Miceli et al., 2004). He made errors only on consonants, but always correctly spelled the first consonant in the string; and his errors increased monotonically from initial to final positions. In this subject, performance on vowels was flawless and the first consonant in the string was always produced correctly. Hence, neither the mechanisms responsible for serial ordering nor the representation of consonants can be completely damaged – if that were the case, he would have to spell vowels as incorrectly as consonants, and would make errors on consonants regardless of their position in the target string. Therefore, his performance was interpreted as the result of an interaction between moderate damage to the representation of consonants (the first consonant was correctly produced) and a more marked deficit in the serial order mechanism (errors monotonically increased).

In CRI's case, consonant damage was associated with an impairment of the representational distinctiveness property, yielding a spelling pattern completely different from that of GSI. Thus, interaction between the same representational damage and different impairment to orthographic WM produced different spelling performances, demonstrating the relevance of interaction between orthographic representations and WM properties in the spelling process.

Interim Conclusion

For two subjects reported on, different length effect for graphemes and consonants can be attributed to distinct impairments at the orthographic WM level. Moreover, we have demonstrated that both the monotonic and the bow-shaped error distribution functions can be explained by assuming damage to the same level of the spelling system, but to different properties: the monotonic curve was produced by a rapid decay of orthographic consonant representation (caused by a temporal stability deficit) and the bow-shaped curve by crowding of consonant representations (caused by a representational distinctiveness deficit) at the WM level. This interpretation contrasts with previous literature that localized the two curves in different loci of impairment (orthographic output lexicon and orthographic WM). Furthermore, the third set of analyses (Figures 5 and 6) was consistent with the interpretation provided for the length and serial order effects.

Moreover, the different spelling patterns of these subjects evidenced an interaction between damaged consonant representation and different WM properties, also affected by impairment.

In the following chapter we present a case of acquired dysgraphia supporting the distinction and the interaction between representations and working memory. This subject, however, will show a different spelling pattern as regards GSI and CRI, because he suffers from a consonant disorder, like GSI and CRI, but he does not have a graphemic buffer disorder.

Chapter 3

The distinction between representation and working memory

Introduction

The abstract orthographic representation of words and pseudowords, processed by lexical and sublexical procedures respectively, reaches the graphemic level in a word-format. What happens at this level of the spelling process?

Since writing is a sequential process, in which one letter at a time can be spelled, it is necessary to think of a working memory (WM) system that maintains the representation of the whole word active, while processes converting abstract representation into a specific format occur.

At this level of processing, in addition to the WM system operating on orthographic representation in order to ensure correct written production (Ellis, 1982), the formal properties of orthographic representation are specified, such as identity, order, quantity, C/V status and syllabic structure of graphemes (Caramazza & Miceli, 1990).

In the previous chapter we focused on internal operations of the orthographic WM, identifying two properties necessary to the spelling of a word: temporal stability and representational distinctiveness. We reported spelling analyses of GSI and CRI, two dysgraphic subjects whose performance could be explained as the result of damage to these different properties of the orthographic WM. Moreover, GSI and CRI presented a selective disorder of consonant representation.

Therefore, the error patterns of these two subjects showed how orthographic representations are processed when damage affects both the properties of working memory and the orthographic representations themselves.

What kind of performance would be expected in the case in which only the representation and not the WM properties were affected by damage?

Case LiB (Cotelli et al., 2003) offers an interesting example. She selectively misspelled vowels, but did not show any serial order effect. Errors occurred on vowels, irrespective of their position in the string, thus yielding a flat error distribution. Interestingly, LiB showed a length effect (the main feature of GBD) only when performance on words (and not on letters) was considered. Thus, her performance was significantly more accurate to 2-7 letter words (67% correct) than to 8-13 letter words (93% correct). However, when the percentage of correct responses was measured in terms of letters instead of words, no differences were documented between 2-7 letter words (93% correct letters) and 8-13 letter words (92% correct letters; see p.103, Table 3). In sum, her pattern of performance was consistent with highly selective damage to a specific feature of orthographic representation (vowel graphemes), in the face of spared WM mechanisms operating on such representations.

In this chapter we introduce a third dysgraphic subject, PPO, who had a selective consonant disorder but did not show specific damage to the orthographic WM.

An investigation of the spelling performance of this subject will allow us to infer that orthographic representation and WM properties can be independently affected by functional/cerebral damage, confirming the general belief that a distinction exists between cognitive representations and WM systems that maintain these representations active for further processing. Furthermore, the interactions between structural properties of orthographic representations (specifically, consonant representation) and WM properties (stability and distinctiveness) will emerge from PPO's performance in spelling tasks.

3.1 Effects of selective impairment for consonants in the absence of orthographic WM damage: predictions

In the case of selective impairment to consonant representations with spared orthographic WM, the following predictions concerning serial position effect, length effect and interaction between accuracy by position and length can be made (see Table 1).

If we accept that temporal stability and representational distinctiveness deficits are responsible for monotonic and bow-shaped distribution error curves respectively, and if these properties are not damaged, then no specific serial order effect should be observed. In fact, neither rapid decay nor crowding of representation should occur in the case of spared temporal stability and representational distinctiveness.

Length effect, a distinctive feature of GBD, is usually attributed to the fact that an already limited capacity system is further weakened due to cerebral damage, and that therefore the more elements there are in a string, the greater the error probability. In the case of selective disorder for consonants without orthographic WM problems this effect should not occur; a length effect for consonants might appear, because of a specific deficit for consonants (not because of the crowding of consonant representation). Thus, accuracy on words with the same number of graphemes but a different number of consonants (for example, *figlia*, daughter, and *tromba*, trumpet) might differ.

Finally, performance on the same consonant position for words with different numbers of consonants should be comparable, since the number of consonants in a word should not interfere with spelling accuracy in a given position. In fact, a selective disorder for consonants, with normal representational distinctiveness, should not reduce the representational space for consonants. For example, *r* in *tromba,* the second consonant in a word with four consonants, should not be spelled differently from *g* in *figlia,* the second consonant in a word with three consonants. Moreover, accuracy on consonants in the same consonant position but in a different absolute position should not differ, since temporal stability is undamaged and consequently fast abnormally decay should not occur. Thus, the subject should spell with comparable accuracy *g* in *figlia* and *r* in *tromba* (both appearing in the second consonant position), even though *r* is in the second and *g* in the third (absolute) letter position.

Table 1 summarizes the predictions that can be made in the event of damage to consonant representation without damage to the orthographic WM.

Before presenting the experimental investigation, PPO's general linguistic and spelling abilities will be described.

Table 1. Predictions in the event of damage to consonant representation without WM disorder.

Serial Order Curve	FLAT
Length Effect	CONSONANTS
Effect of Absolute Grapheme Position	ABSENT
Effect of number of Consonants on Specific Positions	ABSENT

3.2 Case PPO. Neuropsychological background

PPO is a right-handed man, 51 years old, an office worker. In August 2005 he suffered a stroke in the territory of the left middle cerebral artery, with extensive damage to the frontal, parietal and temporal lobes. Spelling and language data were collected between September and October 2006, when his disease was stable. PPO completed the same battery for aphasia (BADA) administered to GSI and CRI (see Table 2).

Across all sublexical transcoding tasks, PPO produced errors related to the target (repetition of pseudoword: *nacro* > /macro/; reading aloud: *geba* > /zeba/). Repetition of words was excellent; reading aloud was impaired, and spelling-to-dictation was even more impaired. In these tasks, segmentally related errors were produced (reading aloud: *monumenti*, monuments > /motumentri/; spelling-to-dictation: *fuoco*, fire > /fuoto/). Some morphological errors were observed in reading (*orologi*, watch > *orologio*, watches; *fucilati*, shot > *fucili*, rifles; *detestare*, to detest > *detestato*, detested).

Oral picture naming was moderately impaired. Errors on this task resulted mostly in semantic substitutions (tasca, pocket > giacca, jacket) and, with verbs, in nominalizations (segare, to saw > sega, saw; scavare, to dig > pala, shovel). Written picture naming was more impaired (the verb list was not administered); in this task PPO only produced segmental errors (*dente*, tooth > detne; *torta*, cake > trora). Auditory and visual word-picture matching was errorless, as was the auditory sentence-picture matching task, whereas the visual sentence-picture matching task was slightly below normal; errors resulted in choosing the picture representing the reversal of thematic roles (4/45, 9%).

Spontaneous speech was reduced for fluency and characterized by anomic pauses and agrammatic production. Articulatory difficulties influenced the accuracy of oral production, yielding phonetic errors. Constrained narratives were agrammatical: they were often reduced to sequences of nouns, due to difficulties with verbs and functors. The Little Red Riding Hood story told by PPO is reported below:

La favola è che Cappuccetto Rosso aspetta il lupo e poi il lupo mangia. Il lupo agguanta la nonna, cappuccetto rosso e tutti, poi..(pausa) "hei tu! E così cacciatore spara il lupo e tutti felici e contenti. Basta.

Table 2. Incorrect responses produced by PPO on the subtests of the BADA.

Phoneme Discrimination	0/60 (0%)
Auditory-visual matching	ns
Pseudo-words transcoding tasks	
Repetition	9/36 (25%)
Writing to dictation	6/15 (40%)
Delayed Copy	2/6 (33%)
Reading aloud	18/45 (33%)
Lexical decision	
Auditory	0/80 (0%)
Visual	9/80 (11%)
Word transcoding task	

Repetition	0/45 (0%)
Writing to dictation	8/46 (17%)
Delayed Copy	3/10 (30%)
Reading aloud	12/92 (13%)
Auditory word-picture match	
Nouns	0/40 (0%)
Verbs	0/20 (0%)
Visual word-picture match	
Nouns	1/40 (3%)
Verbs	0/20 (0%)
Spoken naming	
Nouns	4/30 (13%)
Verbs	11/28 (39%)
Written naming	
Nouns	15/22 (68%)
Verbs	ns
Spoken naming to definition	
Nouns	9/16 (56%)
Grammatically judgments	
Auditory	5/48 (10%)
Visual	1/24 (4%)
Sentence transcoding task	
Repetition	2/20 (10%)
Reading aloud	3/6 (50%)
Sentence picture match	
Auditory	0/60 (0%)
Visual	4/45 (9%)

3.2.1 General spelling abilities

As is clear from the BADA, PPO’ s spelling abilities are impaired. In order to explore his spelling difficulty more accurately, PPO was asked to perform a dysgraphia battery including spelling-to-dictation of words and pseudo-words and written picture naming (this is the same battery as that administered to GSI and CRI, but PPO completed the battery only once).

PPO spelled incorrectly to dictation 270/360 (75%) words and 51/60 (85%) pseudo-words. In terms of letters, he misspelled 628/2303 (27%) letters in words and 83/358 (23%) in pseudo-words ($\chi^2(1)=2.64$; p= ns). Note that the spelling difficulty of PPO did not allow him to write all 80 pseudo-words in the battery; he spelled only short pseudo-words (4, 5 and 6 graphemes length and some 7-grapheme pseudo-words).

The analyses in Table 3 show the different error types produced by PPO in dictation: he made very few lexical, morphological and PPE errors, no semantic errors and a large number of segmental errors (85% of the total errors).

Table 3. Subject PPO. Types of error in the word writing-to-dictation task.

Total Errors		**PPE**	**Morph**	**Sem**	**Word Errors**	**Nonword Errors**
	%	2	2	0	10	85
270	**N**	6	7	0	28	229

The analysis of segmental errors shows that PPO predominantly made letter omissions (335/628, 53%, *guanto*, glove > guano), followed by substitutions (181/628, 29%, *carota*, carrot > carola), letter transpositions (93/628, 15%, *scudo*, shield > sudco) and infrequent insertions (19/628, 3%, *cieco*, blind > cienco). In pseudo-word spelling-to-dictation the number of substitutions (34/83, 41%) increased relatively to omissions (37/83, 45%) and transpositions (8/83, 10%), whereas the number of insertions remained stable (4/83, 5%). In written picture naming, within incorrect letters (44/248, 18%), he produced 25 omissions (57%), 11 substitutions (25%), 4 transpositions (9%) and 4 insertions (9%) (see Table 4).

Table 4. Subject PPO. Different segmental errors produced in the Dysgraphia Battery. Percentages are in parenthesis.

	Substitutions	**Omissions**	**Transpositions**	**Insertions**
Word Dictation	181/628 (29)	335/628 (53)	93/628 (15)	19/628 (3)
Pseudoword Dictation	34/83 (41)	37/83 (45)	8/83 (10)	4/83 (5)
Written Picture Naming	11/44 (25)	25/44 (57)	4/44 (9)	4/44 (9)

Table 5 shows PPO's performance accuracy in word spelling-to-dictation tasks. Spelling was uninfluenced by abstractness/concreteness, or frequency of usage. A significant grammatical class effect ($\chi^2(3)= 11.17$, p=.010) was observed, as nouns and adjectives were spelled more accurately than verbs and functors.

PPO's letter accuracy was not significantly affected by length ($\chi^2(2)= 5.27$, p= ns) and his spelling was characterized by a contrasting error distribution on consonants and vowels. This difference was consistent across tasks (see Table 6).

On the whole, PPO wrote incorrectly 742/2909 (25%) letters. He misspelled 643/1492 (43%) consonants and 108/1417 (8%) vowels ($\chi^2(1)= 475.71$; p<.0001). In other words, 87% of his spelling errors affected consonants, and 13% vowels.

Table 5. Subject PPO. Summary of incorrect responses (letters) produced in word spelling to dictation (n=360).

Frequency	
High frequency word	97/346 (28%)
Low frequency word	87/343 (25%)
Abstractness/Concreteness	
Abstract words	37/97 (38%)
Concrete words	28/97 (29%)
Grammatical class	
Nouns	23/121 (19%)
Adjectives	21/125 (17%)
Verbs	38/127 (30%)
Functors	38/121 (31%)
Length	
4-5 letters	138/603 (23%)
6-7 letters	227/899 (25%)
8 and more letters	225/797 (28%)

Table 6. Subject PPO. Error rate on consonants and vowels in different spelling tasks (number of incorrect consonants/total consonants and number of incorrect vowels/total vowels are considered). Percentages are in parenthesis.

	Incorrect consonants	**Incorrect vowels**
Words Dictation (n=360)	532/1181 (45)	96/1122 (9)
Pseudowords Dictation (n=60)	77/184 (42)	6/174 (3)
Written Picture Naming (n=40)	37/127 (29)	7/121 (6)
Total	646/1492 (43)	109/1417 (8)

Table 7. Subject PPO. Distribution of consonants and vowels in the corpus, compared to the distribution of the errors on consonants and vowels (percentages are in parenthesis)

cons num / total letters num	**cons errors / total errors**	**vow num/ total letters num**	**vow errors/ total errors**
1181/2303 (51)	532/628 (85)	1122/2303 (49)	96/628 (15)

The comparison between the incidence of incorrect consonants and vowels and the total number of consonants and vowels in the corpus (Ward & Romani, 2000) confirmed a selective deficit for consonants (see Table 7). PPO misspelled more consonants than vowels, relative to the total number of consonants and vowels in the corpus ($\chi^2(1)= 225.72$; $p<.0001$).

When spelling consonants, PPO frequently left a blank space or marked slots for omitted consonants. For example *bando,* proclamation, was spelled *_a__o*. Moreover, PPO, as also reported in other dysgraphic subjects (Katz, 1991; Miceli, et al., 2004, Morton, 1980; Ward and Romani, 1998) did not always spell letters from first to last. Sometimes, he wrote some letters and left one or more blank spaces, which he subsequently tried to fill, in some cases successfully (*paura* (fear): *_aura* -> *paura*; *bugie* (lies): *_u_ie* -> *bugie*), in others incorrectly (*fiume* (river): *fiu_e* -> *fiune*) or incompletely (*loquace* (talkative): *lo_a_e* -> *lo_ace*).

PPO’s locus of impairment

In summary, PPO’s performance on spelling tasks presented the following features: a grammatical class effect, without frequency or abstractness effects, no semantic errors in written picture naming or writing-to-dictation, and rare lexical substitutions. All these features make an impairment to the orthographic output lexicon unlikely. Moreover, he showed no length effect and although performance in spelling-to-dictation of words and pseudo-words was comparable, he failed to spell altogether 25% (20/80) of the pseudo-words contained in the battery, suggesting a problem in the sublexical route. A possible post-graphemic buffer deficit can be excluded, given the specificity of the disorder for consonants, the high rate of substitutions (91%) that respect the C/V status, and the results on the confusion matrix for substitutions (see Appendix A). Finally, the type of errors and the disproportionate deficit to one type of grapheme (consonants) suggests a disorder at the segmental level. In fact, the C/V status of a word is specified at the post-lexical level, when a representation is elaborated in terms of single letters rather than of whole words (Caramazza & Miceli, 1990).

In the next section, we will present PPO's spelling data with specific regard to a) the serial position effect, b) the length effect and c) the effects of consonant length and absolute position on accuracy by consonant position. The results of these analyses demonstrate that PPO's deficit affects consonant representation, whereas the orthographic working memory system is spared.

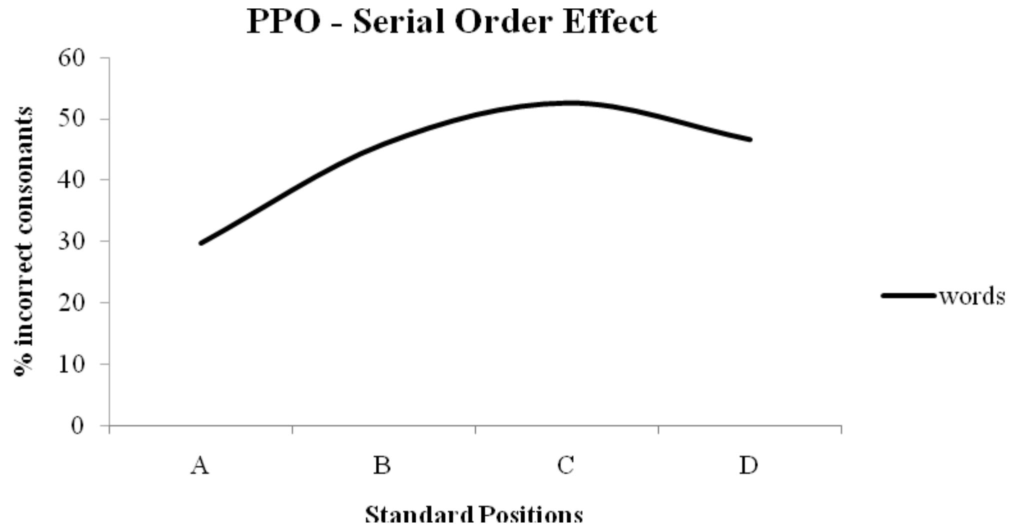
3.3 Serial position effect

PPO mostly produced complex errors (the response deviated from the target by more than one letter). Uninterpretable errors were excluded from the analyses. We decided to consider as uninterpretable all responses in which more than three types of errors occurred (e.g., *antichi*, ancients -> *avvini*; *comincia*, she starts -> *occila*). Overall, 501 errors out of 532 involving consonants in word spelling-to-dictation were retained for analysis.

Macthynger and Shallice's method (see Chapter 2) was used for normalizing words of different length. We normalized errors across 4 positions because 4-consonant words were the most represented in the corpora spelled by PPO.

Error percentages on consonants across the four normalized positions were 30, 46, 53 and 47, respectively (see Figure 1). The curve was not a monotonic function, because the proportion of errors was lower in the last position; and it was not a true bow-shaped function, because the error rate was similar across positions, except from the first to the second position, where the errors increased significantly (this point will be discussed later). As already mentioned, there is another case in the literature with selective disorder for vowels with a flat error distribution (Cotelli, et al., 2003). However, for PPO there is a substantial difference: the curve corresponds to the distribution of errors on consonants.

Figure 1. Subject PPO. Spelling accuracy as a function of the serial letter position. Different letter lengths are normalized to four positions on the basis of the scheme developed by Macthynger and Shallice (2009).



3.4 Length effect

A crucial aspect of PPO's performance on the dysgraphia battery was the lack of a length effect (see Table 5). Although he spelled consonants significantly worse than vowels, and errors were mainly segmental, PPO did not display the critical feature of GBD. In order to evaluate this error distribution more in depth, response accuracy for each length, in spelling-to-dictation task, on words that contained from 4 to 11 graphemes and from 2 to 5 consonants was calculated. The corpus spelled by PPO contained 360 words.

Table 8 and Figure 2a show the proportion of incorrect letters produced by PPO as a function of the number of graphemes in the stimulus. They demonstrate that performance was not influenced by number of letters (consonants and vowels) in the words. In fact, error percentage increased in words containing from four to five letters, then decreased in 6-letter words, increased again in 7-letter words and slightly decreased for words of 8 and more letters. At any rate, there was a significant difference across words of 4 and 8 and more letters ($\chi^2(4) = 39.52$; $p<.0001$). Table 9 and Figure 2b show the proportion of incorrect consonants produced by PPO as a function of the number of consonants in the stimulus. In this case, 2-consonant words were produced more accurately than 3 and 4-5 consonant words ($\chi^2(2)= 13.24$; $p=.001$).

Table 8. Subject PPO. Incidence of incorrect responses in word spelling-to-dictation as a function of grapheme length.

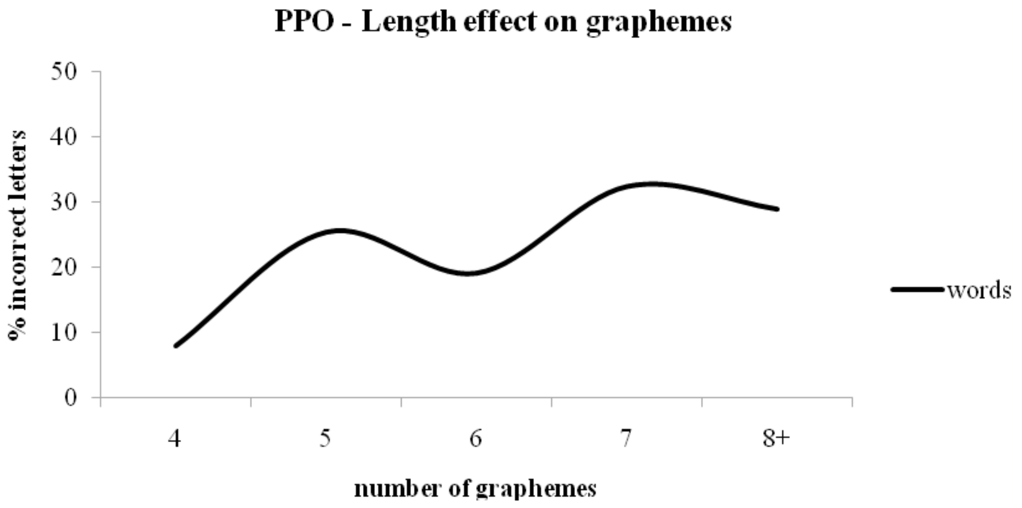
Graph length	**# words**	**# letters**	**# incorrect letters**	**%**
4	22	88	7	8
5	103	515	131	25
6	81	486	93	19

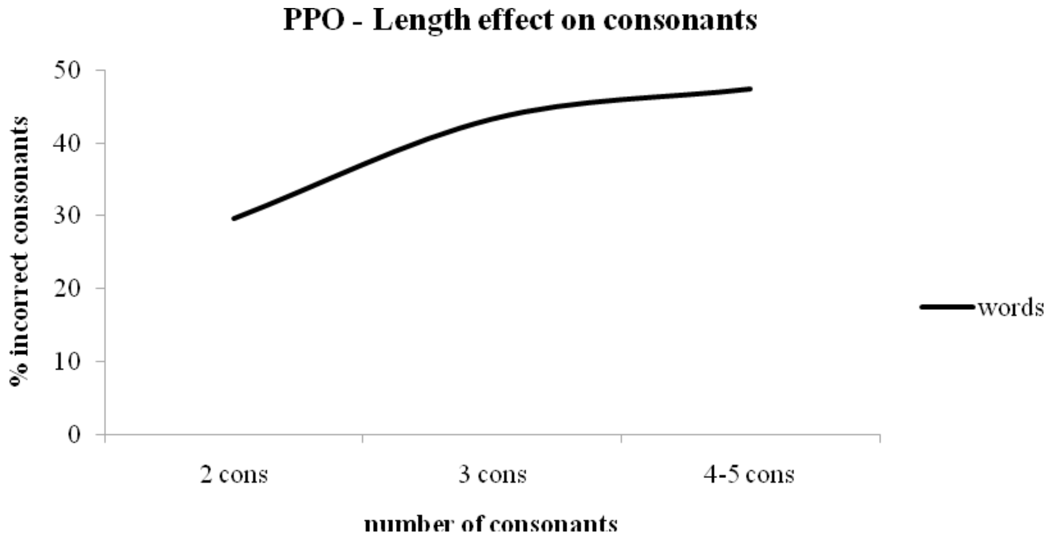
7	59	413	134	32
8+	94	801	232	29

Table 9. Subject PPO. Incidence of incorrect responses in word spelling-to-dictation as a function of consonant length.

Cons length	**# words**	**# consonants**	**# incorrect consonants**	**%**
2 cons	64	128	38	30
3 cons	151	453	196	43
4-5 cons	130	549	260	47

Figure 2. Subject PPO. Incidence of incorrect letters in words of different grapheme length (a) and incidence of incorrect consonants in words of different consonant length (b).

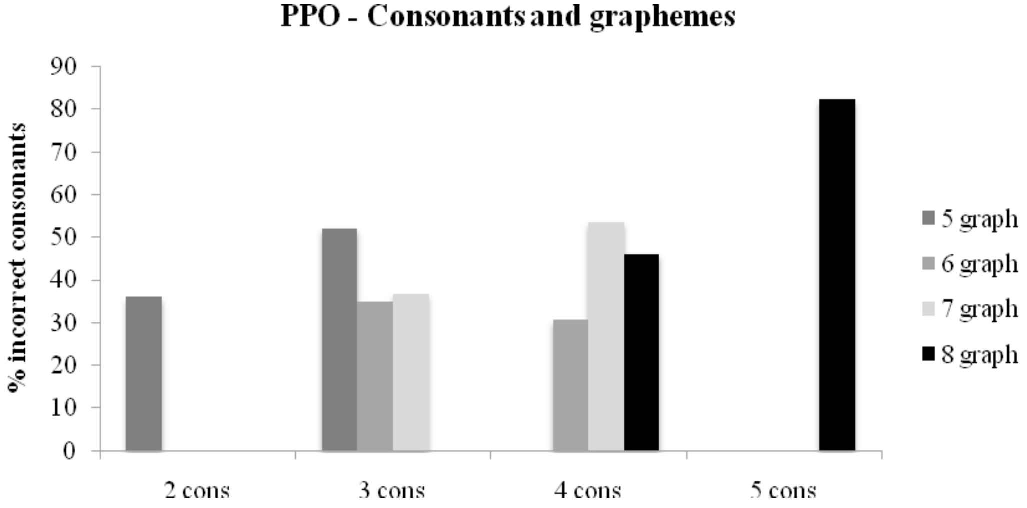




PPO's spelling accuracy looks to be constrained mostly by the number of consonants. Moreover, when the effects of consonant and of grapheme length were analyzed on words with same number of graphemes but a different number of consonants, and vice versa, this pattern was confirmed.

Given that PPO made errors mainly on consonants (87%), accuracy was measured by calculating the number of errors on consonants/number of total consonants present in each word group. As we can see in figure 3, PPO showed a significant tendency to spell less accurately words with the same number of graphemes but a larger number of consonants. For instance, in 5-grapheme words PPO made more errors on 3-consonant words than on 2-consonant words ($\chi^2(1)=6.02$, $p=.014$); in 7-grapheme, 3-consonant words he spelled incorrectly 23/63 (37%) consonants, whereas in 7-grapheme, 4-consonant words he misspelled 77/144 (53%) ($\chi^2(1)=5.05$, $p=.024$). A comparable pattern was observed on 8-grapheme words: he spelled incorrectly 92/200 (46%) consonants in 4-consonant words and 37/45 (82%) in 5-consonant words (χ^2 (1)= 19.33, $p<0001$). However, this pattern was not repeated for 6-grapheme words, in which the number of consonants did not affect spelling performance (68/195 or 35% of errors in 3-consonant words, 11/36 or 31% of errors in 4-consonant~~s~~ words; χ^2 (1)= 0.1; p= ns).

Figure 3. Subject PPO. Error rate on consonants in words with different number of graphemes and consonants.



3.4.1 Regression analyses and Monte Carlo simulation

PPO’s performance in 6-grapheme words contrasted with the trend observed with the other group of words (see Figure 3). To better understand these results we carried out a logistic regression on all incorrect responses (that is, not only on 5-8 grapheme words and 2-5 consonant words) and subsequently verified the statistical reliability of the results by regression analyses with the Monte Carlo resampling procedure (see Chapter 2, for an explanation).

Across two models, Consonant Length and Letter Length, in PPO the Consonant model represented the best fit for the data. The likelihood that each consonant would be produced incorrectly was determined by the number of consonants in the target, rather than by the number of graphemes (Letter Model, r^2= .024; Consonant Model r^2= .04).

To determine the stability of these differences a Monte Carlo Analysis was performed:

(1) 500 letters from the responses were randomly selected (Total: 1182);

(2) Simple logistic regression with Consonant and Letter Length regressors on this subset of data was calculated;

(3) The model with the better fit for the random subset of data was determined;

(4) This procedure was repeated 10,000 times.

The results for PPO were clear. Consonant length was a better fit than Letter length for ~99% of the random subsets of data. Therefore, the Monte Carlo analysis for PPO was consistent with the tendency reported in Figure 3: accuracy depends on the number of consonants in the target.

3.5 Effects of consonant length and absolute position on accuracy by consonant position

The results given in the previous section suggested that in PPO the error rate increased in proportion to the number of consonants in a word.

If PPO had a consonant distinctiveness deficit, then consonants in medial positions should be more prone to errors, because a greater number of flanking letters decreases distinctiveness. This is not the case in PPO (Figure 1).

In this subject, what are the predictions on accuracy for consonants occupying specific positions in the target string?

First, since PPO does not have a temporal stability deficit, spelling accuracy on consonants that occupy the same (relative) consonant position but a different absolute position should not differ. This means that the *v* in *tavolo*, table, should not be spelled better than the *s* in *odioso*, hateful (both are second consonants, but occupy the third and the fifth absolute positions, respectively).

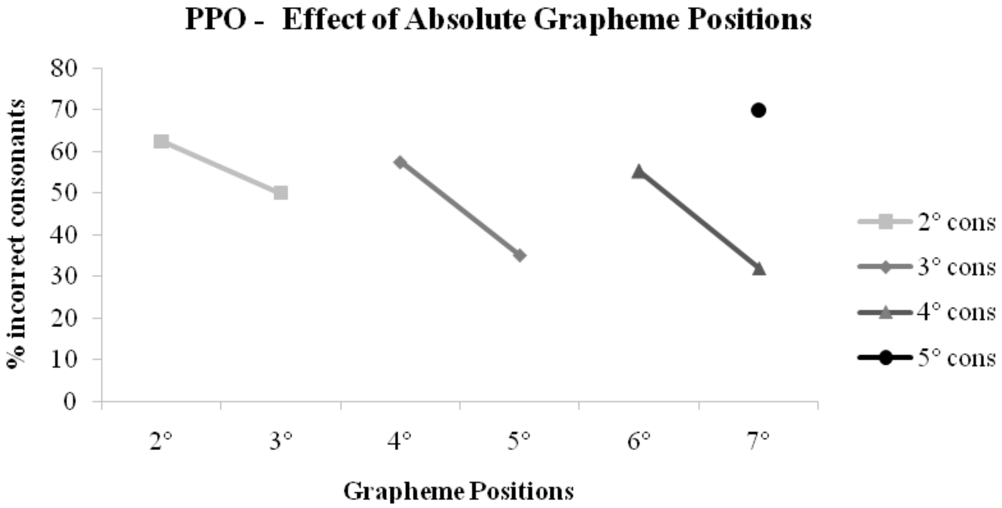
In order to obtain a more stable measurement of the length effect on specific positions, for each word length only the orthographic structures most represented in PPO's corpus (that is, more numerous) were considered. For example, in the corpus of 5-grapheme words collected from PPO the following four orthographic structures were considered: CVCCV (*padre*, father), n=38; CVVCV (*ruolo*, role), n=21; CCVCV (*creta*, clay), n=12; CCVGV (*prezzo*, price), n=10.

Figure 4 and Table 10 (the latter duplicates the data presented in Figure 4) show that PPO's performance on a specific consonant position was not influenced by its absolute position. Curiously, he made more errors on consonants occupying absolute positions nearer to the beginning of the word. For example, the performance on third consonant in sixth grapheme position was significantly better than in fifth grapheme position ($\chi^2(1)=7.95$, p=.004), and the same (statistically insignificant) trend was observed in spelling the fourth consonant ($\chi^2(1)=3.32$, p=ns). The second consonant was spelled comparably in second (20/32, 63%) and third (75/150, 50%) absolute position ($\chi^2(1)=1.65$, p=ns). How can these results be explained?

Table 10. Subject PPO. Error rate on consonants occupying one position as consonant and one position as grapheme. For example, in the word tavolo, table, the consonant v occupies the cell corresponding to the second consonant and to the third grapheme. Words from 5 to 8 graphemes are considered.

5-8 GRAPH	**PSN GRA**		**PSN CON**		
		2°	**3°**	**4°**	**5°**
# cons err	**2°**	20			
	3°	75			
	4°		65		
	5°		21		
	6°			16	
	7°			8	7
	2°	32			
# cons	**3°**	150			
	4°		113		
	5°		60		
	6°			29	
	7°			25	10
	2°	63			
% err	**3°**	50			
	4°		58		
	5°		35		
	6°			55	
	7°			32	70

Figure 4. Subject PPO. Error rates on consonants that appear in the same consonant (relative) position but in different letter (absolute) positions.

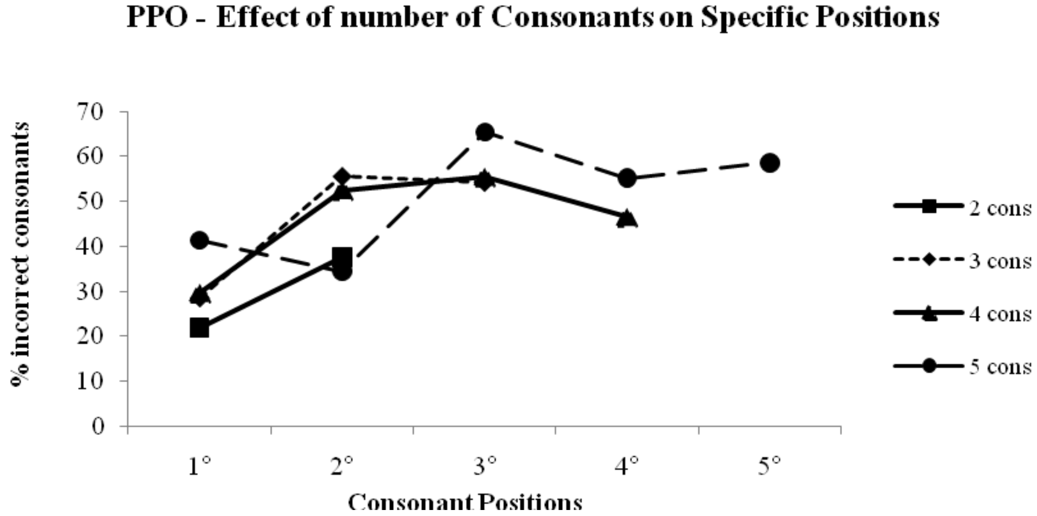


Let us consider performance on the third consonant in the fourth and fifth absolute positions (the only statistically significant result). In this case, the third consonant was spelled better when it occupied the fifth absolute position. Across the syllabic structures chosen for this analysis, the third consonant in the fifth position occurred mainly in simple-CV words (45/60 or 75% of times, CVCV**C**V), whereas the third consonant in the fourth absolute position occurred only in complex-CV words (113/113 or 100%, for example, CVC**C**VV). Thus, PPO's tendency to make more errors on absolute positions nearer to the beginning of the word could arise from a syllabic structure effect: positions occupied by a simple syllable with a singleton consonant (CV) have a greater probability of being correctly spelled, as compared to the positions occupied by a syllable with a consonant cluster as the onset (eg, CCV).

A second analysis was conducted on the consonants that occupy specific positions in the string in words with different number of consonants. The incidence of errors on specific positions in words that contained from two to five consonants was calculated. The prediction in this case was that the number of consonants should not affect accuracy in a given position. In fact, if it is true that PPO does not have a representational distinctiveness deficit, performance on specific positions should not change with increasing numbers of consonants in the word.

Data in Figure 5 demonstrate that the number of consonants did not affect PPO's spelling performance on a specific position. For instance, the error rate on the third consonant was the same in words with 3 (82/151, 54%) and 4 consonants (56/101, 55%), ($\chi^2(1)$= 0.03, p=ns) and no significant difference was found between these words and 5-consonant words (19/29, 66%; $\chi^2(2)$= 1.25, p=ns). Again, on the fourth consonant PPO produced 47/101 (47%) errors in 4-consonant words and 16/29 (55%) in 5-consonant words ($\chi^2(1)$= 0.67, p=ns). A significant error increase was observed only on the second consonant, between 2- (24/64, 38%) and 3-consonant words (84/151, 56%; $\chi^2(1)$= 5.91, p=.015), but error rate on this position did not increase for 4-consonant words (53/101, 52%) and it even decreased for words with 5 consonants (10/29, 34%).

Figure 5. Subject PPO. Error distribution on consonants in different relative (consonant) positions, as a function of consonants number in the word.



3.6 Discussion

PPO presented with a disproportionate deficit to consonant representations (87% of his errors regarded consonants) and most of his errors (85%) consisted of non-words. These two features are normally attributed to a deficit at the level of orthographic WM, whose role is to keep word-format graphemic representation active. However, PPO showed a length effect, a distinctive feature of GBD, on consonants (and not on graphemes) only when a more accurate analysis was conducted.

After having excluded deficits involving earlier or later processing stages, PPO's locus of damage was identified at the graphemic level, at which word representations have to be elaborated in terms of single graphemes, before their transformation into written words. PPO suffers from a categorical disorder for consonants that can be localized at the graphemic level of the spelling process.

In the experimental section it emerged that:

1) The probability of producing an error was independent of the position of a letter. This resulted in an almost flat error distribution (Figure 1);
2) The probability of making an error depended on the number of consonants in a word. This yielded a length effect on consonants (Figure 3 and Monte Carlo simulation);
3) The number of consonants did not affect spelling accuracy in specific consonant positions (see Figure 5).

The first result established that the probability of producing an error was independent of the letter position. In the previous chapter, CRI's bow-shaped error curve was interpreted as the effect of a crowding of consonant representations, produced by damage to representational distinctiveness, making the medial position more prone to error. By contrast, GSI's monotonic curve was attributed to a rapid decay of consonant representations, caused by a temporal stability deficit. PPO's error distribution was different from those of the two subjects described in the previous chapter. Indeed, PPO showed neither a bow-shaped nor a monotonically increasing serial order distribution. There was a significant error increase from first to second position, but performance was comparable on the second and on the following positions. The significant difference between the first and the other positions might be explained by the special status of the first letter in a word, whose representation is stronger than that of the other letters in the string (see Papagno & Capitani, 1988, for a case of anomia with sparing of first letter knowledge; and Brown, 1991, for a review on the TOT phenomenon (see also, Abrams, White, & Eitel, 2003; Semenza & Sgaramella, 1993). For example, Miozzo & Caramazza (1997) reported that their subjects, in a forced-choice condition, correctly produced the first phoneme of the noun in the TOT state 76% of the times. This result confirmed the critical role of the first letter in lexical access (the subject knows the first letter of a noun but cannot name it). Thus, in the event of a spelling disorder, caused by cerebral damage, first letter representation could be more resistant to damage.

It is important to underline that the error distribution curve in Figure 1 only concerned consonants; consequently, the explanation just provided for different performance on the first letter cannot be relevant for words beginning with a vowel (e.g., *azione*, *ignoto*, *audace*, etc.). Removing these words from the analyses (40/360, 11%) the error distribution curve essentially did not change: the error rate produced by PPO on words beginning with a consonant was 29, 44, 52 and 46% for the four positions, respectively.

In sum, if it is accepted that the bow-shaped curve results from a representational distinctiveness deficit and that the monotonic curve arises from a temporal stability deficit, PPO's error distribution suggests that in his case stability and distinctiveness of the elements of the orthographic string WM were spared.

A crucial point of PPO's performance was the selective difficulty with consonants. Data in Tables 6 and 7, showing the proportion of errors on consonants and vowels in different spelling tasks; Figure 3, where a significant tendency emerged to make more errors on words with more consonants but with the same number of graphemes; and the analyses with the MonteCarlo simulation, in which for 99% of the random subset of data the Consonant Model was a better accuracy predictor than the Letter Model, confirmed this point.

On the basis of our previous proposal, these results would be consistent with a representational distinctiveness deficit. However, a different hypothesis must be considered for PPO. He showed no effect of position (his error distribution curve was flat). This is not consistent with damage to representational distinctiveness, as in this case a bowed curve is expected due to greater crowding of consonants in the medial position. Thus, in the absence of a coherent result on the serial order effect, the length effect must be interpreted differently. PPO has a greater probability of making an error in words with more consonants because of his specific difficulty with consonants. The effects of consonant length and of the absolute position of letters (Figures 4 and 5) are consistent with this proposal. PPO's performance differed from that of CRI, since the number of consonants in the word did not affect his accuracy on a given position (Figure 5). As already mentioned, in our hypothesis, a representational distinctiveness deficit should cause an increase in errors in the same consonant position in words with more consonants, due to the crowding of consonant representations. Thus, PPO's error distribution curve and the effect of consonant length on accuracy by consonant position did not meet the criteria for a representational distinctiveness deficit.

Finally, a possible deficit of the temporal stability of orthographic representations can be excluded because it should produce an increase in errors on consonants in more advanced absolute letter positions in the string. PPO's performance was not consistent with this prediction (see Figure 4). Indeed, he displayed an opposite trend, as he tended to spell more accurately consonants occupying absolute positions that were more distant from the beginning of the string. This pattern contrasts with GSI's performance, who spelled, e.g., the second consonant of a word more accurately when it appeared in second absolute position (e.g., t in stadio, stadium) than when it appeared in third absolute position (e.g., t in patria, home country); and this pattern is also different from that of CRI, who spelled the second and third consonants with the same accuracy when they occupied different absolute positions. As already mentioned, the significant effect found on the third consonant in the 4th and 5th absolute positions could arise from the influence of syllabic structure. Moreover, PPO showed a clear syllabic structure effect: in simple-CV words he produced 42/67 (63%) errors, whereas he incorrectly spelled 85/102 (83%) of complex-CV words ($\chi^2(1)= 9.23$, $p=.002$). Furthermore, a finer-grained analysis that considers error types on singletons (CV) and clusters (CCV) shows that PPO made 38% (98/255) omissions and 54% (138/255) substitutions on singletons, but 70% (185/264) and 21% (55/264) on clusters. For example, in a word like *culturale*, cultural, PPO was more likely to substitute the consonant *r* or the last *l* (two singletons), and to delete the *l* or the *t* of the cluster *lt*. In other words, he tended to preserve simple-CV structure and to simplify more complex syllabic structures.

In sum, since PPO did not show either a monotonic error function or a length effect on graphemes or an effect of absolute letter position on consonant accuracy, a temporal stability deficit can be excluded for this subject.

Another case in the literature showed segmental errors, with an ambiguous length effect and a flat distribution error curve: subject LiB (Cotelli, et al., 2003). Interestingly, this subject suffered from a selective spelling impairment for vowels, which also extended to reading: 84% (112/133) of her errors affected vowels and 16% (21/133) involved consonants. Moreover, LiB's error pattern in reading was very similar to that observed in spelling: almost all errors consisted of letter substitutions. This result strengthens the idea that LiB suffered from a categorical impairment of orthographic vowels, which appears regardless of the vowel position within the string and of the length of a word.

PPO too showed a similar pattern in reading pseudo-words. Almost all his errors involved consonants: out of 22 incorrect letters, 4 were vowels (18%) and 18 consonants (82%). Unfortunately, the number of errors produced by PPO in reading was very small, and does not allow strong claims.

In conclusion, for PPO the effects of serial order, length, and number of consonants, and the effect of absolute grapheme position on accuracy on specific consonant positions fit very well with the predictions in the event of selective impairment for consonants in the face of normal orthographic WM.

Chapter 4

General Discussion

The general aim of the present thesis was to study graphemic-level representations in the spelling process. In particular, the research aimed at clarifying the processes involved in graphemic buffering and the relation between orthographic representations and WM in spelling. Using the framework of cognitive neuropsychology, we contrasted the spelling performance of three dysgraphic subjects, all presenting with a selective deficit for consonants. In two cases the disorder co-occurred with two different forms of damage to the orthographic WM (Chapter 2), in the third case the disorder for consonants occurred in isolation, leaving the orthographic WM unimpaired (Chapter 3).

The following sections summarize and discuss the implications of these results.

4.1 The properties of orthographic working memory

Chapters 2 and 3 addressed the problem of variability across Graphemic Buffer Disorder cases. In the literature, the spelling performance of these subjects, in spite of some common features, was characterized by different error patterns concerning the position of the errors in the string (serial order effect), the degree of damage to the various elements of orthographic representation (consonants, vowels, geminate) and the distribution of error types (for a review, see Miceli & Capasso, 2006).

We presented cases of GSI, CRI, and PPO, whose spelling performance was characterized by some features that are usually attributed to a Graphemic Buffer Disorder: lack of influence of lexical factors (except for the grammatical class effect shown by PPO), modality invariance, segmental errors and selective impairment for consonants. However, these subjects presented different results concerning length effect and error distribution, thus revealing the presence of distinct disorders.

GSI showed a monotonic error curve (Figure 1a, Chapter 2); the length effect was determined by the number of graphemes in the to-be-spelled string (Figure 4a, Chapter 2); in his case, accuracy in writing consonants was constrained by the absolute position of consonants in the string (i.e., by whether a given consonant it is the second, third, fourth, etc. grapheme in the target) (Figure

5, Chapter 2). For CRI, errors clustered at the centre of the word, yielding a bowed error distribution curve (Figure 1b, Chapter 2); his performance was affected by the number of consonants in the word (Figure 4b, Chapter 2), and the error rate on the same consonant position was influenced by the number of consonants in the string (i.e., by whether the target contained three, four, five, etc. consonants) (Figure 6b, Chapter 2), and regardless of its absolute (grapheme) position (Figure 5b, Chapter 2). The results of PPO contrasted with those obtained by GSI and CRI. He produced a flat error distribution (Figure 1, Chapter 3) and fared worse on words with larger numbers of consonants (Figure 3, Chapter 3), but the number of consonants in a word did not significantly influence his accuracy on a given consonant position (Figure 5, Chapter 3); finally, he did not show any effect of absolute grapheme position (Figure 4, Chapter 3).

Table 1 summarizes the results for GSI, CRI and PPO.

Table 1: Summary of results obtained by GSI, CRI and PPO

	GSI	**CRI**	**PPO**
Serial Position Curve	Monotonic	Bow-shaped	Flat
Length effect	Graphemes	Consonants	Consonants
Effect of Absolute Grapheme Position	Present	Absent	Absent
Effect of number of Consonants on Specific Position	Absent	Present	Absent

We suggested that these patterns arise from different functional deficits. Specifically, all three subjects had a deficit concerning consonant representation. In the case of PPO, this deficit is isolated. In the case of GSI and CRI, an additional impairment involved two WM properties, which are important for correct written production: temporal stability and representational distinctiveness. In order to spell correctly, a temporally stable and distinctive representation of the graphemes comprising the to-be-spelled string is required. The pattern of performance observed for GSI and CRI can be accommodated by assuming a temporal stability deficit and a representational distinctiveness deficit, respectively. In the case of GSI, a temporal stability deficit resulted in the rapid decay of the orthographic representation. Since the orthographic representation decayed rapidly after each letter (consonant and vowel) was produced, errors increased monotonically; furthermore, even though GSI misspelled only consonants, the probability of making an error depended on the number of letters in a word, and accuracy on the same relative consonant position depended on its absolute position. In CRI's case a representational distinctiveness deficit resulted in crowding of the representation elements. Errors concentrated at the centre of the string because crowding increased with the number of letters; the length effect was determined by the number of consonants, because of increased crowding of consonant representation; finally, errors on the same consonant position increased in words with more consonants because the consonant representational space was reduced.

Thus, rather than suggesting a single mechanism explaining the functioning of WM as a whole, we proposed two different mechanisms to account for the performance of GSI and CRI – decay and crowding of graphemic representations – consistent with the two functions of orthographic WM: keeping the letters within a string temporally stable and well-distinct. This explanation is consistent with the hypothesis that multiple factors rather than a single mechanism limit working memory capacity (Miyake & Shah, 1999).

Since PPO did not display clear signs of rapid decay or crowding of representation elements, we can assume that his orthographic WM was spared (or, at least that stability and distinctiveness were not impaired). In fact, the position of errors in the string indicated that PPO had the same probability of making an error in the initial, medial or final part of the word. Furthermore, the lack of effects of absolute grapheme position and of the number of consonants in a specific position confirmed that neither rapid decay nor crowding of representation affected his spelling accuracy.

Our findings demonstrated that the graphemic level of the spelling process can be degraded in different ways and that distinct type of spelling patterns “may result from the loss of particular kinds of information held in the graphemic buffer” (Katz, 1991).

4.2 Representations and Working Memory

The comparison between these three subjects was interesting because all three suffered from selective disorders for consonants but their spelling patterns were very different. From fine-grained analyses, an interaction emerged between consonant representations and the orthographic WM system that processes them, when a lexical entry must be converted into a specific letter-shape or letter-name.

GSI flawlessly spelled vowels and his errors exclusively concerned consonants (99%). Monotonic error increase only regarded consonants. For this subject, rapid decay of representation, due to temporal stability deficit, selectively affected one element of graphemic representation (consonants).

CRI showed the same representational disorder, but his spelling pattern was completely different from that of GSI. In his case, consonant damage was associated with an impairment of the representational distinctiveness property rather than to the temporal stability.

Finally, analyses of PPO's spelling performance revealed a specific problem with consonants, but no sign of rapid decay or reduced distinctiveness. PPO presented a disorder of orthographic structure, which interacted with unimpaired WM properties.

Table 2 describes the possible interactions between representation and WM in six subjects with graphemic buffer disorder. In addition to the three patients studied in this project, three other cases are reported (subject LiB of Cotelli, et al., 2003, subject LB studied by Caramazza & Miceli, 1990, and subject HR, presented by Katz, 1991). Three main patterns emerge. First, the spelling patterns of GSI and CRI result from the interaction between damaged consonant representation and two impaired WM properties (stability for GSI, distinctiveness for CRI). Second, the independence between the structure of orthographic representation and the WM properties is consistent with the performance of subjects PPO and LiB, where a structural disorder (respectively, for consonants and vowels) occurs with a spared WM (they showed no length effect and their curves were flat). Third, comparable error numbers for consonants and vowels in LB and HR and their error distribution (bow-shaped for LB, monotonic for HR) can be interpreted as the result of damage to representational distinctiveness and to temporal stability, respectively, affecting both consonants and vowels.

Table 2: Interaction between Consonant and Vowel representations and Temporal Stability and Representational Distinctiveness in six patients with graphemic buffer disorder. The respective error distribution curves are reported.

✓= Spared ✗= Damaged

CURVES	Flat	Flat	Bowed	Bowed	Monotonic	Monotonic
CASE	LiB	PPO	LB	CRI	HR	GSI
CONSONANTS	✓	✗	✗	✗	✗	✗
VOWELS	✗	✓	✗	✓	✗	✓
STABILITY	✓	✓	✓	✓	✗	✗
DISTINCTIVENESS	✓	✓	✗	✗	✓	✓

4.3 Relations with other proposals on graphemic-level functioning

The proposal of an orthographic buffer divided into several components has already been presented in the literature. Rapp e Kong (2002) claimed that buffering consists of at least of two main operations: activation of the graphemes constituting a word, and selection of graphemes for the temporally ordered production of nouns or shapes of letters (for a similar proposal, see also Kan, et al., 2006). What kind of relation could connect these operations (activation and selection) with the WM properties suggested in this work (stability and distinctiveness)?

It would be plausible to assume that temporal stability is a property linked to the activation component, given that activation of orthographic representations must be adequate and sustained (temporally stable); whereas representational distinctiveness could be relate to the selection component, because letters have to be clearly distinguished from each other to be correctly selected. Therefore, our proposal, in addition to being successful in explaining the data of three dysgraphic subjects reported in this work, is consistent with, and enhances, a previous suggestion on orthographic WM separation.

This two-component view of the buffering process (activation and selection) was based on the competitive queuing architecture proposed by Houghton, Glasspool, & Shallice, (1994) and Shallice, Glasspool, & Houghton (1995). In this model essentially two components were present: an activation mechanism, responsible for setting up the appropriate activation level for each letter, and an output mechanism selecting the most active grapheme.

In the CQ model each element of the string has a specific activation gradient, and the letter that must be produced has the highest level of activation. Depending on this activation level, letters active at the same time compete for output. The selection process of the dominant response resolves the competition between this set of responses. After selection, the winning response is inhibited.

A difficulty about CQ models concerns the problem of taking into account the effect of CV-status. Some of these models reject the distinction between consonants and vowels (Houghton, et al., 1994; Shallice, et al., 1995). These models cannot reproduce neuropsychological data, specifically in cases in which a pattern performance results from damage to a single grapheme type (consonants vs vowels). In a late version of this model (Glasspool & Hougthon, 2005), information about the CV-status of a letter was represented in an abstract “CV template”, separated from the letter identity (the authors did not rule out the possibility that letters have a distributed internal representation, including a CV dimension). Selective damage to consonants or to vowels was simulated by lowering the level of activation of the segments marked as consonants or as vowels in the word. In the simulation, however, all letters in the string were spelled incorrectly, consonants relatively better than vowels or vice versa, but never did a grapheme type prove to be exclusively damaged. Thus, the model was not able to predict the error pattern in which a complete dissociation between consonants and vowels was present (Miceli, et al., 2004). Thus, even though connectionist models like CQ specify the possible mechanisms that process orthographic representation they cannot explain patterns of performance that can best be interpreted by assuming damage to symbolic (CV-status) aspects of graphemic representation. In other words, if a distinction between consonants and vowels is not included, the model cannot explain the empirical data. When this distinction is considered and a CV template that marks graphemes as consonants or vowels is incorporated, then the CQ model accommodates the empirical observations. However, in this case the CQ model was adjusted by inserting representational assumptions, which are typical of a cognitive model like that originally proposed by Caramazza & Miceli (1990) (here, figure 3, Chapter 1).

Finally, concerning the lexical or segmental origin of the error curves, findings of this research demonstrate that monotonic, bow-shaped and flat error distributions could arise from graphemic level.

In fact, GSI, CRI and PPO's patterns of performance were attributed to distinct deficits, but all arising at the segmental level of the spelling process. According to our proposal, an undamaged orthographic lexical representation arrives at the segmental level, where its consonant elements cannot be processed correctly due to representational damage. This representation is subsequently processed correctly (case PPO), or its processing can be further disrupted by damage to the representational distinctiveness (case CRI) or to temporal stability (case GSI).

Future research should gain better knowledge about the origin of the other sources of variability in the graphemic buffer disorder. It would be interesting to discover how other dimensions of orthographic representations (gemination and syllabic structure) interact with the two WM properties described here. Furthermore, computational work could draw from empirical studies like the present project, in which explicit assumptions on the properties of the WM contributed to the further understanding of the processes underlying the spelling system.

Conclusions

Four main facts were confirmed in this thesis:

1) The so-called graphemic buffer disorder does not reflect a homogeneous cognitive deficit;
2) Orthographic WM can be divided into subcomponents;
3) Orthographic representations held in the buffer are independent of the processing they undergo in the buffer;
4) Representation and WM interact in the spelling process.

Our proposal accommodates some elements of variability that emerge in the GBD literature. From results in spelling tasks of two dysgraphic subjects we proposed that the two main distribution error curves (monotonic and bow-shaped) arise from damage to distinct WM properties, temporal stability and representational distinctiveness. We demonstrated the distinction between segmental representations and WM systems that process them, describing a case of orthographic structure disorder without orthographic WM deficit. Finally, the error patterns of GSI, CRI and PPO showed the interaction between a specific grapheme type (consonants) and different properties of the orthographic WM (temporal stability and representational distinctiveness).

APPENDIX

Confusion matrix of error consonant in word spelling-to-dictation.

Letters were spelled in uppercase. The rows report the substitution number for each target consonant. Percentage of substitutions of target consonant and percentage of times in which a consonant was spelled in place of the target consonant are showed.

PPO'S CONFUSION MATRIX (n=360)

RESPONSE

	# Letters	**TARGET**	**b**	**c**	**d**	**f**	**g**	**h**	**l**	**m**	**n**	**p**	**q**	**r**	**s**	**t**	**v**	**z**	**# Sub**	**% Sub**
	31	**b**	0	1	1	0	0	0	0	0	1	0	0	0	0	0	1	0	4	13
	143	**c**	0	0	0	0	1	0	0	0	0	1	1	1	3	0	0	0	7	5
	48	**d**	0	2	0	0	0	0	0	0	5	0	0	1	0	1	1	0	10	21
	35	**f**	0	1	0	0	1	0	1	0	0	0	0	1	2	0	1	0	7	20
	73	**g**	0	0	0	0	0	0	3	0	0	0	0	1	1	0	0	0	5	7
	23	**h**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	87	**l**	0	1	0	0	0	1	0	0	2	0	0	0	0	1	0	0	5	6
	51	**m**	2	0	1	0	0	0	1	0	3	1	0	1	1	0	0	0	10	20
	127	**n**	0	0	0	0	0	0	5	0	0	0	0	3	2	2	1	0	13	10
	66	**p**	0	1	0	0	1	0	1	0	1	0	0	1	2	0	0	0	7	11
	18	**q**	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	6
	142	**r**	0	2	0	0	0	0	2	0	1	0	0	0	4	2	1	0	12	8
	136	**s**	0	2	1	0	0	0	0	0	0	0	0	4	0	1	0	0	8	6
	101	**t**	0	5	2	0	0	0	1	1	3	0	0	5	2	0	0	0	19	19
	32	**v**	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	3	9
	20	**z**	0	1	0	0	0	0	0	0	1	0	0	0	3	1	0	0	6	30
Tot	1133		3	16	5	1	3	1	14	1	18	2	1	18	21	8	5	0	117	
%			3	14	4	1	3	1	12	1	15	2	1	15	18	7	4	0		

CRI'S CONFUSION MATRIX (n=360)

RESPONSE

	# Letters	**TARGET**	**b**	**c**	**d**	**f**	**g**	**h**	**l**	**m**	**n**	**p**	**q**	**r**	**s**	**t**	**v**	**z**	**# Sub**	**% Sub**
	31	**b**	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	3	10
	143	**c**	0	0	1	0	1	0	1	0	1	0	2	2	2	1	0	0	11	8
	48	**d**	2	0	0	0	0	0	2	0	0	0	0	0	0	7	0	0	11	23
	35	**f**	0	1	1	0	0	0	1	0	0	0	0	0	0	1	0	0	4	11
	73	**g**	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
	23	**h**	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	4
	87	**l**	1	0	1	0	0	0	0	0	1	0	0	1	0	4	0	0	8	9
	51	**m**	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	4
	127	**n**	0	0	0	0	0	0	1	2	0	0	0	2	0	2	0	0	7	6
	66	**p**	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	2	3
	18	**q**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	142	**r**	0	0	0	0	0	0	1	0	1	0	0	0	2	1	0	1	6	4
	136	**s**	0	2	0	1	0	0	0	0	2	0	0	6	0	4	0	0	15	11
	101	**t**	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1
	32	**v**	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	1	4	13
	20	**z**	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	10
Tot	1133		3	5	4	1	1	0	8	2	9	1	2	13	7	20	0	2	78	
%	%		4	6	5	1	1	0	10	3	12	1	3	17	9	26	0	3		

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