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# Procesamiento fonológico en la escritura manual de palabras aisladas

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*Reading maketh a full man, conference a ready man,*

*and writing an exact man.*

Sir Francis Bacon

# Part I: General introduction

# 1

# Introduction

## 1. The origin and development of writing

Initial attempts made by humans to visually represent information can be dated back to at least 30,000 years ago, with the appearance of the cave paintings. However, the first vestiges of writing (strictly speaking) cannot be identified until 5,000 years ago, when pictograms started to be used. Although cave paintings are considered the forerunners of writing, they are better placed among the pictorial arts, because they are not believed to represent a specific message, but probably they just tried to bear witness to some meaningful events (Yule, 2006). Unlike these paintings, the first pictograms *consistently* represented a specific object. A graphic form can be classified as some sort of painting-writing (i.e., as pictograms) only when the same picture is used to represent the same referent by different individuals and in different situations (Yule, 2006). Thus, pictograms are considered the first true examples of writing, and they are thought to have evolved giving rise to some symbols which are present in current writing systems.

*Pictograms* physically resemble the object/phenomenon that they represented. For example, the symbol ☼ meaning "the sun" would be a pictogram provided a group of individuals made systematic use of this picture to visually represent the sun. It is thought that some of these symbols would have evolved to denote related concepts, such as “day” or “warm” in the case of ☼. That is to say, some pictograms became *ideograms*. It is important to notice that neither pictograms or ideograms represented sounds or words, so their use could be extended to the communication with individuals who spoke a different language. It is with the introduction of *logograms*, which denote whole words, that a writing system started to represent the language. One of the most important of the logographic systems is that introduced by the Sumerians: the cuneiform script. In the 30$^{th}$ century B.C., the Sumerians used a strictly pictographic writing system, but the pictograms slowly evolved to less iconic forms. Consequently, by the year 700 B.C., the Sumerians represented most of the words by means of forms completely unrelated with the visual aspect of the referent (see Figure 1). Nowadays, some languages have writing systems that include logographic characters (for example, Chinese). However, it would be difficult (if not impossible) to find a system purely based on logograms, mostly due to the excessive number of symbols that would need to be learned only to express the most common concepts. Instead of representing words, *phonographic* systems represent the sounds of the spoken language. In hieroglyphic writing, for example, logograms and pictograms started to be used to denote the sound of the word they represented, so they could be included in other words containing that sound. Besides, the Phoenicians used a syllabic writing system, in which Egyptian logograms were adopted with minor modifications to represent syllables. Finally, the *alphabetic* scripts are constituted by symbols representing simple sounds of the language. Although semitic languages made use of consonantal alphabets, it is the Greeks who are thought to have created the first alphabet with consonants and vowels. As it spread to the rest of Europe, this Greek alphabet was progressively modified, leading to the emergence of the Latin alphabet among others (Yule, 2006). Compared to logographic systems, in which a huge number of symbols have to be known,

**Figure 1.** Evolution of the sign for “head” from the pictographic to the cuneiform script.

alphabetic writing systems are relatively easier to learn. The fact that in alphabets a limited number of symbols are able to represent any sound of the language certainly favored the success of alphabetic scripts and the popularization of handwriting.

## 2. The impact of writing in human development

The emergence of the written language is probably one the most important breakthroughs made by humankind. If speaking allowed our ancestors to communicate with other (physically present) individuals who shared the same language, writing introduced the possibility of producing a long-lasting message, which can be decoded in other points of the time and/or the space. Moreover, it provided the possibility of keeping a more efficient and accurate historical record of events than by word of mouth. Although not all cultures have a written language, it has been claimed that the appearance of writing was crucial to the development of the ability to manipulate symbols (Cardona, 1994; Kellogg, 1994), and it is partially responsible for the extraordinary development of the human brain. For all these reasons, it is clear that the Human Being would be unrecognizable without the writing skill.

Learning to write is also a crucial skill for academic, professional and social success. While the relationship between writing expertise and development in the educational and the work field seems obvious, it has also been observed that social abilities explained a 35% of the variability in the quality observed in texts written by children. Elementary school is dedicated, sometimes almost exclusively, to teaching children to write and read, and writing difficulties are one of the main problems reported by teachers at all levels of formal education. In fact, it has been claimed to be a recurrent complaint among the employers of graduates (Miró, 2003).

Handwriting is a cognitive and motor skill. Although the cognitive elements involved in the task may not have drastically changed in recent phylogenetic development, it is obvious that motor aspects of writing have vastly and rapidly changed, especially during the last century. Initially, writing was usually carved in a wide range of materials. The first Cuneiform scripts were engraved in clay; in Ancient Egypt, wood tablets coexisted with papyrus, considerable more expensive; waxed tablets were used in Ancient Greece and Rome, and even large animal bones or tortoise shells were inscribed in China around the $11^{th}$ century b. C. Nowadays, the most extended kind of handwriting is performed with ink on paper, with a pen (handwriting) or a key (typewriting). The specific writing tools used to write partially determine the motor behavior required to produce a legible output (i.e., the peripheral processes). The introduction of typing in the $18^{th}$ century revolutionized the motor patterns of writing. But it has been the more recent omnipresence of computers in our lives that have consolidated these new patterns, to the point that typing is likely to be the most common way of writing for adult writers in the developed world. Although it has been recently claimed that "handwriting is dying" (in *Bild*, 2012, June 27), children from all countries in the world still learn handwriting before typing, and adults who have mastered handwriting still outnumber those who have mastered typing. In fact, some scientific studies have indicated that the handwriting process may be somewhat different to the typing process regarding its impact on other language domains. Kandel, Orliaguet, & Böe (1994) presented to participants the same letter produced within different bigrams in a static or in a dynamic way (similar to real-time handwriting). Then, participants were then asked to predict the following letter. Results showed that the percentage of correct predictions was higher in the dynamic condition. It seems that visual perception of letters was influenced by implicit knowledge of the laws of motor production. In the same line, Longcamp, Zerbato-Poudou, & Velay (2005) observed that children recognized previously learned letters faster when the study phase involved learning to write them by hand than when it involved learning to type them. Moreover, children's compositional quality seems to be superior in handwritten than in keyboarded scripts (Connelly, Gee, & Walsh, 2012; Swamson & Beringer, 1996). Apparently, the typing process (and other ways of writing) might not be fully interchangeable with handwriting. Evidence in this direction is growing, and it has been even claimed that the interest in the handwriting skill is in fact reinvigorating (in *Wall Street Journal*, 2010, October 5). Handwriting is, then, a very complex but largely automatized linguistic skill, so the relevance of knowing the mechanisms underlying this process is incontestable.

# 2

# The cognitive study of handwriting

The cognitive study of language production was for many years relegated to investigation about the language comprehension process. Speech production research began some decades ago, but the literature about handwriting remains comparatively scarce. The factors that have contributed to this falling into oblivion of the handwritten production process are mostly related to the late development of an appropriate technology. But methodological reasons do not exhaust the causes of the late development of this field of research.

Firstly, learning to write is a complex task which can only be mastered with years of practice. In most literate societies children start to write when they are around 5 years old, but adult writing speed is not achieved until adolescence (Van Galen, 1991). This fact seems to have made the writing process less appealing to some psycholinguists, who are more interested in other linguistic processes considered to be learned with relatively less effort, like speaking. However, it should be kept in mind that handwriting is a largely automatized task for literate adults. Moreover, the necessity of a long period of training to acquire the skill should not discourage researchers from studying it from a psycholinguistic approach, as it has not been an obstacle in the case of reading.

Secondly, and according to Van Galen (1991), early handwriting research mainly focused on developmental and educational aspects of writing, so the impact of body posture, pen-holds or the effect of instructional principles on the "quality" of the written product (for example, on legibility) were some of the most addressed topics. A shift was made during the eighties from this *product-oriented* to a *process-oriented* approach. Consequently, analyses of errors performed by patients with acquired dysgraphia and by healthy adults proliferated, aimed at determine the underlying cognitive processes (Ellis, 1982; Morton, 1980; Hotopf, 1980). Some chronometric studies started to assess the impact of writing composition on cognitive resources (Kellog, 1994). Moreover, the number of experiments conducted on latencies and writing durations progressively increased, and interest in handwriting as a cognitive skill augmented (Van Galen, 1991). As well as the decline of behaviorism in favor of cognitive approaches, the reasons for this shift were mostly related to the emergence of electronic devices which enabled researchers to trace the dynamics of handwriting. Accurate and reliable on-line measures of the handwritten response were not available until very recently, with the appearance of digitizer tablets. The development of specific software for the analysis of handwriting from a cognitive perspective (e.g., Ductus, Spellwrite) have multiplied the number of measures that can be obtained, so the dynamics of a written response can be analyzed with a high level of detail. Of course, some questions regarding the interpretation of some measures and effects remain controversial, given the short age of the discipline.

## 1. Theoretical background to the handwriting production process

An early attempt to describe the processing modules and units involved in handwriting production was made by Van Galen in 1991 (see Figure 2). He sketched a hierarchical model in which the output of one stage of processing constitutes the input of the next stage. The first three modules are concerned with the activation of intentions, semantic retrieval and syntactic construction, and they are thought to be common to the speech production process. The rest of the modules are specific to the writing process, so we will focus on them.

According to Van Galen, in the spelling module elements of an utterance are substituted by their corresponding graphic codes. The specific mechanisms by which this is achieved are not detailed, although the author suggested that access to the orthographic form could be gained through more than one route of processing. At the motor level the model distinguishes between selection of allographs, size control and muscular adjustment. An allograph is understood as a motor program corresponding to a graphemic representation in a specific writing mode (lower case, upper case, cursive, etc.). The modules devoted to size control and muscular adjustment are the most peripheral processes included in the model, and they are claimed to apply at the letter and the stroke levels respectively. These motor modules would be highly dependent on the biophysical context of the task.

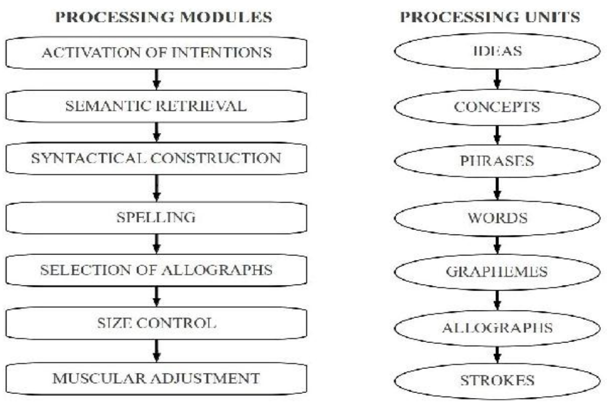


**Figure 2.** Model of handwriting, adapted from Van Galen, 1991.

The model assumes that all processing modules are engaged in parallel, so higher modules are further ahead than the peripheral levels of processing. This is to say, while size control and muscular adjustment are being processed for the unit actually being executed, central processes deal with forthcoming parts of the written response. Thus, manipulations at the central levels of processing might produce differences in writing durations due to the sharing of resources between central and peripheral processes. Recently, Kandel, Peereman, Grosjaques, &

Fayol (2011) have proposed a model which adapts Van Galen's model to include a syllable module. Syllables have been largely studied in reading and speech production research, and syllabic effects have been observed in writing studies. Regarding the flow of information, both models share the same principles. The architectures sketched by Kandel et al. (2011) and Van Galen (1991) should be considered as very general frameworks of the handwriting production process, in which the processing units supported by the previous literature are included, and claims are made about how the different processing modules relate to each other. For example, how orthographic codes are accessed and selected is not detailed in these proposals. Whereas Kandel and colleagues claim that the spelling route is "a one route structure" (Kandel et al., 2011, p. 1319), Van Galen refers us to the more popular dual-route theory (Van Galen, 1991).

According to dual process theories, spelling may be achieved through two different processing routes. The so-called *lexical route* gives access to the spelling of whole-words from long-term memory, so it would be used when spelling familiar words. In contrast, the *sublexical* or *assembled route* makes use of knowledge about phonology-to-orthography (henceforth, P-O) correspondences existing in the language, and provides a phonologically plausible spelling for nonwords or low-frequency words (Caramazza, 1988; Tainturier & Rapp, 2001). The sublexical route is thought to operate on the basis of how individual phonemes are usually spelled, so it would be unlikely to produce a correct spelling for those words with atypical phonology-to-orthography correspondences (irregular words). The lexical route would be largely insensitive to the frequency of the P-O mappings. The existence of both routes is almost undisputed, even in remarkably shallow languages (such as Spanish or Italian), in which writing could be accomplished by resorting merely to the phonology-to-orthography conversion procedures (Cuetos, 1991; Cuetos & Labos, 2001; Valle, 1987; Barry & De Bastiani, 1997). What is less clear is whether or not these routes are so dichotomously engaged during writing. Several studies have confirmed that the lexical route might influence the spelling given to nonwords (Barry & Seymour, 1988; Campbell, 1983; Cuetos, 1991). However, little evidence has been provided about the involvement of the assembled route during the written production of well-known words. This is the scope of the present PhD dissertation, so we will focus on the literature about the written production of words. Those studies addressing phonological effects in nonword spelling are of little interest for our work, so only the findings from this line of research that may be relevant for word production will be commented.

*1. 1. Phonological information in handwriting*

Early theoretical proposals stated that the recovery of an orthographic representation had to be unavoidably preceded by the retrieval of the phonological word-form (Aitchison & Todd, 1982; Brown, 1972; Geschwind, 1969; Hotopf, 1980). From a naïve point of view, this hypothesis is in line with our subjective experience, in which some kind of inner speech seems to be present during writing. Assuming this so-called *obligatory phonological mediation hypothesis* (Rapp & Caramazza, 1994, 1997), the writing process would be completely subsidiary to the speech production process (see Figure 3). This kind of theory mainly relied upon the results obtained from the analysis of slips-of-the-pen (Hotopf, 1980). Slips-of-the-pen are errors made by normal populations during handwriting, which are thought to reflect a failure during the process of selection of the orthographic form. They are different from misspellings because in slips-of the-pen the writer actually knows what the correct form of the intended word is, so he or she would be able to recognize the error (Ellis, 1982). There are several types of slips-of-the-pen, but cases of homophonic substitution (for example, writing *there* instead of *their*) have received the most

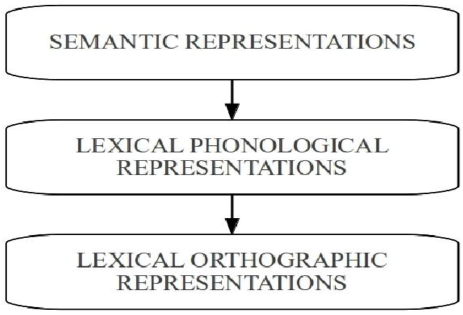


**Figure 3.** Schematic representation of the obligatory phonological mediation, adapted from Rapp, Benzing, & Caramazza, 1997.

attention (Aitchison & Todd, 1982). It has been argued that homophonic substitutions reflect the conflict generated by a phonological entry activating more than one orthographic (output) form. However, from this point of view it would not be clear how a writer would be able to correctly select between both orthographic word-forms in the case of heterographic homophonic items such as *there* and *their* if only phonological information is considered during the selection process (Morton, 1980).

The *obligatory phonological mediation hypothesis* has been challenged by findings from neuropsychological studies (Miceli, Benvegnù, Capasso, & Caramazza, 1997; Lhermitte & Dérouesné, 1974; Rapp, Benzing, & Caramazza, 1997; Tainturier & Rapp, 2001; Cuetos & Labos, 2001). It is not unusual to find patients who exhibit better performance in written production compared to spoken production tasks (Lhermitte & Dérouesné, 1974; Rapp et al., 1997; Caramazza & Hillis, 1990). For example, Rapp et al. (1997) reported the case of PW, a patient who was often unable to produce the spoken name of an item although he was able to produce its written name. In addition, Miceli et al. (1997) observed that the patient WMA produced different semantic errors for the same picture in oral picture naming and in written picture naming. When faced with a picture representing peppers WMA said “artichoke” but wrote the word *tomato*. How this kind of error can occur if the same phonological form underlies both modalities of response is a problematic issue for the obligatory mediation hypothesis. This evidence motivated the formulation of the *orthographic autonomy hypothesis* (Miceli et al., 1997; Rapp & Caramazza, 1997; Rapp et al., 1997), which establishes that an orthographic word-form could be directly accessed from the semantic system without any phonological involvement.

It is worth noting that the *orthographic autonomy hypothesis* does not preclude the possibility of phonological information affecting the spelling process, but this would occur through *optional* rather than *obligatory* links. Two versions of the *orthographic autonomy hypothesis* have been proposed on the basis of the level at which this optional influence is thought to take place (Miceli et al., 19947; Bonin, Peereman, & Fayol, 2001). The *lexical version of the orthographic autonomy hypothesis* proposes that the phonological output lexicon and the orthographic output lexicon are connected through non-obligatory links (see Figure 4). From this point of view, the semantic system would activate in parallel the corresponding entries in both lexicons. Then, phonological word-forms would boost the selection of their associated representations in the orthographic lexicon through optional links. In contrast, the *sublexical version* claims that phonological influence on the writing process could come from the application of phoneme-to-grapheme conversion patterns (see Figure 5). Consider, for example, the Spanish word "vaca" (in English, "cow"). According to the lexical version, the phonological word-form /baka/ is linked to the orthographic word-form *vaca*. In contrast, the sublexical

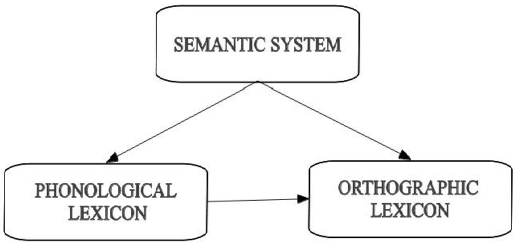

**Figure 4.** Schematic representation of the lexical version of the orthographic autonomy hypothesis, adapted from Rapp, Benzing, & Caramazza, 1997.

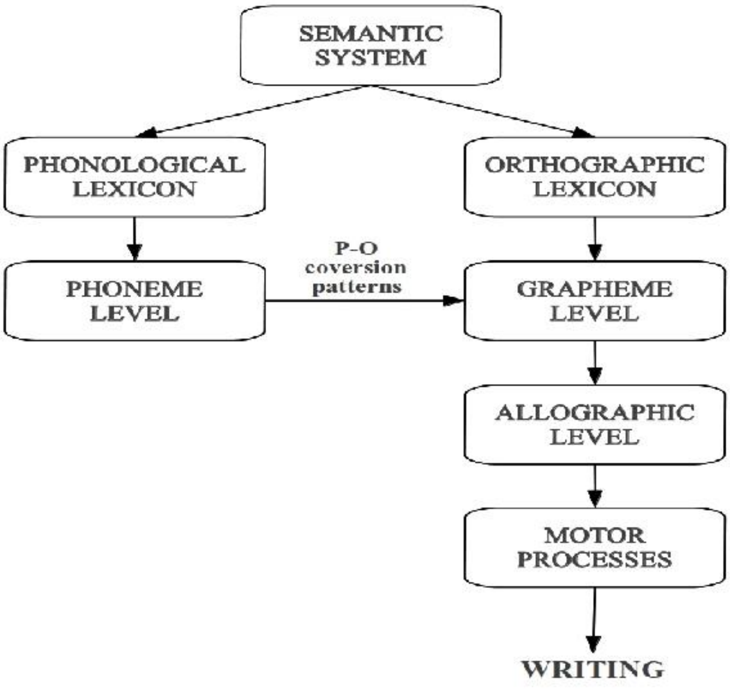

**Figure 5.** Schematic representation of the sublexical version of the orthographic autonomy hypothesis, adapted from Bonin, Peereman, & Fayol, 2001.

version states that the phonological form /baka/ activates its constitutive phonemes ([b]+[a]+[k]+[a]) and these phonemes would activation to the corresponding graphemes (*v*+*a*+*c*+*a*) through phoneme-to-grapheme conversion mechanisms. Therefore, in the two cases phonological information would be able to affect the handwriting performed by normal adults, but it *need not* be recovered, due to the existence of a direct link between the semantic system and the orthographic output lexicon.

Bonin, Peereman et al. (2001) obtained evidence in French favoring the sublexical version of the orthographic autonomy hypothesis using a written picture-naming task. In their study, the authors manipulated the consistency of the phono-orthographic mapping of the picture names at the lexical and at the sublexical level. At the lexical level, heterographic homophones (e.g., the picture of a *pool*, which is homophonic with *pull*) were compared with nonhomophonic picture names (e.g., *doll*). At the sublexical level, words containing sublexical units that have more than one phonologically plausible spelling (for example, the word *j*ee*p* could be spelled *j*ea*p*) were compared with consistent picture names (e.g., *map*). No effect of homophony was observed. Nevertheless, picture names which were inconsistent at the sublexical level showed longer written latencies than consistent picture names. These results were interpreted by the authors as evidence of phonological information coming into play during written picture naming at a sublexical but not at a lexical level. Some studies using the priming technique have addressed this issue, but the results have been rather contradictory (Bonin, Fayol, & Peereman, 1998; Bonin & Fayol, 2000; Bonin, Fayol, & Malardier, 2000; Bonin, Fayol, & Gombert, 1997; Zhang & Damian, 2010; Roux & Bonin, 2012). For example, Bonin and colleagues (1998) failed to obtain a phonological masked priming effect in a written picture naming task, even when a reliable effect of orthographic priming was found. In a more recent study using the picture-picture interference paradigm, Roux & Bonin (2012) did not observe facilitatory effects when a phonologically but not orthographically related distractor was presented. However, phonological priming effects have been found to affect written picture naming latencies when auditory and visually presented words were used as distractors (Bonin, Peereman et al., 2001; Zhang & Damian, 2010).

Some authors have claimed that lexical and sublexical (phoneme-to-grapheme conversion patterns) information could integrate at a grapheme level (Rapp, Epstein, & Tainturier, 2001; Tainturier & Rapp, 2001; Bosse, Valdois, & Tainturier, 2003). Both processes (lexical and sublexical) would "vote for" a candidate graphemic element, so when both systems produce the same output (the same grapheme is activated) the selection would be reinforced. As a result, sublexical phonological information would influence the writing of well-known words at the level of grapheme selection. This means that orthographic lexical information can be accessed independently of the phonological information, but in normal writing conditions phonology may strengthen the activation of the graphemes constituting a word. However, it must be stressed that this proposal has been made specifically for the spelling-to-dictation task, since the phonology-to-orthography conversion patterns are thought to be activated by the phonological input itself. Thus, phonological effects during other writing tasks seem not to be predicted from this perspective. However, phonology might constrain orthographic selection during the spelling-to-dictation task (Delattre, Bonin, & Barry, 2006). The assemble route would affect not only the time needed to start writing (written latencies), but also the time devoted to actually produce a given stimulus (writing durations). This latter prediction is closely related to the controversy inherited from the speech production research about the cascaded or staged organization of central and peripheral processes. The assumptions that one makes about the flow of information within the spelling system will determine which effects are expected along the time course of the written response, when and in which circumstances phonological effects are thought to be observable.

*1. 2. Cascaded versus staged processing in the writing system*

In language production research central processes are those that are common to all the output modalities. Contrarily, peripheral processes are those involved in the articulation of the output, and they differ based on the motor behavior required to produce a response. In spoken word production research it has been widely debated whether or not central processes must be completed before peripheral processing begins. On the one hand, the staged processing point of view claims that the spoken response is initiated only when central processes have been finished (Damian, 2003; Rastle, Harrington, Palethorpe, & Coltheart, 2000). This means that response duration can never be affected by manipulations tapping into the central stages of processing. On the other hand, the cascaded processing hypothesis establishes that if task demands are increased, articulatory processes can be initiated before central processes had concluded. Consequently, the spoken response might be influenced by variables which have an impact on the central levels of processing. Experimental evidence concerning this issue has not been conclusive. Some authors have provided evidence favoring the cascaded vision of the speech production process. Morsella & Miozzo (2002) observed that English participants named pictures faster when a context picture phonologically related was superimposed than when the context picture was unrelated. This phonological facilitation effect was interpreted as evidence that the phonology of the context picture name was automatically activated, suggesting that phonological encoding can begin before lexical selection has finished. Moreover, some evidence seems to indicate that the spoken response can begin as soon as the initial phoneme of the intended word is available (Kawamoto, Kello, Higareda, & Vu, 1999). However, this proposal has been challenged by some results obtained with different tasks (Rastle, et al., 2000; Jescheniak, Oppermann, Hantsch, Wagner, Mädebach, & Schriefers, 2009). Crucially, Damian (2003) failed to obtain effects on response durations of central variables that did affect response latencies, so they concluded that the speech production process is staged. Thus, in the field of speech production research, this controversy remains unsettled.

In handwriting theory, central processes have been considered to embrace those processes related to the retrieval and activation of an orthographic representation (which has been referred to as *spelling*) whereas peripheral processes are concerned with the regulation of local parameters such as amplitude, orientation or force (which has been called *writing*). Central processes are common to all the spelling tasks, regardless the motor behavior used to give a response (oral spelling, handwriting, typing, etc.). On the contrary, peripheral processes are specific to each output modality, and they refer to the mechanisms required to correctly execute the formal aspects of the response (the intended case, appropriate letter-form, the specific muscles involved if a motor response is demanded). This distinction is supported by analysis of the writing produced by patients with acquired dysgraphia (Shallice, 1988). Patients with central dysgraphia show similar performance in all writing tasks irrespectively of the output modality (handwriting, typing, etc). In contrast, in peripheral dysgraphias the deficit can be restricted to one modality. Moreover, central and peripheral processes have been recently found to have different neural substrates (Purcell, Turkeltaub, Eden, & Rapp, 2012). The debate about the staged or cascaded nature of the writing system has not been introduced until very recently (Delattre et al., 2006; Roux & Bonin, 2012), so evidence concerning this issue is rather limited so far. Besides the emergence of new methodologies which permit analysis of writing durations, a key factor that has promoted interest in this debate in writing production research has been the introduction of the idea that the writing production process may not be a mere reflection of the speech production process. Specially, it has been argued that the long duration of writing compared to speaking and the fact that speakers but not writers must strive for fluency makes the spelling system a particularly reasonable candidate for staged processing (Roux & Bonin, 2012). Nonetheless, some evidence has confirmed that central variables can affect writing durations, at least in some circumstances (Delattre et al., 2006; Roux & Bonin, 2012). In a recent study, Roux and Bonin (2012) reported evidence that information flows in a cascaded manner from the orthographic lexeme level to the grapheme level. Delattre and colleagues (2006) observed in a dictation task performed by adults that sound-to-spelling regularity affected both written latencies and whole-word durations. In a study with children, Kandel & Valdois (2005) also reported a regularity effect, in this case in the mean stroke duration percentages (see below a description of this measure). Moreover, other central variables have been found to affect the writing durations produced both by adults and children (Van Galen, 1991; Kandel, Soler, Valdois, & Gros, 2006; Kandel & Spinelli, 2010). However, it is noteworthy that in order to assert that the effects observed in written durations constitute evidence supporting the cascaded point of view it is necessary to demonstrate that they originate at the central and not at the peripheral levels of processing.

The theoretical question about how information flows within the writing system is inextricably linked to methodological factors. The position adopted in this debate will determine what measures of the written process are collected, and how effects in writing duration are interpreted.

## 2. Methodology in handwriting production research

Handwriting is a multi-component task involving at least linguistic, motor and spatial processing. As a matter of fact, writing production has been claimed to be "one of the most striking examples of a task characterized by a high degree of motor equivalence" (Van Galen, 1991; p. 168). The concept of motor equivalence in motor control refers to the fact that the same product can be obtained by means of different ways of performing a movement (Bernstein, 1967). The affirmation of Van Galen is supported by the fact that similar letter forms are observed when writing is produced with different limbs and instruments (Van Galen, 1991; Maarse, Schomaker, & Thomassen, 1986), or when writing at an abnormal size or speed is required (Wing, 1980, Van Galen, 1991). This means that some parameters have to be locally processed to adapt to the specific contextual demands of the task, while other parameters have to be kept constant to obtain similar forms across different situations. This fact makes it difficult to identify which parameters of the written response reflect actual high-level processing, and not mere adjustment of local parameters to keep the constancy of the more abstract motor pattern. Therefore, an overwhelming number of parameters have been analyzed (such velocity, acceleration, duration, pressure, size, slant, curvature, etc.) at different unit sizes (strokes, letters, words, pair of strokes, etc.). Obviously, the convenience of using one specific measure or unit largely depends on the process being studied and the variable being tested. For example, it is clear that analysis of the most peripheral aspects of handwritten response might be particularly interesting for the movement sciences. However, from a psycholinguistic approach it is fundamental to identify those measures reflecting the dynamics of processing at a more central level. Here, we discuss briefly some of the units and measures most frequently considered in the cognitive study of handwriting.

### *2. 1. Dependent variables in handwriting production research*

*Number of errors, disfluencies and gaze-raising* have been analyzed mainly in developmental studies of handwriting. Children produce numerous and varied errors, ranging from misspellings to mere letter orientation errors. The analysis of the type of errors made by children during the writing instruction period has provided valuable insights about the way in which children acquire the writing skill, and it has helped to identify distinctive subgroups of developmental dysgraphia. In the case of studies conducted with adults, error rates are usually very low, so analyses of errors have not been systematically reported. Moreover, the interpretation of the errors produced by adult writers is not straightforward. As pointed out by Bonin, Peereman et al. (2001), these errors might reflect inaccurate spelling knowledge (the fact that the spelling of the intended word is not stored or is incorrectly stored), and not the processing demands exerted by the task. In any case, neuropsychology has provided detailed analyses of the errors made by neurologically damaged patients, and analyses of the spontaneous writing errors made by non-damaged adults (slips-of-the-pen) were reported in the early years of the discipline. If the number of errors decreases dramatically with the automation of writing, disfluencies (defined as the number of velocity extremes) and gaze-raisings (to consult the model in the course of copying) disappear completely, so their analysis has been circumscribed to children's performance. It should be noted that these measures are likely to tap into the peripheral processes of writing, given their absence once writing movements have been automatized.

Written latency refers to the time between the presentation of a given stimulus and the occurrence of the first contact of the pen with the digitizer tablet. This measure was adapted to handwriting research from speech production research, and has been collected and analyzed in many writing studies (Delattre et al., 2006; Qu, Damian, Zhang, & Zhu, 2011; Bonin, Peereman et al., 2001; Bonin & Fayol, 2000; Bonin et al., 1998; Bonin et al., 1997; Zhang & Damian, 2010; Damian, Dorjee, & Stadthagen-Gonzalez, 2011; Damian & Stadthagen-Gonzalez, 2009). Written latencies are thought to reflect central spelling processes (Delattre et al., 2006), and they seem to be sensitive to semantic (Bonin & Fayol, 2000; Bonin & Méot, 2002), lexical (Bonin, Fayol, & Chalard, 2001; Bonin, Malardier, Méot, & Fayol, 2006; Bonin & Méot, 2002) and sublexical variables (Delattre et al., 2006; Bonin & Méot, 2002; Bonin, Peereman et al., 2001). Although in a strictly modular model writing latencies are considered to reflect the total amount of time necessary to complete the central levels of processing, in a cascaded architecture effects emerging at the central levels could affect writing durations. For this reason, the number of studies that measure writing durations as well as written latencies is growing.

*Writing and intervals duration* are the total time needed to produce a given segment of writing and the time between the production of two different segments, respectively. Letter durations are measured as the time between the first contact of the pen with the tablet for a letter and the last first lift in that letter. Inter-letter intervals are defined as the time between the last pen lift in a letter and the first pen down in the following letter. While writing durations have been considered for different units (total duration of the whole word, mean stroke duration and total letter duration have been the most common), inter-letter intervals are virtually the only writing intervals that have been taken into account. Within-letter interval durations have not been systematically measured from a cognitive perspective, and between-word intervals durations have been reported in few studies (e.g., Van der Plaats & Van Galen, 1990; Delattre et al., 2006). Although it was initially assumed that writing times reflected peripheral processing demands, we have already commented that it has been recently proposed that writing movements can also be affected by manipulations tapping into central levels of processing. The specific mechanisms producing variations in the movement times remain unsettled. Van Galen (1991) claimed that increased movement times may reflect the sharing of resources between the processes involved in real-time stroke production and the concurrent preparatory processing of forthcoming segments. Thus, an increment in central processing demands concerning one specific position would concur with the peripheral processing of those units located in the previous position (see also Kandel et al., 2011). This is to say, the manipulation of some variables affecting central processing concerning the second letter of a word would produce an effect in the duration of the previous letter (in the case of cursive writing). It is worth noticing that this is different from the claim that increased writing times indicate the presence of a conflict between the outputs produced by different processing routes which would remain unsolved before the written response has been initiated (Delattre et al., 2006). From this point of view, an increment in total writing durations reflects the consequences of the resolution of this conflict, which would cascade to affect peripheral processes. No specific predictions about the expected position of these effects have been made from this perspective, but it is assumed that cascaded processes may have a considerably long temporal scope, which could last several seconds (Delattre et al., 2006). In spite of the dissimilarities between these two claims, there seems to be increasing agreement regarding the idea that writing durations are sensitive to peripheral but also to central processing.

*Writing velocity* is a measure which can be now easily obtained with specific software, like Ductus (Guinet & Kandel, 2010). However, it has not been reported in any psycholinguistic study. In the present study we have chosen writing durations instead of writing velocity (which can also be obtained with Ductus) as dependent variable for several reasons. First, whereas velocity is a relatively novel measure in psycholinguistics, writing durations have been repeatedly reported in the literature. Second, we cannot measure the velocity for latencies or intervals, so different measures should be provided for letters and intervals. Thus, potential effects appearing in both letters and interval would not be easy to compare. Last, but certainly not least, if only writing velocity is analyzed, potential effects occurring in the within-unit intervals would pass undetected. By measuring total duration of the unit (instead of only total writing duration or velocity) we make sure that we do not miss any information potentially relevant for our understanding of the time-course of the written response.

*2. 2. Units of programming and measurement in handwriting production research*

The size of the units of processing in the preparation of handwriting is a complex debate. No one specific unit of programming has been unanimously accepted, leading some authors to claim that there is not a fixed unit of processing in handwriting production (Van Galen, 1991). Instead, it has been asserted that the programming of the written response proceeds along different steps, with units of different sizes being involved in each level (Van Galen, 1991; Hulstijn & Van Galen, 1983). The assumptions made regarding the unit of programming in handwriting will partially determine at what size measures are collected. Several units have been proposed to be functional during handwriting, so evidence has been reported at highly variable unit sizes. The units that have received more attention have been whole words, letters and single strokes.

Some studies have recorded total writing times for *whole words* as a measure of peripheral and even central processing (Delattre et al., 2006). These studies have been mainly concerned with the debate about staged versus cascaded processing in handwriting production. For example, writing times for the entire response were reported by Delattre and colleagues (2006). They manipulated the sound-to-spelling regularity of French words, and asked participants to write each word three times consecutively. They reasoned that if central spelling were staged irregularity should be observed to affect writing latencies, but not total writing durations. On the contrary, if processing were staged, irregularity effects would be obtained in both measures only for the first production of the word, since second and third replications were assumed to reflect only peripheral processing. Results revealed irregularity effects in writing latencies and durations for the three written responses, so it was concluded that the conflict generated by the sound-to-spelling irregularity had a scope of between 5 and 7 seconds. It is obvious that in this study the regularity and irregularity condition included different sets of words. This fact raises the possibility that differences in total writing times were due to differences in word-form. Although in this study regular and irregular words were matched for lexical and sublexical variables (word frequency, age of acquisition, bigram and trigram frequency), different letters have in most of the cases very different durations. Besides, the interpretation of the effects in terms of peripheral processing would be in line with the fact that they were observed also for the second and third response. Given the limited amount of paradigms currently available which allow for a comparison of the same set of words in different conditions (mostly, priming paradigms), reliable differences in total writing times might not be easy to obtain depending on the variable being manipulated. Although Roux & Bonin (2012) have provided evidence supporting the cascade of information from lexical orthography to graphemes comparing the same targets, such a design would be considerably more difficult to ideate when, for example, phonology-to-orthography consistency is the variable being manipulated.

It could seem superfluous to mention that *letters* might be a unit of programming in handwriting. During writing instruction, children learn to produce the movement patterns for individual letters, which would be later combined to produce more complex orthographic units. Moreover, the fact that the letter-form is remarkably consistent across replications suggests that a motor pattern for each letter is available. A motor pattern is understood as the set of specifications of abstract movement parameters that sufficiently describe the movement (Teulings & Schomaker, 1993). Although scarce, experimental evidence seems to confirm that letters are processing units in handwriting. In an early study, Teulings, Thomassen, & Van Galen (1983) tested pairs of letters which consisted either of identical letters, or of letters with similar initial strokes or dissimilar letters. It was expected that if strokes were units of programming in handwriting the initiation of the second letter would be facilitated in similar pairs as much as in identical pairs. However, results showed that only precueing an identical pair facilitated the initiation of writing, indicating that whole letters and not individual strokes were used as unit of programming. Additionally, sequences of repeated letters show a peculiar slowing of execution speed (Wing, Lewis, & Baddeley, 1979). The high consistency in form showed by the same letters performed by the same writer makes letter durations especially appealing as a dependent variable. Letter durations have been reported in some handwriting studies. However, the analysis of this measure requires strictly control of the experimental materials, since differences in letter identity might have a considerable impact on writing times. For this reason, and similarly to the case of total writing times, it is crucial to conceive of experimental designs which permit analysis of the same letters in the same positions in all the experimental conditions.

A *stroke* has been defined as the writing trajectory between two consecutive zero crossings of the vertical velocity function (Van Galen, 1991). In an early study, Wing (1978) observed the duration of consecutive downstrokes and upstrokes in cursive letters *v*, *n*, *w* and *m* in order to establish whether single strokes were units of programming in handwriting. Based on previous findings (Wing & Kristofferson, 1973), the author reasoned that if this were the case, then negative correlations should be obtained for the durations of consecutive strokes. However, only the first and the second stroke correlated negatively in Wing's study, so he proposed that arcades (pairs of up- and downstrokes), but not single strokes were functional units in handwriting. Although strokes have been thoroughly studied from the movement sciences, from a psycholinguistic approach durations for individual strokes have rarely been measured. Nonetheless, results from the analysis of *mean stroke durations* have been reported in many cognitive studies (Kandel, Soler, et al., 2006; Kandel et al., 2011; Kandel & Spinelli, 2010). This measure is obtained by applying a normalization procedure to the writing durations obtained for each letter. The total writing time registered for a given letter is divided by the number of strokes that constitute that letter. According to Kandel, Soler et al. (2006) such a procedure would allow comparison of different letters, regardless of their number of strokes. Nevertheless, it is worth noticing that this implicitly assumes that different letters with the same number of strokes are fully comparable, which is an arguable point. A superficial examination of our own handwriting would reveal substantial differences between the time needed to handwrite upper-cases forms of the letter *A* and letter *S*. Although these two letters consist of the same number of strokes (three strokes), to produce letter *A* usually requires around 500 ms, while writing durations for letter *S* are of 230 ms approximately (means extracted from writing durations produced in the present work). This is due to the fact that stroke durations critically depend on some characteristics of the specific stroke, such as its length or curvature (Van Galen, 1991). In fact, stroke durations are considered to be rather variable, even between replications of the same letter made by the same writer (Teulings & Schomaker, 1993). Moreover, compelling evidence suggests that different kinds of strokes (downstrokes, upstrokes, horizontal strokes) display different velocity profiles (Van Galen, 1991; Wing, 1978; Teulings & Schomaker, 1993). Finally, it is not clear that a variation in the number of strokes has such a decisive impact on letter duration. Teulings, Mullins, & Stelmach, (1986) did not observe an increase of movement time per stroke as a function of number of strokes. Therefore, we consider that results from mean stroke durations should be taken with caution, since observations obtained for different letters might not exclusively reflect those effects due to the experimental manipulation, but also to differences in letter identity.

In the present dissertation written latencies, letter duration and inter-letter interval durations are reported, depending on the experimental manipulation. These measures were obtained with SpellWrite II (Cottrell, 1999) and Ductus (2010), two software programs specifically developed for stimuli presentation in handwriting studies and the posterior analysis of the kinematic parameters of the written response. SpellWrite II offers information about the duration of any segment of the response, and Ductus additionally provides values of pressure, velocity, and trajectory length for any segment of the response chosen by the experimenter. Our selection of letters as the unit size for the collection and analysis of writing durations has been guided by the evidence provided by the literature, which indicates that letters are processing units in handwriting. Moreover, the consideration of letters as the unit size for the measurement of movement times permits comparison of the same element in different conditions. While words including the same letter in the same position can be found in any alphabetic language relatively effortlessly, to create experimental designs with the same target words per condition would be considerably more complicated. Besides, to measure writing durations at a more local level than in the case of whole-word writing durations can provide more detailed information about the time-course of the writing process. Specifically, it can help us to establish whether the effects of central variables affect writing durations or, on the contrary, if central effects in writing durations reflect the concurrency of the peripheral processes related to the segment being produced and the central processing of forthcoming segments, as follows from the anticipatory motor programming conception of handwriting postulated by Van Galen (1991). If differences in writing duration reflect the presence of a conflict which continues to affect movement times, a general slowing of the whole writing output is expected. From Van Galen's proposal, effects emerging at the central level are predicted to be observed in the segment immediately prior to the unit causing the effect.

## 3. The present study

Nine behavioral experiments are reported in the present manuscript. The goal of the present series of experiments is manifold. It is our primary objective to shed some light on the controversy about the role played by phonology during handwriting production. We focus on the effects of phonological information in several writing tasks involving well-known words. Secondarily, we aim to provide reliable evidence to contribute to other theoretical and methodological debates about handwriting production research.

Our purpose is to provide evidence concerning the following theoretical questions:

- ***Does phonological information play a role during adult handwriting of words? If it does, which model of handwriting production can account for the potential effects observed here and in previous literature?***

  A satisfactory answer to these questions should include: (a) specifications about the level of processing at which phonology would affect the written production process (lexical, sublexical), (b) a thorough description of how and in what situations phonological information is thought to have an influence (which are the tasks affected by phonology and what architecture of the spelling system could bring about the reported phonological effects), and (c) a proposal concerning the phonological units that would be functional during handwriting. Chapter 3 is concerned with the possibility of obtaining phonological effects in a task different from spelling-to-dictation. Chapter 4 tests whether grapheme-to-phoneme probability affects handwriting, and reports phonological effects during copy, one of the less studied writing tasks. Chapter 5 and 6 address the functionality of two of the most studied units of phonological origin: the syllable and the grapheme. The evidence obtained will be commented in the context of the models of handwriting that have been suggested, and a more inclusive model is tentatively proposed.

- ***Do central (phonological) processes affect writing duration? If this is the case, are these effects consistent with the presence of a conflict at the central level which continues to affect the more peripheral processes, or are they better explained by the***

***anticipatory theory of handwriting?***

If a long-lasting conflict affects writing durations for more than 5 seconds, as proposed by Dellatre and colleagues (2006), then all the segments produced during this time interval should take longer to be produced. In contrast, if anticipation of the forthcoming segments is responsible for the increases in writing durations, then the effects should be observable in the writing durations obtained for the segment prior to the element being manipulated. Although these two hypotheses are not mutually exclusive, we will collect writing durations for individual letters and inter-letter intervals in order to establish which of them provides a better account of the results.

Moreover, we aim to make relevant methodological contributions to handwriting production research. They can be summarized as follows:

- ***About the dependent variable that should be considered to assess the handwritten response.***

  Different studies have reported different dependent variables, above all writing durations for the whole response and mean stroke durations. In this PhD dissertation we claim that individual letters should be measured, and that letter identity (and position) should be preserved, as far as possible, across the different experimental conditions. We comment this issue in the discussion to the light of the results obtained here.

- ***About the experimental paradigms used in handwriting research.***

  In Chapter 3 we introduce the use of the odd-man-out version of the implicit priming paradigm. Although the standard version of this paradigm has been successfully used in a writing production study by Damian and Stadthagen-Gonzalez (2009), the version with an odd-man-out presented here allows us to assess a wider range of variables, so we think it constitutes a valuable contribution to the discipline. Moreover, we have made some modifications to the paradigm that may extend the scope of its use. We expect our findings to provide interesting insights about the paradigm itself.

# Part II: Experimental section

# 3

# The role of phonology in handwriting

The first goal of the present chapter is to address whether phonological information actually comes into play during unimpaired handwriting production processes. Additionally, we will try to explore the level of processing (lexical or sublexical) at which this influence may occur. To achieve this, we made use of the implicit priming paradigm (Meyer, 1990, 1991; Roelofs, 1996, 1998, 1999, 2006; Roelofs & Meyer, 1998; Damian & Bowers, 2003; Chen, Chen, & Dell, 2002; Bi, Wei, Janssen, & Han, 2009; Alario, Perre, Castel, & Ziegler, 2006). The implicit priming paradigm has been repeatedly used in the area of speech production research and it is thought to be sensitive to the early stages of phonological encoding (like the classic priming paradigm), but it is also believed to tap into later stages at the interface of phonological and phonetic encoding (Cholin, Schiller, & Levelt, 2004). This paradigm has been recently adapted to handwriting investigation (Damian and Stadthagen-Gonzalez, 2009). Here we use the odd-man-out version of the implicit priming paradigm in order to test whether phonological information can facilitate a written response independently from the orthographic information.

## 1. The implicit priming paradigm

### *1. 1. The basic paradigm*

In the implicit priming paradigm (Meyer, 1990, 1991; Roelofs, 1996, 1999), participants have to produce the response words included in a small set of prompt-response pairs previously learned. During the learning phase, participants have to memorize a list of paired words in which the first word of the pair is the prompt and the second word is the response. During the test phase, the studied prompts are presented in random order, and for each prompt the participants have to produce the corresponding response word. In the basic version of the paradigm two types of lists are created. In one of them, called the *homogeneous* set, all the response words share a part of the sublexical units (e.g., the first syllable in *loner*, *local*, *lotus*; the first syllable in *major*, *maker*, *maple* or the first syllable in *beacon*, *beadle*, *beaker*). In the *heterogeneous* set, response words are regrouped to create a list with non-related response words (e.g., *loner*, *major*, *beacon*). Thus, the same word is tested in both the homogeneous and the heterogeneous condition. The logic of the paradigm is the following: since in the homogeneous blocks the first segment is shared by all the response words, participants are able to successfully anticipate it, so this information can be used to prepare the corresponding motor program. This is reflected in shorter response latencies (the time between the onset of the prompt and the onset of the response) in the homogeneous than in the heterogeneous condition.

It could be argued that memory mechanisms and not linguistic processes are responsible for this preparation effect. Nevertheless, this memory account has been ruled out in a wide range of studies, based on converging evidence suggesting that preparation effect originates at the level of phonological planning. It has been observed that preparation effect is sensitive to abstract lexical properties such as number of syllables (Roelofs & Meyer, 1998) or syllable structure (Meyer, 1991). This pattern of results was interpreted as showing that the preparation effect was due to neither articulatory nor memory processes, but to partial phonological planning. Furthermore, Roelofs (1998) obtained a preparation effect for Dutch particle-verb combinations when the particle was shared, such as in "*op*zoeken", "*op*draaien", "*op*geven"; however, there was no preparation effect when responses shared the verb, such as in "op*zoeken*", "af*zoeken*", "uit*zoeken*". In a second experiment, the imperative forms of the same particle-verb combinations were used as response words. In the imperative form, the order is reversed (verb-particle). The results showed that in this case preparation was observed when the verb was shared, but not when the particle was shared. This pattern of results is difficult to conciliate with an account of preparation in terms of memory processes, since the lexical item was the same in both experiments.

Probably the more striking evidence against the memory account is the fact that preparation effect has been obtained when pictures instead of associated-pairs have been used in order to trigger a response (Roelofs, 1999; Alario et al., 2006; Santiago, 2000). This fact seems to confirm that the preparation effect is due to language production processes instead of memory processes. In Spanish, Santiago (2000) reported that the same size effect was observed whether associated-pairs or pictures were used, but this effect reached significance only in the case of picture names serving as responses. This evidence suggests that the memory component of the associated-pairs version of the paradigm introduces noise in the data, making it more difficult for the preparation effect to be statistically significant. This means that the use of prompt-response pairs would be detrimental (instead of beneficial) in order to observing a reliable preparation effect.

The implicit priming paradigm has been recently adapted to the handwriting investigation. Damian and Stadthagen-Gonzalez (2009) conducted an experiment (Experiment 1) using this paradigm in which participants were asked to write the response words. In the homogeneous blocks, response words shared the phonological and orthographic initial segment (for example, *flow*, *flat*, *flip*, *flap*). The results showed a significant preparation effect in response latencies. These results suggest that implicit priming paradigm can be successfully used in handwriting research. However, it remains unsolved whether phonological information is able to induce a preparation effect in the absence of orthographic overlap. We address this issue by adapting a version of this paradigm in which an odd element (a so called *odd-man-out*) is included in a homogeneous block.

*1. 2. The paradigm with an odd-man-out*

The implicit priming paradigm with an odd-man-out (Janssen, Roelofs, & Levelt, 2002; Cholin et al., 2004; Bi et al., 2009; Roelofs, 2006) has been employed to assess which units are used by the participants in order to build up the oral response. In this variant of the paradigm an item which does not share some property with the rest of response words is included in a homogeneous set. The homogeneous set of words with an odd-man-out is called a *variable set*. For example, Cholin et al., (2004) used this paradigm to test the involvement of the syllable during preparation of the speech production process. In the variable homogeneous set *beacon*, *beatnik*, *beaker* the odd-man-out is the word *beatnik* because it differs from the other words in the first syllable (*beat* versus *bea*), even though it shares with them an initial segment of the same length (*bea*). Cholin et al. (2004) reasoned that if syllabic information is used by the participants in order to produce a spoken word, then the introduction of this odd-man-out should spoil the preparation effect because of the impossibility of unambiguously predicting which syllabic program has to be prepared (*beat* or *bea* in our example).

In the present study we used this paradigm to test if phonological information can affect written latencies. If phonology is retrieved in order to produce a written word, an odd-man-out phonologically related (although not orthographically related) to the other response words would not produce spoil-of-the-preparation effect (or a reduced spoil effect) because the initial phonological segment can still be prepared. This sort of odd-man-out even could activate all the phonologically plausible orthographic forms: the orthographic form included in the odd-man-out but also the alternative orthographic form included in the rest of the response words in the block. For example, in the variable set *banana*, *balada*, *vacuna*, the odd-man-out "vacuna" is phonologically related to the targets (in Spanish both "va" and "ba" are pronounced /ba/). This odd-man-out might not produce spoil of the whole preparation effect because writing the word "vacuna" involves the activation of the phoneme /b/ that would activate the orthographic segment "va", but also the orthographic segment "ba".

Our objective was to test if the possibility of anticipating the phonological initial segment of a response word could lead to the absence of spoil effect or at least to reduced spoil effect compared with a condition in which the odd-man-out is not phonologically related to the target words. In contrast, if phonological information is irrelevant for the retrieval of the orthographic units, then a preparation effect should be observed only in the responses sharing the orthographic initial segment, but not when a phonological relationship exists without orthographic relationship. We chose the odd-man-out variant of the implicit priming paradigm for several reasons. Firstly, this paradigm allowed us to manipulate the phonological relationship of an odd-man-out with the target words while keeping constant the orthographic overlap. Secondly, in the implicit priming paradigm the words serving as odd-man-out are actually produced, differently from prime words in other priming paradigms used in handwriting research. This is important because, as mentioned above, these paradigms have not revealed consistent phonological effects in handwriting (Bonin et al., 1997; 1998; Bonin & Fayol, 2000). It might be possible that phonological influence occurs in a later stage of the spelling process. If phonological information comes into play at a later sublexical level (for example, at the graphemic level) then a paradigm in which the primes (or context words) have to be processed at these later stages seems to be more suitable.

**2. Experiment 1**

In Experiment 1, we examine whether we can induce preparation and spoil of the preparation effect. Longer written latencies are expected in the heterogeneous (*banana*, *mujer*, *periódico*, *recuerdo*) than in the homogeneous block (*banana*, *balada*, *baraja*, *basura*), as previously reported by Damian and Stadthagen-Gonzalez (2009). In addition, the use of a variable set in which the odd-man-out does not share the initial segment with the other response words (*banana*, *balada*, *baraja*, *camisa*) is expected to produce spoil of the preparation effect resulting in written latencies similar to those in the heterogeneous set. More importantly, we created a second variable set in which the odd-man-out did not share the initial segments with the other responses (i.e. with the same orthographic overlap as the former variable set), but did share the phonological initial segment (*banana*, *balada*, *baraja*, *vacuna*). We consider that if phonological information is used by the participants to prepare the written response, a phonologically related odd-man-out should be still able to induce some preparation effect. In contrast, if phonological information is not used when handwriting well-known words, then no differences should be observed between both variable sets.

*2. 1. Method*

<u>Participants.</u> Eighteen students from introductory courses of the University of La Laguna took part in this experiment to fulfill a course credit requirement. All of them were native Spanish speakers, right-handed and with no known motor or perceptive disorders.

<u>Materials.</u> Nine words were selected as responses in order to create three different sets of

three words each. Every set was constructed on the basis of a different first syllable ("ba-", "ve-" and "bo-"). We selected a further nine words, three for each set of words, in order to create the three homogeneous conditions (one constant and two variable conditions). Three additional words totally unrelated to the targets were included to generate the heterogeneous blocks (*mujer*, *periódico*, *recuerdo*). These unrelated words were common to all the sets. Altogether, the experiment consisted of 21 response words. For each set, four experimental conditions were created depending on the relationship among the response words: (1) the *constant homogeneous condition* in which the response words were three target words and one filler word which shared the first syllable with the targets (for example, *banana*, *baraja*, *balada*, *basura*), (2) the *variable homogeneous condition with a phonologically related odd-man-out*, constituted by the three target words and one odd-man-out sharing the first phonological syllable with the targets but not the first orthographic syllable (*banana*, *baraja*, *balada*, *vacuna*), (3) the *variable homogeneous block with a non-phonologically related odd-man-out,* in which the response words were the three target words and a word with a different phonological and orthographic first syllable and with the same orthographic overlap with the target words as the odd-man-out included in (2) (*banana*, *baraja*, *balada*, *camisa*), and (4) the *heterogeneous condition*, constituted by three different blocks, each block containing only one target response plus the three totally unrelated words (*banana*, *mujer*, *periódico*, *recuerdo*). Thus, the experiment included six different experimental blocks (one constant homogeneous, two variable homogeneous and three heterogeneous). For a given set of words, the words used as odd-man-out were matched in word length, syllabic structure, number of syllables, word frequency, orthographic neighborhood, and stress pattern. Each response word was paired with a prompt word which was a synonym of the corresponding response word. We chose this procedure in order to make the relationship between the prompt and the response as similar as possible for all the pairs. Prompts and response words had no obvious orthographic or phonologic overlap. A full set of words is shown in Table 1 as an example. A complete list of the materials used in Experiment 1 is given in Appendix A. Two extra pairs were selected to be used as practice block.

| Condition | | | | | | | |
|---|---|---|---|---|---|---|---|
| Homogeneous | | Variable phonologically related | | Variable phonologically unrelated | | Heterogeneous | |
| Prompt | Response | Prompt | Response | Prompt | Response | Prompt | Response |
| poema | **BALADA** | poema | **BALADA** | poema | **BALADA** | poema | **BALADA** |
| naipes | **BARAJA** | naipes | **BARAJA** | naipes | **BARAJA** | señora | MUJER |
| plátano | **BANANA** | plátano | **BANANA** | plátano | **BANANA** | memoria | RECUERDO |
| suciedad | BASURA | inyección | VACUNA | blusa | CAMISA | diario | PERIÓDICO |

**Table 1.** Prompts (in lowercase) and response (in uppercase) words corresponding to each condition for the "ba-" set of words. Target word appear in bold.

Design. The factor 'Set of words' was a between-subject factor with three levels depending on the syllable used to create the target response words ("ba-", "ve-", "bo-"). The within-subject factor 'Condition' had four levels (constant homogeneous, variable homogeneous with a phonologically related odd-man-out, variable homogeneous with an odd-man-out not phonologically related and heterogeneous). The between-subject factor 'Order' had six levels depending on which out of the 6 experimental blocks was the first being learned and tested. In the data analysis, only the latencies for the three target words were included.

Apparatus. The software SpellWrite II (Cottrell, 1999) was used for stimuli presentation and data collection. The experiment was run on an Apple PowerMac computer. A graphic tablet connected to the computer and an Intuos Pen were used to register the participants' responses.

Procedure. The experiment was run individually in a sound-proof cabin. For each experimental block, the procedure was as follows. In the study phase, participants were asked to learn a block made up of four prompt-response words that were presented on a screen. They were told not to pronounce the words aloud. This phase ended as soon as the participants believed that they could correctly spell the response word in answer to each prompt. During the test phase, the prompt presentation was preceded by an auditory signal. When the prompt word appeared, participants had to write as soon as possible in uppercase letters the associated response word on a lined sheet of paper placed over the graphic tablet. As a pen without ink was used and so no marks were left on the sheet, participants were told to start writing each response word always on the same line. The prompt word disappeared as soon as the written response started. After writing the word, they had to press with their left hand a button labeled "Next" which was set to the left of the workspace of the graphic tablet. By doing this, the next stimuli appeared on the screen. If they did not remember the response word, they were instructed to sketch a horizontal line and then to press the "Next" button. Between trials, participants were instructed to keep the pen (without making contact) above the line used to be written on. Each prompt word was presented three times in a pseudo randomized order, making sure that a given prompt did not appear more than once consecutively and, that the odd-man-out was presented at least once before the last repetition of each target word appeared. The whole experiment lasted around 25 minutes.

*2. 2. Results*

Only correct responses were included in the written latency analysis. The responses registered during the practice block were not included in the analysis. Latencies above and below 2.5 standard deviations from the mean by participant and word were also excluded from the analysis (1.39% of the data). Responses containing misspellings and hesitations or those in which a recording error occurred were considered as errors and also removed from the analysis (0.46%). Table 2 shows the mean and standard deviation for written latencies for each condition. An analysis of variance by participants was conducted over correct responses with 'Condition' as a within-subject factor and 'Set of words' and 'Order' as between-subjects factor. Only the main effect of condition was significant, $F(3, 45) = 3.06$; $MSE = 42{,}416.72$; $p < .05$. *T* tests were carried out in order to clarify which conditions were actually different. Significant differences were observed between constant homogeneous condition and heterogeneous condition ($t(17) = 2.45$, $p < .05$), reflecting the fact that target words were produced faster in the former than in the latter condition. In addition, the constant homogeneous condition was significantly faster than the variable homogeneous condition with a non-phonologically related odd-man-out ($t(17) = 2.93$, $p < .01$). Importantly, no differences were observed between the constant condition and the variable condition with a phonologically related odd-man-out ($F < 1$). The comparison between both variable conditions was marginally significant ($t(17) = 1.90$, $p = .074$), with shorter written latencies when the odd-man-out was phonologically related to the targets.

| Condition | *M* | *SD* | Preparation effect |
|---|---|---|---|
| Homogeneous | 1167 | 283 | 101 |
| Variable phonologically related | 1187 | 272 | 81 |
| Variable phonologically unrelated | 1250 | 309 | 18 |
| Heterogeneous | 1268 | 304 | |

**Table 2.** Mean written latencies (in ms), standard deviations and preparation effects (in ms) in Experiment 1

*2. 3. Conclusions*

In Experiment 1 we obtained a preparation effect, indicating that participants were able to prepare their written responses based on the shared segments of the words within a block. Furthermore, the preparation effect vanished when an odd-man-out not sharing the initial orthographic or phonological segment was included, suggesting that participants were no longer able to anticipate the initial segment of the response. These results indicate that this paradigm is indeed adequate for handwriting research: we were able to induce both a preparation effect and a spoil of the preparation effect. Crucially, no differences were observed between the constant homogeneous condition and the variable condition containing an odd-man-out phonologically related to the target words. The absence of spoil effect when the odd-man-out shared with the target words the initial phonological segment points to the use of the phonological information during the writing process, benefiting the speed of the written response.

However, there could be alternative explanations for the absence of spoil effect in the variable phonologically related homogeneous condition. It is possible that Experiment 1 is not powerful enough to capture differences between the constant homogeneous condition and the variable phonologically related condition. Our experimental design was rather complex, crossing three factors and resulting in a very high number of conditions (3x4x6 = 72 levels). It is possible that the odd-man-out is in fact spoiling the preparation effect but this cannot be observed with the present experimental power. In order to confirm or to rule out this hypothesis, a greater number of participants took part in Experiment 2.

Additionally, it could be that some characteristics of the stimuli affected the pattern of results. If the movements involved in the production of the first letter of the odd-man-out are more similar to the movements involved in the first letter of the targets in the phonologically related condition than in the phonologically unrelated condition, then faster latencies can be expected in the former condition purely due to an effect of practice. In Experiment 2 we replaced the words used as odd-man-out in Experiment 1 by words starting with letters which had a similar first stroke in both variable conditions. For example, for the "vi-" set *bidón* and *pitón* were used as phonologically and not phonologically related odd-man-out respectively, because *B* and *P* are both letters with an initial down stroke. By doing this, we expected to avoid potential effects due to pure repetition of the hand-movements. Moreover, in Experiment 2 we used four instead of three set of words in order to control for potential effects due to the identity of the target phonemes: differently from Experiment 1, in Experiment 2 two sets were generated based on syllables starting with the grapheme *B* ("ba-", "bo-") and the other two sets were based on syllables starting with the grapheme *V* ("ve-", "vi-"). These modifications allowed us: (a) to enhance the amount of trials performed in a particular condition, (b) to focus just on the size of the spoil effect, and (c) to make the new experimental conditions as comparable as possible.

**3. Experiment 2**

Experiment 2 tested the hypothesis that a real spoil effect due to the phonologically related odd-man-out was not detected in Experiment 1. For this reason, in Experiment 2 we focused on the comparison of the spoil effect produced by each variable condition (odd-man-out phonologically versus not phonologically related). Differently from Experiment 1, we generated four set of words: ("ba-", "bo-", "ve-", "vi") instead of three, and we replaced the words serving as odd-man-outs in order to make them as comparable as possible across conditions.

*3. 1. Method*

Participants. Forty-eight students from introductory courses of the University of La Laguna took part in this experiment to fulfill a course credit requirement. All of them were native Spanish speakers, right-handed and with no known motor or perceptive disorders. None of them participated in Experiment 1.

Materials. The same stimuli as in Experiment 1 were used with the modification mentioned above. Furthermore, the pairs of words used to create the heterogeneous condition in Experiment 1 (*señora-mujer*, *diario-periódico*, *memoria-recuerdo*) were not included in Experiment 2. A full list of the materials used in Experiment 2 is shown in Appendix B.

Design. The experimental design was the same as in Experiment 1, but in this case each participant was asked to learn just three experimental blocks: (1) one constant homogeneous block, (2) one variable homogeneous block with a phonologically related odd-man-out and (3) one variable homogeneous block a non-phonologically related odd-man-out. Thus, the between-subject factor 'Order' had three levels depending on which block was the first being presented.

Apparatus and procedure. Apparatus and procedure were the same as those used in

Experiment 1, but in this experiment each prompt word appeared four times per block instead of three times.

*3. 2. Results*

An analysis of variance (ANOVA) was carried out on the written latencies, with ‘Condition’ (constant, variable phonologically related and variable phonologically unrelated) as within-subject factors and ‘Order’ and ‘Set of words’ as between-subject factors. The same exclusion criteria as in Experiment 1 were applied. 1.56% of the trials were extreme outliers and 1.85% of the data were treated as errors. Mean written latencies and standard deviations for each condition are shown in Table 3. A main effect of condition was found, $F(2, 72) = 9.06$; $MSE = 63{,}037.37$; $p < .001$. *T* tests were carried out in order to clarify which conditions were significantly different. Significant differences were observed between constant homogeneous condition and variable condition phonologically related ($t(47) = 2.32$, $p < .05$), and between the constant homogeneous condition ant the variable condition without phonological relationship ($t(47) = 3.66$, $p < .01$), reflecting shorter written latencies in the constant condition than in both variable conditions. More importantly, the difference between the variable phonologically related condition and the variable condition not phonologically related was also significant ($t(47) = 2.30$, $p < .05$). Longer latencies were measured when the odd-man-out was not phonologically related to the target words. Besides, the variable ‘Set of words’ was significant, $F(3, 36) = 2.92$; $MSE = 418{,}483.93$; $p < .05$. *T* test revealed that the set of “ve-” words was slower than the set “ba-” ($t(35) = 4.23$, $p < .01$, than the set “bo-” ($t(35) = 3.76$, $p < .01$) and finally than the set “vi-” ($t(35) = 6.16$, $p < .01$). No other differences were significant.

| Condition | *M* | *SD* | Spoil effect |
|---|---|---|---|
| Homogeneous | 913 | 222 | |
| Variable phonologically related | 947 | 226 | 34 |
| Variable phonologically unrelated | 985 | 233 | 72 |

**Table 3.** Mean written latencies (in ms), standard deviations and spoil effects (in ms) in Experiment 2

*3. 3. Conclusions*

The results obtained in Experiment 2 are similar to those observed in Experiment 1, but in this case a spoil effect in the variable phonologically related condition was also observed. The improvements introduced in Experiment 2 in the materials and the design allowed us to detect an advantage of the constant homogeneous blocks over both variable blocks, indicating that the preparation effect is stronger when all the words within a block share orthographic onset. Critically, participants were faster when the odd-man-out was phonologically related to the target words that when there was no phonological relationship, even though orthographic overlap with the targets was the same in both variable groups.

The results obtained in Experiments 1 and 2 suggest that phonology is used by the participants during the writing process. Written latencies were benefited when participants were able to prepare the initial phonological segment of a response word in advance. It seems that sublexical phonological information is retrieved during handwriting, so the constant homogeneous blocks and the variable blocks with a phonologically related odd-man-out allow the anticipation of the phonological unit to be produced. However, it is possible to propose a lexical explanation for our findings. It could be the case that the phonological lexical form of the phonologically related odd-man-out *vacuna* (/bakuna/) activates other lexical entries related to it in the phonological lexicon (for example, /baka/, /baliente/, /banana/, /baraja/, etc.). These phonological word-forms would in turn activate the corresponding orthographic word-forms (*vaca*, *valiente*, *banana*, *baraja*, etc.) through links between the phonological lexicon and the orthographic lexicon (Bonin, Peereman et al., 2001). This kind of process would offer a lexical account of the results obtained in Experiment 1 and 2. In order to confirm or overrule this account, we conducted a third experiment in which we used articulatory suppression to selectively interfere with the sublexical processes. Articulatory suppression involves making a participant repeatedly produce an irrelevant word or sublexical unit. This procedure has proved successful in selectively disrupting the sublexical process in written spelling by interrupting the subvocal rehearsal. For example, the patient MMD, studied by Folk, Rapp, & Goldrick (2002), produced more form-related substitutions with articulatory suppression than without articulatory suppression. In addition, MMD made more errors on words containing low-frequency phoneme-to-grapheme segments than on words with high-frequency phoneme-to-grapheme segments when spelling in normal conditions. However, this difference disappeared under articulatory suppression. This pattern suggests that articulatory suppression affected sublexical processing while sparing the lexical processing. This ability of articulatory suppression to "disconnect" phonological sublexical processing offers us a unique opportunity to test if the phonological preparation effect originates at the lexical or at the sublexical level.

## 4. Experiment 3

In Experiment 3 the participants performed the same task as in Experiment 2 but in this case under articulatory suppression. If the effects observed in Experiment 2 originated at a sublexical level they should disappear in Experiment 3. Conversely, if the lexical account is correct, the preparation effect and spoil effect should be equivalent to those obtained in Experiment 2.

### *4. 1. Method*

Participants. Forty-eight students from introductory courses of the University of La

Laguna took part in this experiment to fulfill a course credit requirement. All of them were native Spanish speakers, right-handed and with no known motor or perceptive disorders. None of them participated in Experiments 1 or 2.

Materials and design. The same materials and design as in Experiment 2 were used.

Procedure. The procedure was the same as in Experiment 2, but in this case participants had to repeat the meaningless syllable /lu/ during all the test phase. We chose this syllable because it was not present in any of the response words used in the experiment. During the practice block they were instructed to produce this syllable in a systematic manner, with an equivalent time interval between repetitions. During the test phase they had to start producing it as soon as they saw the first fixation point.

*4. 2. Results*

An analysis of variance (ANOVA) was carried out on the written latencies from Experiment 2 and 3, with 'Condition' (constant, variable phonologically related, variable phonologically unrelated) as a within-subject factor and 'Order' and 'Set of words' as between-subject factors. Extreme outliers (1.62%) and errors (1.86%) were excluded from the analysis following the same criteria as in Experiments 1 and 2. Mean written latencies and standard deviation obtained in Experiment 3 for each condition are shown in Table 4. None of the included variables reached significance ($F < 1$). Constant homogeneous blocks were not faster than the variable blocks and both variable blocks did not differ from each other. Another ANOVA was conducted over the latencies of Experiment 2 and 3, including 'Condition' as a within-subject factor and 'Order', 'Set of words' and 'Experiment' (Experiment 2, Experiment 3) as between-subject factors. We wanted to know whether the introduction of articulatory suppression reliably changed the pattern of results. The analysis showed that the two-way interaction

Experiment x Condition was significant ($F(2, 144) = 4.31$; $MSE = 20{,}732.53$; $p < .05$), showing that the effects observed in Experiment 2 were absent in Experiment 3.

| Condition | *M* | *SD* | Spoil effect |
|---|---|---|---|
| Homogeneous | 966 | 221 | |
| Variable phonologically related | 989 | 218 | 23 |
| Variable phonologically unrelated | 985 | 230 | 21 |

**Table 4.** Mean written latencies (in ms), standard deviations and spoil effects (in ms) in Experiment 3

*4. 3. Conclusions*

In Experiment 3 we failed to obtain preparation effects. Participants did not benefit from the shared segments of the response words. These results suggest a sublexical nature of the effects observed using the implicit priming paradigm in Experiments 1 and 2. It seems that participants were unable to use the information about the shared initial segments when the sublexical pathway was engaged in processing a different sublexical unit. This indicates that the preparation effect was attributable to anticipation of the shared initial segments of the response words, and not due to an advantage coming from the activation of related words in the phonological lexicon.

## 5. Discussion

We report three experiments investigating the role of phonology during the writing process. We used the odd-man-out variant of the implicit priming paradigm in order to determine if phonological information was used by the participants to prepare the written response. In this paradigm, participants produced a previously-learned list of words which could share or not the initial segment. In Experiment 1 we observed shorter response latencies when the target words were embedded in constant homogeneous blocks (all the response words shared the initial segment) than in heterogeneous blocks (none of the responses shared the initial segment). This indicates that participants used the information about the shared segments of the response words to prepare the forthcoming written response. However, when an odd-man-out completely unrelated to the target response words was included, the participants were no longer able to anticipate the initial segment of the response, leading to a spoil effect. Crucially, we failed to obtain a spoil effect in Experiment 1 when the odd-man-out was phonologically related (but not orthographically related) to the target words. In addition, we found differences between both groups of odd-man-out (phonologically related vs. not phonologically related). In Experiment 2, with improved materials and design, we obtained a spoil effect due to the phonologically related odd-man-out, but this was significantly smaller than that observed in the non-phonologically related condition. This pattern of results suggests that participants' written responses profited from the phonological information provided by the phonologically related odd-man-out. Experiment 3 showed that the preparation effect vanished under articulatory suppression. We interpret these results as evidence supporting the involvement of phonological information during handwriting at a sublexical level.

Our findings fit with a functional architecture in which lexical and sublexical processes integrate information at a grapheme level (Houghton & Zorzi, 1998, 2003; Rapp et al., 2002, Folk et al., 2002), so the activation of the same graphemic element from both processes would strengthen the correct selection of the initial segment (Tainturier & Rapp, 2001; Bonin, Peereman et al., 2001). If such a mechanism is assumed, a strong preparation effect is expected for the constant homogeneous condition, because the lexical orthographic information is reinforced by the constant activation of an orthographic element through the sublexical system. When performing a variable block, an initial segment different from the target one is introduced by the odd-man-out, so participants cannot unambiguously select the correct initial segment in advance. However, when the odd-man-out is phonologically related to the target responses, the target initial phonological segment can still be prepared, even before response selection (Roelofs, 2008). It is also possible that the initial phonological segment of the phonologically related odd-man-out activates all the orthographic forms linked to it, including the orthographic form present in the target response words. This process would produce an advantage of the variable phonologically related condition over the non-phonologically related condition.

For example, in the variable phonologically related block constituted by the response words *baraja*, *balada*, *banana*, *vacuna*, the written performance of the initial segment of the odd-man-out *vacuna* ("va-") implies the retrieval of the sublexical phonological unit /ba/, which is in fact shared by all the response words of the block. Even when the participants cannot anticipate the actual initial grapheme (the next response word can start with either the letter *b* or the letter *v*), they are still able to predict the initial phonological segment of the next response. It is possible that this phonological segment activated both the grapheme *b* and the grapheme *v*. Conversely, when the odd-man-out is neither phonological nor orthographically related to the targets, such as *tarima* in our example, target words cannot profit from either the orthographic or the phonological sublexical information. In consequence, spoiling of the whole preparation effect is observed.

If a sublexical account of the observed effects is correct, then both orthographic and phonological preparation should disappear when the sublexical process is disconnected, because only lexical information would be available to perform the task. In Experiment 3 we tested this prediction by using articulatory suppression. It is generally assumed that the continual repetition of a meaningless syllable selectively disrupts the sublexical process by interrupting the subvocal rehearsal. We did not obtain a preparation effect when participants performed the writing task under articulatory suppression. It seems that participants were not able to use the information about the segments shared by the response words when sublexical processes were engaged in a different task (in our experiment, producing the syllable /lu/). This suggests that the preparation effects observed in Experiments 1 and 2 originated at a sublexical level.

Although we cannot discard the obligatory phonological mediation hypothesis based on the results obtained in the present study, this kind of theory has been progressively disregarded due to a large amount of experimental and neuropsychological data that it cannot account for. As mentioned above, from the obligatory mediation point of view it is difficult not only to explain the performance of several neuropsychological patients, (Miceli et al., 1997; Lhermitte & Dérouesné, 1974; Rapp et al., 1997), but also the normal writing process in an opaque language (Hotopf, 1980). Therefore, we consider that the sublexical version of the orthographic autonomy hypothesis represents the optimum perspective in order to account for the pattern of results obtained in the literature concerning the spelling process, including the evidence reported here.

We think that our data provide strong evidence for the involvement of phonological information in the unimpaired handwriting production process through sublexical mechanisms. It seems that the sublexical process would strengthen the correct selection of the constitutive graphemes of a word. Some particularities of our experimental design allow us to rule out several alternative explanations for the phonological preparation effect reported here. Firstly, it is worth noting that both odd-man-outs had the same orthographic overlap with the target words, so this cannot be the cause of the reduced spoil effect observed in the variable phonologically related blocks. Furthermore, this effect cannot be attributed to the influence of the visual information given by previous responses, because the ink of the pen was removed so participants could not see what they wrote. Likewise, the reduced spoil effect cannot be explained by differences in latency between the words used as odd-man-out, because only the target words (which were the same across all the conditions) were considered for the analysis. Finally, it is unlikely that general memory retrieval processes were responsible for the present results. Studies using immediate serial recall tasks report slower response times when the items have a phonological relation (Baddeley, 1997; Cholin et al., 2004), while we observed faster written latencies when the odd-man-out was phonologically related to the targets. Moreover, preparation effects have been obtained even when the memory component of the task was absent (Roelofs, 1999; Alario et al., 2006; Santiago, 2000).

In summary, the experiments included in Chapter 3 confirm the involvement of phonological information in the spelling process, and support those models of handwriting that propose that both the lexical and assembled routes integrate information in a later stage of processing. In Chapter 4, we will address the involvement of the sublexical route in the copy task, which has been less studied than other spelling task. Moreover, we will try to establish how the phoneme-to-grapheme conversion patterns are organized, and specifically if the activation level for a phoneme affects the execution of its corresponding grapheme

.

# 4

# The organization of the phonology-to-orthography correspondences

## 1. Phonological effects in the copy task

We have seen in Chapter 3 that phonology plays a role during a task with associated-pairs, which suggests that sublexical procedures can affect writing beyond the spelling-to-dictation task. However, it is unclear if phonological information is functional when the orthographic form of the stimulus is presented, as in copy. The involvement of phonological information during copy has given rise to significantly less debate than other writing tasks, such as spelling-to-dictation or written picture naming (Zhang & Damian, 2010; Delattre et al., 2006; Bonin et al., 1997; Bonin, Peereman et al., 2001). This is mainly due to the extensive agreement about the relative insensitivity of this task to phonological effects, especially when experienced writers copy well-known words. When adults copy words two groups of processes intervene: reading processes and spelling processes. As a result of the reading processes, a semantic representation is activated by the visual presentation of a word. By means of the spelling processes, this semantic representation would give access to the appropriate orthographic form stored in the output lexicon. Although other processing routes for copy have been proposed to be available, the described route is thought to be the most commonly used by an adult writer (Cuetos, 1991; Jiménez & Muñetón-Ayala, 2002). This means that the copy task is usually considered to be performed via lexical access, so an impact of the assembled (phonological) route during the spelling processes is not expected. Nonetheless, some authors have proposed the existence of a phonologically mediated route for copy (Cuetos, 1991), although it has been claimed to have little impact on handwriting, and only in very limited circumstances.

The functional architecture depicted in Figure 6 (Tainturier & Rapp, 2001; Folk et al., 2002; Folk & Rapp, 2004; Rapp et al., 2002) has been specifically introduced to model the spelling-to-dictation process. In this proposal, it is stated that the phonology-to-orthography (henceforth, P-O) conversion system is activated by the phonological input itself. This is the main difference between this model and that described in Chapter 2 (Bonin, Peereman et al., 2001; see Figure 5), in which the sublexical route is thought to be initiated by the individual phonemes, which are activated by the phonological output lexical representation. According to the latter perspective, phonological effects could be observed in written picture naming because the semantic system would activate both the phonological (output) lexicon and the orthographic (output) lexicon. In contrast, according to the work frame sketched by Tainturier & Rapp (2001), the sublexical route would have no influence on the process of copying well-known words. Phonological information would come into play almost exclusively with auditory stimuli, and especially when an orthographic (output) lexical representation is

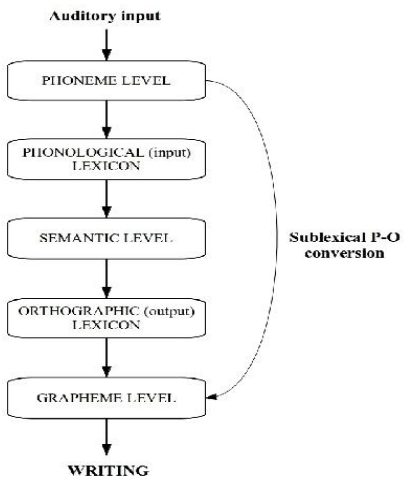


**Figure 6.** Model of spelling-to-dictation, adapted from Folk & Rapp, 2004.

unavailable or impoverished (nonwords, low-frequency words). Thus, it would not be clear how this perspective could be conciliated with the phonological effects predicted by the model postulated by Bonin, Peereman et al. (2001) for written picture naming. Even though it is not impossible to adapt the proposal of Tainturier & Rapp so as to integrate potential phonological effects in this task, several modifications (or at least further specifications) should be added to this model to fit phonological effects in semantically driven tasks in which the input is not auditory.

Differently from these proposals, the working model introduced by Cuetos (1991) explicitly describes those mechanisms assumed to underlie the copy task (see Figure 7). The author contemplates at least three different linguistic[1] processing routes that might be engaged

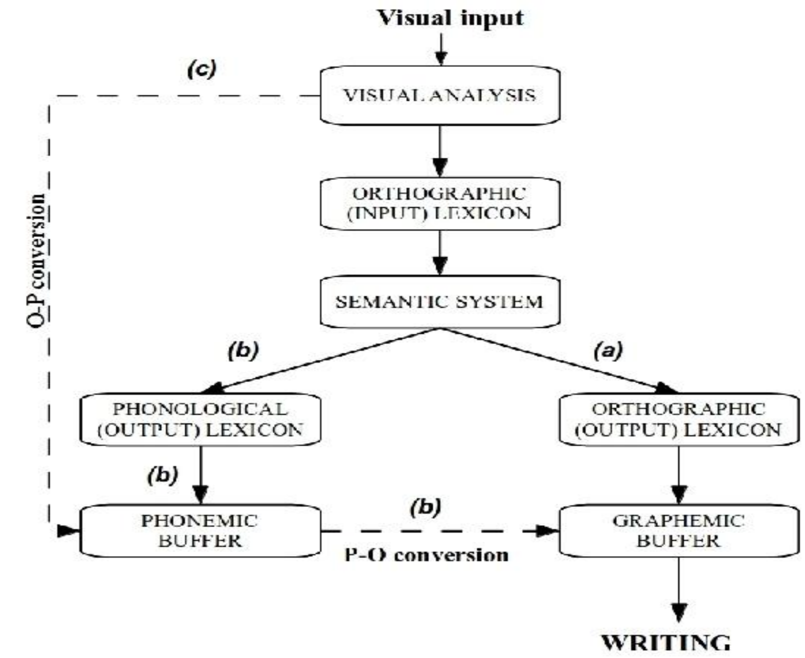


**Figure 7.** Model of copy, adapted from Cuetos, 1991.

[1] It has also been claimed that a non-linguistic route would be available for copy. This route would consist in the reproduction of letters as meaningless forms (just like replicating a drawing). Because this route would not engage any linguistic process, we will not discuss it in further detail. In any case, this route is highly unlikely to be used in normal skillful writing, since it would be extremely slow and resource-consuming.

during copy: a non-phonologically mediated route and two phonological routes. The dotted lines represent the routes that are thought to be used for spelling nonwords.

(a) According to the author, the lexical route described above is the most common path for copy. The appropriate orthographic lexical form is directly accessed via the semantic system, just after the visual input has been decoded.

(b) In this route a semantic representation is also activated as a result of the reading process. This semantic representation, besides retrieving the corresponding word-form from the orthographic output lexicon, would also activate a word-form in the phonological (output) lexicon. The individual phonemes constituting this phonological word-form would then be identified and kept in a sort of phonological buffer (the pronunciation buffer). The phonemes maintained in this buffer would activate the corresponding graphemes according to the phoneme-to-grapheme conversion patterns permitted in the language.

(c) Finally, the copy process could start with the identification of the individual letters by means of the visual analysis. These letters would activate their corresponding phonemes[2] through the orthography-to-phonology (O-P) conversion patterns. Subsequent to the retrieval of the associated phonemes, P-O correspondences would activate a phonologically plausible graphemic candidate for each phoneme. Obviously, this route would operate in the absence of semantic/lexical activation, so it would be bound to produce numerous misspellings when orthographically ambiguous phonemes (e.g., phonemes with more than one possible graphemic representation) are present in the input. The use of this route by young children explains why they produce misspellings even

[2] We use the term phoneme for the sake of clarity. Although is widely accepted that the sublexical system links phonemes to graphemes, the precise nature (and size) of the units involved during the P-O conversion process remain unclear (Folk & Rapp, 2004).

during copy.

Although the existence of these routes has been virtually undisputed, the use of (b) and (c) is thought to be rather limited in normal writing conditions. When faced with well-known words, adult writers are likely to understand them and to retrieve the corresponding word-form directly from the orthographic lexicon without any phonological mediation. The phonological routes of copy would be used almost exclusively by children learning to write and by adults copying pseudowords (Cuetos, 1991), as well as dysgraphic patients with serious damage to the lexical system. To put it differently, when normal adults copy well-known words, phonological information is believed to have little or no impact on writing latencies or durations.

## 2. The organization of the P-O conversion system

The phonology-to-orthography conversion patterns are thought to consist of phoneme-to-grapheme mappings weighted according to their frequency in the language. Specifically, it is claimed that the more frequent a grapheme is, the more accessible it becomes. This idea has been supported by psycholinguistic and neuropsychological evidence (Miceli, 1989; Cuetos, 1991; Barry & Seymour, 1988; Sanders & Caramazza, 1990; Goodman & Caramazza, 1986). For example, Barry and Seymour (1988) observed that P-O probability affected the spelling of nonwords. In their study, English speakers were more likely to spell the phoneme /i/ as *ee* (consistently with the most frequent mapping in the language) than as *ie* (a lower-frequency mapping). Moreover, Sanders and Caramazza (1990) reported the case of a dysgraphic patient who relied on the sublexical processes to spell many words. An analysis of his phonologically plausible errors (PPEs) revealed that the relative frequency of a grapheme correlated with the frequency of the spellings given by the patient when spelling an inconsistent phoneme. This effect has been observed to interact with lexical processes during the spelling of nonwords

(Barry & Seymour, 1988; Cuetos, 1991; Folk & Rapp, 2004; Tainturier, Bosse, Valdois, & Rapp, 2000; Bosse et al., 2003). Tainturier and colleagues (2000) observed that nonwords were more probable to be spelled with a low-frequency mapping if they had a phonological neighbor (a word different to the nonword only by one phoneme) containing that mapping. In addition, low-probability mappings are more likely to be produced in spelling-to-dictation of nonwords when a prime word including the low-probability mapping is previously presented (Barry & Seymour, 1988; Folk & Rapp, 2004).

More importantly for the present study, the relative frequency of graphemes seems to have an effect not only on nonwords, but also on word spelling. The so called regularity effect refers to the fact that there is a processing advantage for words containing high-probability mappings over low-probability mappings, as manifested by shorter latencies and writing durations and/or less errors. This effect has been observed in the spelling-to-dictation task (Delattre et al., 2006), in a copy study conducted with children (Kandel & Valdois, 2005), and in the evaluation of some dysgraphic patients (Rapp et al., 2002), and it has been interpreted as evidence of the integration of the outputs of the lexical and sublexical routes. Based on these convergent results, there is general consensus about the probabilistic organization of the P-O mappings.

In a similar way, the relative frequency of the activated phonemes might well have an impact on the accessibility of the intended graphemes. If phonemes mediate during grapheme retrieval process, as proposed in Figure 7, more frequent phonemes could give faster access to their corresponding graphemes than lower-frequency phonemes. This would be due to the fact that each time a phoneme is associated to a given grapheme the connection between them would be strengthen, so frequent phonemes would be faster mapped onto their corresponding graphemes. The impact of relative phonemic frequency has not being experimentally addressed until now. This fact is not surprising if we consider the paucity of experimental evidence regarding the organization of the sublexical route.

The finding of an effect of grapheme-to-phoneme (G-P henceforth) probability during copy would confirm that phonological information is retrieved also during this task. More importantly it would manifest that the sublexical route is sensitive not only to the relative graphemic frequency, but also to the relative phonemic frequency. For example, both phonemes /k/ and /θ/ can be represented by the grapheme *c* in Spanish. If only grapheme frequency has an impact on the organization of the P-O conversion rules, then the grapheme *c* should be retrieved equally fast regardless of its specific pronunciation in a given word. However, *c* may be faster accessed at the grapheme level when representing a relatively more frequent pronunciation. That is to say, it might be the case that the assembled route is organized not only based on how consistent is a P-O correspondence (i.e., regularity), but also on the frequency with which a writer has to apply that specific conversion pattern. Those graphemes which are phonologically ambiguous (such as *c* in Spanish) are called polyvalent graphemes (Alarcos-Llorach, 2011; Jiménez & Muñetón-Ayala, 2002), and they have never been tested in a handwriting study.

**3. Polyvalent graphemes**

Whereas monovalent graphemes represent the same phoneme in any context (e.g., the grapheme *d* in Spanish, which is always pronounced /d/), polyvalent graphemes correspond to different phonemes depending on the letters nearby or their relative position within a word. For instance, the grapheme *c* is polyvalent in Spanish because it may represent either the sound /k/ or either the sound /θ/ depending on the surrounding letters (for example, in *casa –house–* and *cesta –basket–*, /kasa/ and /θesta/ respectively). This particularity of polyvalent graphemes provides an incomparable opportunity to test two different phonemes (with two different frequencies of use) by measuring the duration of the same grapheme. In the present chapter, we used polyvalent graphemes with a twofold aim. First, we tested the hypothesis that the activation level reached by a phoneme has an impact on the retrieval of the corresponding grapheme. If this is indeed the case, it would have major implications for current models of handwriting, since only the relative frequency of graphemes has been the hypothesized to be relevant for the application of the P-O conversion patterns. Second, if a phonemic relative frequency effect is obtained with words, this will confirm the existence (and regular use) of a phonologically-mediated route for copy, even when a lexical representation is available.

We decided to address this issue in French, a language in which polyvalent graphemes are relatively common. French is a highly opaque language, especially concerning the P-O correspondences. Thus, it would be reasonable to think that phonological information may have a reduced impact on the writing process. Whereas spelling in Spanish (and other transparent languages) may be successfully accomplished by resorting exclusively to the sublexical processes (Ardila, 1998), writers in an opaque language must possess accurate orthographic (lexical) knowledge, in order to avoid misspellings. In other words, the involvement of phonological information during the spelling process in French could be highly counterproductive, since it would be likely to lead into error. This means that in the following experiments we are stacking the deck against the possibility of finding a reliable phonemic relative frequency effect.

**4. Experiment 4**

We aimed to test whether a given grapheme is written faster when it represents a typical (high-frequency) sound than an atypical (low-frequency) sound. The logic is that the connection between a frequent phonemic form and its corresponding grapheme would be stronger than the connection between an infrequent phonemic form and the same grapheme. Therefore, a highly frequent phoneme would be a better trigger of its associated graphemes. More precisely, we predict that, given the same orthographic sequence, this will be produced faster when representing a typical than an atypical sound for that sequence. For example, in French the grapheme *e* is most frequently pronounced /ɛ/, such as the first *e* in *service* (in English, *service*); however, it can also be pronounced /ø/, such as the first *e* in *semaine* (*week*). However, the latter is a less common pronunciation for this letter. If phonemes mediate during the grapheme retrieval process according to probabilistic principles, then /ɛ/ would give faster access to the letter *e* than /ø/. In consonance with the anticipatory vision of handwriting (Van Galen, 1991; Kandel et al., 2011), we predict that the processing advantage of high-frequency phonemes over low-frequency phonemes would affect central processes concerning the critical grapheme, so an effect would be observable in the writing durations obtained for the segments previous to the real-time execution of the target grapheme.

In order to address this issue, we selected words which embedded the same polyvalent grapheme and that differed in its pronunciation. By doing so, we managed to compare the same letter in two different phonological conditions that differed just in the frequency of the phoneme. Of course, phonological influence during copy may be relatively weak, so it is possible that a considerable difference has to exist between both alternative pronunciations to produce a significant effect. We also tested this possibility by assessing two different sequences: in Experiment 4a we tested an orthographic form slightly biased towards one of its pronunciations (*ti*), and in Experiment 4b we used a strongly biased grapheme (*e*). We predicted that the same sequence would be retrieved faster when representing its most frequent phonemic form, but this effect would only be significant (or maybe larger) in the case of graphemes strongly biased (e.g., *e*).

*4. 1. Experiment 4a*

*4. 1. 1. Method*

Participants. Twenty-five students from Psychology introductory courses at the Université Pierre-Mendés-France took part in this experiment to fulfill a course credit requirement. All of them were native French speakers, right-handed and with no known motor or perceptive disorders. None of them participated in any of the other experiments included in this manuscript.

Materials. Fifty-two experimental stimuli including the orthographic sequence "*ti*" were selected. For a half of the stimuli this sequence represented the sound /ti/ (for 66% of the words containing "*ti*", this sequence is pronounced /ti/; for example, *victime*), and the other half represented the sound /sj/ (28.22% of the words with *"ti*"; for example, *martien*). This means that this sequence is not strongly biased towards the /ti/ pronunciation, which is still more frequent than /sj/. All the selected words were matched by the position of the target sequence, lexical frequency, frequency of the bigrams before and after the target sequence (e.g. in the word *victime*, the bigrams "*ct*" and "*im*"), word length (number of letters and number of phonemes), orthographic neighborhood, orthographic uniqueness point and number of syllables. T-tests were conducted to make sure that these variables did not significantly differ across conditions (all $t$s < 1). The full set of stimuli with their values in these controlled variables are given in Appendix C. Ninety additional words were selected to serve as fillers, plus 3 more for the practice phase.

Procedure. Stimuli presentation and digital recording of the responses were controlled by Ductus (Guinet & Kandel, 2010). The experiment was run on an Asus F9Eseries laptop. The experiment consisted of a copy task and it was conducted individually in a sound-proof room. Each trial started with a 200-ms fixation point (+) in the center of the screen immediately followed by the presentation of a centered 16 points lower-case word. The participants had to write the word in upper case on a lined sheet of paper placed over the graphic tablet (Wacom Intuos LD-1218-u) as soon and as accurately as possible. When participants finished a trial, the experimenter clicked the left button of the mouse to lead to a new stimulus. A whole experimental session lasted around 30 minutes.

*4. 1. 2. Results*

Writing durations for critical grapheme *t* and the previous and posterior inter-letter intervals (henceforth, LD, ILI0, ILI1, respectively) were submitted to separate analyses of variance (ANOVAs), with the relative frequency of P-O correspondence (higher vs. lower) as a within-participants variable in the analysis by participants ($F_1$) and a between-participants variable in the analysis by items ($F_2$).

No differences in this experiment reached significance, neither in ILIs nor in letter duration (all *F*s < 1, except ILI0: $F_1 = 1.61$, $MSE = 101.13$, $p = .22$, $1 - \beta = .23$).

*4. 2. <u>Experiment 4b</u>*

Experiment 4a failed to show an effect of relative frequency of the graphemic form when the sequence "*ti*" had to be written. However, we suspect such a pattern of results is due to the fact that both pronunciations are not so different regarding their frequency (approximately 66% versus almost 30%). Phonological effects during the copy of well-known words in an opaque language might be rather weak, so maybe a strong bias is necessary to obtain a reliable effect. Thus, we conducted a new experiment in French, in this case using the letter *e*. Differently from "*t*", this letter is highly biased towards one specific pronunciation: it is pronounced /ɛ/ a 71% of the times and /ø/ only around a 9% of the French words containing the letter *e*.

*4. 2. 1. Method*

Participants. Twenty-five participants from the same population as in Experiment 4a took part in this experiment.

Materials. We selected fifty-eight stimuli containing the letter *e*. This letter was pronounced /ɛ/ in a half of the experimental stimuli and /ø/ in the other half. We matched them according to the position of the first *e* in the word, as well as the number of times that letter *e* was included in the word. Additionally, we matched both conditions by the same variables taken into account in Experiment 4a (all *t*s < 1).

Procedure, apparatus, design. The experimental procedure, apparatus and statistical analyses were identical to those described in Experiment 4a.

*4. 2. 2. Results*

A significant effect of relative frequency was observed in ILI0 durations ($F_1(1, 24) = 9.52$, $p < .005$, $MSE = 191.7$; $F_2(1, 56) = 5.85$, $p < .05$, $MSE = 286.91$), ILI1 ($F_1(1, 24) = 31.03$, $p < .001$, $MSE = 2{,}118.17$; $F_2(1, 56) = 18.95$, $p < .001$, $MSE = 1{,}981.4$), and LD ($F_1(1, 24) = 8.43$, $p < .01$, $MSE = 327.64$; $F_2(1, 56) = 5.12$, $p < .05$, $MSE = 635.59$). All three measures were faster in the condition of high-frequency of pronunciation. As showed in Table 5, participants produced a shorter inter-letter interval before and after the target grapheme *e*, which was also faster executed when corresponded to the most frequent pronunciation.

| G-P probability | ILI0 | LD | ILI1 |
|---|---|---|---|
| High (/ɛ/) | 140 | 541 | 123 |
| Low (/ø/) | 144 | 546 | 136 |

**Table 5.** Writing durations for the critical letter *e* and durations of the previous and posterior inter-letters intervals (ILI0, ILI1) in milliseconds, in Experiment 4b.

Another ANOVA was carried out on the writing durations from Experiments 4a and 4b, with relative frequency (higher, lower) as a within-subject variable and experiment (a, b) as a between-subject variable. We aimed to establish whether or not the frequency effect reliably differed depending on the strength of the pronunciation bias (i.e., depending on the experiment). Regarding LD, the phonemic relative frequency effect was significant, $F(1, 48) = 6.43$, $p = .05$, $MSE = 233.2$, and so was the variable experiment, $F(1, 48) = 42.38$, $p < .001$, $MSE = 812{,}738.67$. LD was longer in Experiment 4b than in Experiment 4a. The interaction Frequency x Experiment was marginally significant, $F(1, 48) = 2.94$, $p = .093$, $MSE = 106.66$). T-tests showed that phoneme frequency affected LD in Experiment 4b ($t(24) = 2.9$, $p < .01$), but not in Experiment 4a ($t < 1$). In the case of the durations of ILI0, we observed a reliable relative frequency effect, $F(1, 48) = 6.9$, $p < .05$, $MSE = 285.63$. Neither the variable experiment nor the interaction Frequency x Experiment were significant (all $F$s $< 1$). Whereas, ILI1 durations showed an effect of the relative frequency of a phoneme ($F(1, 48) = 9.8$, $p < .005$, $MSE = 887.62$), and a significant interaction Frequency x Experiment ($F(1, 48) = 13.76$, $p < .005$, $MSE = 1{,}245.69$). T-tests revealed that frequency only affected the durations of ILI1 in Experiment 4b ($t(24) = 5.57$, $p < .001$; for Experiment 4a, $t < 1$).

*4. 3. Conclusions*

In Experiment 4 we addressed the potential effect of the grapheme-to-phoneme probability of different phonological correspondences of polyvalent graphemes. Results from Experiment 4a did not show any significant effects of relative phonemic frequency. Neither the duration of letter *t* nor ILI duration was affected by our manipulation suggesting that differences in the frequency of the P-O correspondence did not impact on the retrieval or execution of graphemes. However, we attributed the absence of effects to the small difference in frequency between the phonemic forms included in this experiment. As mentioned, the more common sound for letter *t* used in Experiment 4a (/t/) is only slightly more common than its less frequent sound (/s/). In fact, the latter is the corresponding sound for letter *t* almost 30% of times, so this is not a low-probability mapping. To test this hypothesis, in Experiment 4b we tested the more strongly biased letter *e*. In the higher frequency condition, the letter *e* was embedded in words in which it was pronounced /ɛ/, which is the most frequent pronunciation (70% of the words containing that sequence, approximately). In the lower frequency condition, letter *e* was pronounced /ø/, which is a rather infrequent sound for this letter (only 9%). In this case, we did find a significant effect of relative frequency in the durations of the target letter *e* and in the durations of the ILIs previous and posterior to this letter.

Different from those obtained in Experiment 4a, results from Experiment 4b point to a reliable effect of frequency of the P-O mappings. Further analyses showed main effects of the variables phonemic relative frequency and experiment in LD. The main effect of experiment is unsurprising, since the target graphemes are different in each experiment. This effect just indicates that letter *e* takes more time to be written that letter *t*. This hypothesis seems to be confirmed by the fact that this interaction was non-significant in the analyses conducted in ILIs durations. More interestingly, the interaction Frequency x Experiment (although only marginally significant) indicates that G-P probability affected LD only in Experiment 4b. We consider that this interaction reflects the fact that P-O correspondences are weighted by the frequency of each mapping in the language. Furthermore, our results support the claim that this effect is rather weak, so a large difference between phonemic forms is needed to produce an effect.

The analysis of both ILI durations in Experiment 4b showed facilitatory effects of relative frequency. In ILI0, the frequency effect might reveal the greater accessibility of letter *e* when activated by its typical phonological correspondence. However, it is important to note that the interaction between Relative frequency x Experiment was not significant in this measure, which does not allow us to strongly claim that frequency affected differently *e* than *ti* words in this position. However, this interaction was statistically significant for ILI1 durations. In other words, phoneme relative frequency influenced the duration of the ILI right after the critical letter (ILI1) in Experiment 4b but not in Experiment 4a. The interpretation of this effect is not straightforward for several reasons. First, letter *e* is pronounced /ø/ (the pronunciation used in the less frequent condition) in open syllables. Thus, in the lower-frequency condition ILI1 always coincides with the syllable boundary (for example, *se.maine*). This is not the case for most of the words included in the higher frequency condition (*ser.vice*), so this effect could be attributable just to differences in the position of the inter-syllabic interval (Kandel, Álvarez, & Vallée, 2006; Álvarez, Cottrell, & Afonso, 2009).3 This pattern would fit the effect observed in Experiment 4b for ILI1. Second, this ILI is located *after* the critical grapheme. As commented, spillover effects are very rare in the literature of handwriting production process. In contrast, preparation effects are supposed to be the most common outcome when sublexical features are manipulated (Kandel & Spinelli, 2010; Kandel, Herault, Grosjacques, Lambert, & Fayol, 2009; Kandel & Valdois, 2006; Van Galen, 1991), so it would not be clear how relative phonemic frequency could affect such a later position. Thus, it is possible that the effect obtained in ILI1 was due to differences in the position of the syllabic boundary.

It might also be the case that this effect reflects the presence of a conflict which carries on to affect the movement times during a few seconds (Delattre et al., 2006). In this case, a conflict might be generated by the sublexical route when faced with a low-frequency phoneme, producing inhibition in this condition rather than facilitation in the case of high-frequency phonemes. Although the mechanism that would cause a conflict is not immediately clear to us (it

[3] We do not think this explanation can account for the rest of effects reported in this chapter. Syllabic boundary is placed in both conditions after the target letter, so stimuli are comparable until ILI1. Moreover, syllabic boundary effects have been thoroughly detailed in previous studies, and they have never been observed to take place during the execution of upper-case letters.

must be considered that the sequences included in the low-frequency phoneme condition are not irregular, since the sound /ø/ is always spelled with the grapheme *e* in French), the effect obtained in ILI1 could be due to cascading of central processes to peripheral processes. From this point of view, the conflict would affect durations until the moment in which is resolved. In contrast, we consider that the facilitatory effects observed in LD and ILI0 actually reveal that the relative strength of the mappings affected the accessibility of the grapheme to-be-produced, and that the effect found in ILI1 is due to differences in the position of the syllabic boundary. According to Van Galen's model of handwriting, a manipulation at the central levels of processing should be observed in the durations of the preceding segment, but not in the durations of subsequent segments. Obviously, more evidence needs to be collected to confirm that the effect observed in ILI1 durations is related to the position of the syllabic boundary. In Experiment 5 we tested a polyvalent Spanish grapheme to establish the source of the results reported in Experiment 4.

**5. Experiment 5**

In this experiment, we aimed to establish whether the effects observed in Experiment 4b are actually due to our experimental manipulation (the relative frequency of the phoneme represented by a given grapheme) or whether they are due to the position of the syllabic boundary. To this end, we conducted Experiment 5 in Spanish. Although different results could be obtained in different languages, we expect analogous results to those obtained in French, since similar phonological effects in handwriting have been reported in both languages (Kandel, Álvarez et al., 2006). In Experiment 5 we tried to replicate the relative frequency effects observed in LD and ILI0 in Experiment 4b with the Spanish polyvalent grapheme *u*, which is silent or pronounced /u/ depending on the context. For example, in the Spanish word *guerra* (*war*), the first phonological syllable is /ge/, so letter *u* is silent. However, in the word *suegra* (*mother-in-law*), the first syllable is /sue/: this sound /u/ is the most frequent phonological form of letter *u* (approximately 87.77% of the times *u* is pronounced this way; in the remaining 12.23%, *u* is silent). Crucially, using this letter we can generate two frequency conditions that do not systematically differ in the position of syllabic boundary (e.g., *guE.rra* vs. *suE.gra*). If the effect observed for ILI1 in Experiment 4b was a syllabic boundary effect, then it should be absent in Experiment 5.

*5. 1. Method*

Participants. Eighteen students from Psychology introductory courses of the University of La Laguna took part in this experiment to fulfill a course credit requirement. All of them were native Spanish speakers, right-handed and with no known motor or perceptive disorders.

Materials. Forty-two experimental stimuli including the letter *u* were selected. For a half of the stimuli this letter was pronounced /u/ (high-probability G-P mapping), and for the other half this letter was silent (low-probability G-P mapping). All the words were matched across conditions by lexical frequency, frequency of the bigrams before *u* and identity of the letter after *u*[4], frequency of the first syllable, word length (number of letters and number of phonemes), orthographic neighborhood, and number of syllables. T-tests were conducted to make sure that these variables did not significantly differ across conditions (all *t*s < 1). The full set of stimuli with their values in the controlled variables are given in Appendix D. Fifty additional words were selected to serve as fillers, and 4 more were added for the practice phase.

Procedure and apparatus. These were identical to those described in Experiment 4a.

*5. 2. Results*

Writing durations for the critical grapheme *u* and the previous and posterior inter-letter

[4] We were not able to use words with the same letter before u since this would lead to *u* having the same pronunciation in both conditions. For this reason, we controlled just for the frequency of the resulting bigram and syllable.

intervals (LD, ILI0, ILI1) were submitted to separate analyses of variance (ANOVAs), with the G-P probability (higher vs. lower) as a within-participants variable in the analysis by participants ($F_1$) and a between-participants variable in the analysis by items ($F_2$). Mean writing durations and standard deviations obtained in Experiment 4 are given in Table 6.

| G-P probability | ILI0 | LD | ILI1 |
|---|---|---|---|
| High (/u/) | 91 | 267 | 106 |
| Low (/ /) | 110 | 287 | 108 |

**Table 6.** Writing durations for the critical letter *u* and durations of the previous and posterior inter-letters intervals (ILI0, ILI1) in milliseconds, in Experiment 5.

An effect of the G-P probability was observed in LD, $F_1(1, 17) = 4.87$, $p < .05$, $MSE = 3{,}590.73$; $F_2(1, 40) = 48.472$, $p < .001$, $MSE = 4{,}140.21$. Letter *u* was faster produced when it was pronounced in the most frequent way (i.e., /u/). In ILI0, this effect was also significant, $F_1(1, 17) = 16.31$, $p < .005$, $MSE = 3{,}193.9$; $F_2(1, 40) = 20.58$, $p < .001$, $MSE = 3{,}529.17$). Longer inter-letter intervals were observed in the lower-frequency condition. More importantly, there was no difference between conditions in the duration of ILI1 ($F_1(1,17) = 1.38$, $p = .26$, $MSE = 160.65$).

*5. 3. Conclusions*

Experiment 5 aimed to confirm that the effects found in ILI0 and LD in Experiment 4b were truly due to relative phonemic frequency, and to determine whether or not the effect obtained in ILI1 is better accounted for by the position of the syllabic boundary. The results revealed significant effects of phonemic frequency in both ILI0 and LD, but not in ILI1. The duration of the interval previous to the production of the letter *u* was shorter when represented its more frequent pronunciation, and the execution of this target letter was faster as well. We consider that this pattern of results supports the idea that the significant difference observed between conditions in ILI1 is attributable to the position of the syllabic boundary. Moreover, it indicates that G-P probability affects the retrieval of graphemes.

**6. Discussion**

In Chapter 4 we explored the nature of the correspondences between phonemes and graphemes. Specifically, we aimed to establish whether the effectiveness of the P-O conversion procedures is constrained by the relative frequency of the phonemes. In two copy experiments (Experiment 4 conducted in French and Experiment 5 in Spanish) we tested polyvalent graphemes which were pronounced in two different ways, one of them more frequent than the other. Taken together, the results suggested that the selection and execution of a grapheme is affected by the G-P probability of the mapping. Although in Experiment 4a we failed to observe reliable effects when using a grapheme slightly biased towards one of the pronunciations (*t* embedded in the orthographic sequence *ti*), Experiment 4b yielded significant differences between the most frequent and the least frequent pronunciation of letter *e.* The inter-letter interval produced immediately before the target letter (ILI0) was shorter in the higher frequency condition, and the critical letter (LD) itself was faster produced. Additionally, the difference in the durations of the inter-letter interval following the target letter also reached significance. However, since this interval was always inter-syllabic in the words in the lower frequency condition (but not in the case of words in the higher frequency condition), we hypothesized that this might be a syllabic boundary effect. Inter-syllabic intervals have been repeatedly reported to be significantly longer than intra-syllabic intervals (Kandel et al., 2006; Álvarez et al., 2009), so the effect observed in ILI1 may be perfectly explained by this fact. In order to test this possibility, Experiment 5 was conducted with the Spanish polyvalent grapheme *u.* In this case, target ILIs did not differ in their syllabic status: they were both intra-syllabic. Supporting our interpretation, the effects of relative phonemic frequency observed in ILI0 and LD were replicated, but there were no significant differences in the analysis conducted on ILI1 durations.

It seems that G-P probability affects the process of retrieval of graphemes when adults copy words. This finding is relevant for handwriting production theory for several reasons.

Firstly, this pattern of results confirms that phonological information mediates copy in normal writing conditions. This point is a novel idea introduced in the present work. Even though Cuetos (1991) proposed that such a route of copy should exist, until now it had not been claimed that this route might be used by experienced writers when they copy words. As commented in the introduction of this chapter, it is generally accepted that a phonological route for copy would be exploited only by children and by some dysgraphic patients (because they lack strong lexical representations) or when non-lexical material is used. However, here we report evidence supporting the idea that both sublexical and lexical information are functional in the course of normal adult copy. This is a valuable contribution of the present series of experiments because of the impact it may have for handwriting production theory. The architecture proposed by Folk & Rapp (2004) was intended to account for the spelling-to-dictation process, but if we consider that it is claimed that the P-O conversion patterns are activated by the phonological input itself, it is difficult to see how phonological effects may rise during the copy task.

The model sketched by Bonin, Peereman et al. (2001) for written picture naming could easily be adapted to accommodate phonological effects. To obtain a processing route similar to the path (a) in Figure 7 (Cuetos, 1991) it would suffice to assume that a semantic representation is retrieved during the reading process. Then, similarly to the model of object naming of Bonin, Peereman et al. (2001), this semantic representation would activate both phonological and orthographic output lexicons in parallel, and the activation would propagate to the phoneme and grapheme level. The application of the phoneme-to-grapheme conversion procedures would affect graphemic selection, producing the observed phonological effects (Bonin, Peereman et al., 2001). However, it is important to notice that neither of these models has been proposed to account for the copy task, and that the route we have just described has been explicitly assumed by Cuetos (1991). This author has also pointed out the possibility of a second phonologically mediated route for copy, in which the individual graphemes of the visual input activate the orthography-to-phonology correspondences. These phonemes would activate their associated graphemes at the grapheme level, affecting the writing process. However, Cuetos has claimed that the use of both phonologically mediated routes is less common than the non-phonologically mediated route (a), in which the semantic system directly activates the appropriate orthographic word-form from the lexicon. Thus, evidence of the involvement of phonological information during writing should be obtained especially in those cases in which the orthographic lexical representation is not available (nonword copy, in the case of children or patients with impairment at the lexical level). In contrast, we have obtained a phonological effect in a copy task involving known words and performed by skilled writers. This evidence reveals that, in normal writing conditions, sublexical phonological information contributes to correctly retrieve and/or maintain the constitutive graphemes of an orthographic word-form.

Secondly, this pattern of results introduces for the first time the idea that G-P probability affects the accessibility of graphemes. It seems that relatively frequent phonemes are better prompts of their corresponding graphemes than infrequent phonemes. Since no effects were observed when a non-strongly-biased grapheme was used (*t* in Experiment 4a), we think that G-P probability effects might be detectable only if a high- and a low-frequency phoneme are compared (as *e* in Experiment 4b or *u* in Experiment 5). A reliable effect was absent in Experiment 4a because the phoneme /s/ is not so unlikely to be represented by the grapheme *t* in the context of /si/ (30%). It goes without saying that more evidence about the organization of the P-O conversion patterns needs to be collected, but if confirmed in further studies, the effect of relative phonemic frequency in handwriting must be taken into account by theoretical proposals. We suggest that the P-O conversion system consists of interconnected phonological and orthographic sublexical units, and that the strength of these connections depends on the frequency in the language not only of the to-be-written grapheme, but also of the related phoneme. That is, the G-P probability seems to partially determine the time needed to activate the corresponding graphemic representation and the stability of this representation. This latter fact might lead to the activation of a richer motor representation.

Finally, and from a methodological point of view, these results strongly support the claim made by Van Galen (1991) about the locus of central sublexical effects in handwriting. The phonemic frequency was observed to have an effect in the duration of the critical letter and in the interval immediately previous. This suggests that central effects in writing durations are observable in a local better than in a global analysis of the written response. This finding reinforces our proposal about the involvement of central sublexical processing concurrently to peripheral processing in handwriting.

To conclude, effects of G-P probability were observed in French and Spanish. In spite of the fact that Spanish is a fairly transparent language and that French is considerably opaque, phonemic representations seem to be involved in the writing production process in both languages. It has been suggested that the impact of the sublexical route is reduced in those languages with highly inconsistent P-O correspondences (Jiménez & Muñetón-Ayala, 2002). Although it is beyond the scope of the present work to establish a detailed comparison across languages, the results of Experiment 4 and Experiment 5 suggest that the influence of phonological information in the spelling process is more extended that generally thought. Further research must be carried out to elucidate the precise impact of sublexical units and phonological information on the handwriting process depending on the characteristics of each particular language.

The experiments included in the present chapter revealed that the relative frequency of the links between phonology and orthography affects writing durations. This fact provides novel information about the organization of the assembled route, but it says nothing about the size of the sublexical units that are functional in this route. This issue is investigated in Chapter 5 (syllables) and Chapter 6 (graphemes).

# 5

# Syllables as functional units in handwriting

Evidence obtained in Chapter 3 confirmed that phonological information plays an important role during the handwriting process. Our results suggest that access to orthographic representations is mediated by the phonological properties of words, even when they are well-known words, presumably at the later stages of processing. These findings lead to the unavoidable question of which phonological units are functional in handwriting. In Chapter 4 we have already observed that phonemes and graphemes are linked following the P-O rules of the language and in direct relation with their co-occurrence in the lexicon. The earliest cognitive models of handwriting production proposed that orthographic representations included only letter identity and serial order information (Caramazza, Miceli, Villa, & Romani, 1987). However, Caramazza and Miceli (1990) observed that writing errors preserved the orthographic consonant/vowel identity of the target letters, supporting the claim that writing production involves more than the recovery of simple strings of letters (see also Buchwald & Rapp, 2003).

This chapter is aimed at establishing whether syllables are one of these phonological units. We decided to study the potential effect of syllables because they are one of the most studied sublexical units in psycholinguistics, and because they have been demonstrated to influence both comprehensive and productive processes. Nonetheless, the specific role that syllables may play during these processes remains a matter of controversy.

## 1. Theoretical background

Syllables are the most basic of the superior phonological units (Yule, 2006), and they are more stable and independent of context than phonemes (Cutler, Mehler, Norris, & Segui, 1986). A syllable consists of an onset (a consonant segment preceding the vowel) and a rhyme, which includes the nucleus (the vowel) and the coda (a consonant segment following the vowel). Even though a syllable is understood as a co-articulation unit, its influence on spelling research has been considerable. In some languages the writing system is syllabic, with Japanese *kana* one of the most famous examples. A so-called syllabary includes those symbols that represent syllables (or sometimes moras) existing in the language. This system is suitable for those languages with a very restricted number of syllabic structures like Japanese, which uses many CV (consonant-vowel) syllables. In contrast, in languages with alphabetic scripts, such as Spanish, each written symbol included in the alphabet (each letter or grapheme) represents a phoneme of the spoken language. However, this fact does not imply that syllables are irrelevant for the writing process in alphabetic languages. Some orthographic restrictions are applicable only to units longer than a phoneme, so having syllabic-size orthographic representations could be advantageous (Yule, 2006). For example, in Spanish the grapheme *c* sometimes represents the phoneme /k/, but only when is followed by a letter different from *e* and *i*. The syllables /ke/ and /ki/ cannot be spelled *ce* and *ci* (which are actually pronounced /θe/ and (/θi/, respectively). In other words, the context-dependency of the phonology-to-orthography correspondences may bring about the use of longer and more stable sound-to-spelling correspondences. Since syllabic effects have been observed in practically all the domains of language, it seems reasonable to think that the written production process might not be an exception.

*1. 1. Syllables as processing units in language comprehension*

Syllable-size units have been observed to play a role during the reading process. It has been found that positional syllabic frequency (the frequency with which a syllable appears in a specific position) affects behavioral measures, such as reaction times and error rates, during the visual lexical decision task. The pattern of results usually obtained with this task is that words with initial high-frequency syllables are categorized as words slower than those starting with low-frequency syllables (Álvarez, Carreiras, & de Vega, 2000; Álvarez, Carreiras, & Taft, 2001; Álvarez, de Vega, & Carreiras, 1998; Carreiras, Álvarez, & de Vega, 1993; Carreiras & Perea, 2002; Perea & Carreiras, 1998). This inhibitory effect of the positional syllabic frequency has been accounted for in the context of an activational model, in which syllables "trigger" lexical candidates, namely all the lexical units sharing the first syllable. In line with this idea, several studies have found that the inhibitory effect is linked to the number of syllabic neighbors of higher lexical frequency than the target word, and not to the total number of words sharing the initial syllable (Perea & Carreiras, 1998; Álvarez et. al., 2001). The inhibition required to "turn off" the wrong candidates would account for the inhibitory effect of syllable-frequency: the more candidates of higher frequency a word has, the more cognitive load is necessary to inhibit them, as reflected by longer reaction times in word recognition tasks. Some authors have demonstrated that this syllable-frequency effect can also be observed in event-related potentials (ERPs), specifically in the N400 and P200 components (Barber, Vergara, & Carreiras, 2004).

Furthermore, evidence indicating syllabic processing while reading in Spanish extends beyond syllable-frequency effects. In a ERP study, Carreiras, Vergara, & Barber (2005) found that the P200 component was sensitive to the color-syllable congruency effect. The amplitude of this component was higher when targets were colored incongruently with the position of the syllabic boundary. Some priming studies have obtained inhibitory effects when a target word shared the first syllable with a prime of higher lexical frequency (Carreiras & Perea, 2002; Domínguez, de Vega, & Cuetos, 1997), but facilitatory effects when the prime was a pseudoword (Carreiras & Perea, 2002; Álvarez, Carreiras, & Perea, 2004; but see Domínguez et al., 1997 for a different pattern of results). Crucially, it seems that syllabic effects are phonological in nature (Álvarez et al., 2004; Conrad, Grainger, & Jacobs, 2007), target words were primed by pseudowords which either shared the first phonological syllable (but not the orthographic syllable) or the first phonological and orthographic syllable. The results showed that latencies were faster in both conditions, suggesting that the syllabic effects obtained in visual word recognition in Spanish are phonological in nature.

Although syllabic frequency effects seem not to be accounted for by mere letter co-ocurrence, morphological factors or other sublexical units (Carreiras et al., 1993; Álvarez et al., 2001; Álvarez et al., 2004), Seidenberg (1987, 1989) proposed that syllabic effects were caused by mere orthographic redundancy and not by syllabic processing. He argued that syllable-frequency effects can be attributed to the existence of a "bigram trough" at the syllable boundaries. Following this author, words would be segmented according to the presence of a low-frequency bigram; because bigram troughs would be more frequent in inter-syllabic than in intra-syllabic positions, the effect appears to be syllabic, but is in fact due to bigram-frequency. However, empirical evidence coming from more recent studies has ruled out this possibility. Conrad, Carreiras, Tamm, & Jacobs (2009) observed in a series of experiments conducted in Spanish that syllable-frequency effects did not depend on the presence or absence of a bigram trough at the syllable boundary (Experiment 1). In fact, a bigram-frequency effect was obtained when syllable-frequency was kept constant, but it was facilitatory (Experiment 3). This pattern of results suggests that syllable and bigram-frequency effects are independent, so they originate at different levels of processing.

*1. 2. Syllables as functional units in speech production*

Some converging lines of evidence have revealed that syllables may be functional also during the language production process, especially in languages with clear and well-defined syllabic boundaries such as Spanish. A considerable amount of data points to syllables being relevant in speech production (e.g., Carreiras & Perea, 2004; Cholin et al., 2004). Using the naming task, Carreiras & Perea (2004) manipulated the frequency of the first syllable of Spanish target words. Contrarily to the pattern of results obtained with the lexical decision task, a facilitatory effect of syllabic frequency was observed, which revealed that words containing high frequency syllables yielded shorter response latencies than words containing low frequency syllables. Based on this evidence, syllables have been incorporated as functional units by several models of speech production. However, these models differ from each other in several aspects, with the level of processing at which syllables are thought to come into play one of the most controversial topics. Some models propose that syllables are functional at the word-form retrieval level (Dell, 1986; 1988). Thus, phonological word-forms would be pre-syllabified and internal syllabic positions would be specified at early levels of processing. As mentioned above, the first syllable of a word would act as a trigger for lexical candidates, being crucial during lexical access. In contrast, other theoretical proposals assume that syllables are articulatory motor units (Levelt, 1989), so syllabification would occur after lexical access. From this point of view, the facilitatory syllable-frequency effects observed in naming are interpreted as reflecting the existence of a repository of ready-made syllabic motor programs, at least for the most frequent syllables in the language (Cholin, Levelt, & Schiller, 2006). Following these authors, an abstract syllabic representation triggers the activation of pre-compiled gestural scores that are retrieved from this sort of repository, this so-called *mental syllabary*. The interactive activation model (Ferrand, Seguí, & Grainger, 1996) includes syllables as sublexical phonological output units, playing a special role during the phonological-to-phonetic encoding interface and facilitating the articulatory response. This conceptualization is similar to that proposed by Levelt's model (1989).

*1. 3. Syllables as functional units in spelling*

The results obtained in pioneer studies about the role of syllables during the handwriting process have been rather contradictory (Bogaerts, Meulenbroek, & Thomassen, 1996; Zesiger, Orliaguet, Boë, & Mounoud, 1994). Nevertheless, some on-line approaches have recently shown that syllables affect the time course of the written response. Kandel, Álvarez et al. (2006) used a copy task in which French participants were asked to write in uppercase letters visually-presented words on a graphic tablet. The duration of the inter-letter intervals was the dependent variable. Longer ILIs were found when the same intervals were inter-syllabic than intra-syllabic (see also Lambert, Kandel, Fayol, & Espéret, 2007). For example, the pause produced between letters *a* and *c* in words such as *tra.ceur* (the dot marks the position of the syllable boundary) was longer than the same interval in the word *trac.tus*. A similar pattern of results was observed in Spanish by Álvarez, et al. (2009), in a series of experiments using both writing-to-dictation and written picture naming, ruling out the possibility of an explanation of the effect in terms of reading processes. This study also showed that morphological factors cannot account for the syllable-boundary effect. Furthermore, the syllabic boundary effect has been found in the inter-keystroke intervals when typing in German (see Weingarten, Nottbusch, & Will, 2004, for a review) and French (Zesiger et al., 1994). Moreover, it seems that not only inter-letter interval durations are sensitive to syllabic boundaries, but also letter durations (Kandel & Valdois, 2006; Kandel et al., 2009). Kandel and Valdois (2006) found that, when they copied bi-syllabic words, 6- to 12-year-old children systematically produced longer durations for the first grapheme of the second syllable than for any other grapheme in the word. The authors concluded that children programmed the movements involved in writing the second syllable during the execution of its first grapheme.

In a recent study, Kandel and colleagues (2011) tried to establish whether the bigram trough hypothesis (Seidenberg, 1987, 1989) could account for the syllabic boundary effect typically observed in handwriting. These authors manipulated the position of the lowest-frequency bigram within a word (the bigram trough). It could be located at the syllable boundary or at the previous inter-letter interval (at an intra-syllabic position). They reasoned that if the written response was segmented into syllable-like chunks, then a syllabic boundary effect (which, in the case of adult participants, was understood as longer inter-letter intervals at the syllable boundary than at other inter-syllabic positions) should be observed regardless the position of the bigram trough. On the contrary, if writers segment the written response according to letter co-occurrence, then longer ILIs would be expected at the position of the low-frequency bigram. The results seemed to indicate that writing is affected by both syllable position and bigram-frequency. This and previous evidence led Kandel and colleagues (2011) to propose a general model of the handwriting production process similar to that introduced by Van Galen's (1991) but in this case including a syllable module that would be functional between the word and the letter level of processing (see Figure 8). In this proposal, bigram-frequency is thought to

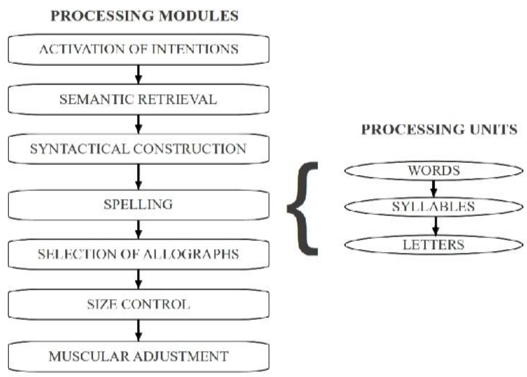


**Figure 8.** Model of handwriting production, adapted from Kandel et al., 2011.

impact the spelling process at the letter module.

In spite of these findings, syllabic frequency has not been manipulated in any handwriting study. If syllables constitute programming units of the written response, it is possible that the most frequent segments have been stored as whole movement units. Similarly to the mechanism proposed by Cholin and colleagues (2006) for the speech production process, hand-movements corresponding to the most frequent syllables in a language might have become pre-compiled motor programs. If this is the case, a syllabic frequency effect could be observed during writing, due to the differences in the grain size of the motor programs between low-frequency syllables (individual letters) and high-frequency syllables (whole syllables). On the contrary, if the role of syllables in handwriting is restricted to providing a frame for the written response segmentation, then the frequency of the syllables of a word should be irrelevant during its written production, so only syllabic boundary effects would be found.

In Experiment 6 the influence of syllabic frequency during handwriting was tested, with special interest in the moment in which this influence may arise. The frequency of the second syllable of trisyllable words was manipulated. We chose the second syllable as target because, as commented in Chapter 2, Van Galen (1991) proposed that the additional demands at the central levels of processing imposed by a unit could affect the processing of the previous unit, which would be being processed at the most peripheral stages. That is to say, the syllabic frequency effect could have an impact on the segments previous to the actual production of the syllable. Since written latencies are sensitive to semantic and lexical variables (Bonin & Fayol, 2000; Bonin & Méot, 2002; Bonin, Fayol, et al., 2001; Delattre et al., 2006), the cause of an effect in this position could be difficult to establish in the case of the first syllable. If the syllabic frequency has an influence in the interval preceding the execution of the first letter of the target syllable, then this effect could be indistinguishable from other effects related to lexical access. In order to obtain a picture of the time-course of the written response as complete as possible, the response latencies, the duration of the first three ILIs and the duration of the first four letters were measured.

**2. Experiment 6**

In this experiment, participants were asked to write aurally presented words. All the stimuli were trisyllable words with a CV.CV.CV syllabic structure. The frequency of the second syllable of the words was manipulated. If only high-frequency syllables are stored as pre-compiled motor programs, syllabic frequency should affect writing durations. High-frequency syllables could be faster retrieved than low-frequency syllables, leading to facilitatory effects. In contrast, it could be possible to observe an inhibitory effect of the syllable-frequency. If only high-frequency syllables are stored as motor programs, then these syllables would act as a unit of programming, whereas in the case of low-frequency syllables the written response would be executed letter-by-letter. Because the second letter of a high-frequency CV syllable would be partially retrieved during the execution of the first letter (due to the concurrent activation at central levels of both letters as a whole unit), writing durations for high-frequency syllables could be hindered. An effect in the segment located immediately before the target syllable is predicted in the context of the anticipatory hypothesis of handwriting (Van Galen, 1991; Kandel et al., 2011).

*2. 1. Method*

Participants. Twenty-nine right-handed students from introductory psychology courses at the University of La Laguna took part in this experiment in exchange for partial fulfillment of a course requirement. All of them were native Spanish speakers. They all had normal or corrected-to-normal vision and reported no hearing or motor impairments.

Materials. We selected 40 words with six letters and three syllables, with a CV.CV.CV structure, from the LEXESP Spanish corpus (Sebastián, Martí, Carreiras, & Cuetos, 2000). For half of the stimuli, the second syllable of the word was a high-frequency syllable (henceforth, HF; mean frequency: 1080) and for the other half this was a low-frequency syllable (LF; mean frequency: 586). Stimuli were chosen in pairs, so each pair of words shared all the graphemes but the first grapheme of the second syllable (e.g., *ca.ni.lla* vs. *ca.pi.lla*; meaning *shinbone* and *chapel*, respectively). It is important to notice that we tried to include this specific grapheme a similar number of times in each condition in order to avoid a potential effect of letter identity. For example, the grapheme *p* was embedded in a high-frequency syllable in the word *do.pa.do* (*drugged*) and in a low-frequency syllable in the word *ca.pi.lla*. Both groups of words were matched by logarithmic word frequency (means: 4,75 and 6,1 for the HF condition and the LF condition respectively); orthographic neighborhood (means: 4,8 and 5,35); frequency of the critical bigram (means: 272,89 and 238,92) and the frequency of the previous bigram (e.g., in *ca.pi.lla*, the bigram *ap*; means: 351,93 and 388,92). T-tests showed no statistical differences between both conditions in any of these controlled variables. Because of the high degree of similarity between each pair of words, 40 extra words served as fillers, which shared length and syllabic structure with the target words. Four words were included to serve as practice. The auditory stimuli were recorded by a male Spanish speaker on a Macintosh computer using SoundEdit.

Procedure. Stimuli presentation and digital recording of the responses were controlled by Spellwrite software (Cottrell, 1999). The experiment was run on a Macintosh G4 computer. The task was a writing-to-dictation task and was conducted individually in a sound-to-proof room. Each trial started with an auditory signal presented via headphones, followed by a word 50 ms later. The word had to be written by the participants on a lined sheet of paper placed over the graphic tablet (Wacom Intuos GD-1218-u). They were asked to write the word with an Intuos Inking pen, in uppercase letters and as soon as they recognized it. If they did not recognize the word they were instructed to sketch a horizontal line. They had to press a button labeled *next* with the pen when they finished writing each word. This led to a new stimulus. A whole experimental session lasted 20 minutes approximately.

Several measures were recorded: a) Response latencies, defined as the time between the auditory stimuli onset and the first pen down in the first grapheme; b) the duration of the first three inter-letters intervals in a word (ILI1, ILI2, and ILI3); c) the duration of the first four letters of the word (LD1, LD2, LD3 and LD4). For example, for the Spanish word *ba.ti.do*, LD3 stands for the duration of the *t*, and ILI1, ILI2 and ILI3 correspond to the interval between *b* and *a, a* and *t* and *t* and *i*, respectively.

*2. 2. Results and conclusions*

Response latencies, grapheme durations and ILI durations more than 3.0 standard deviations above or below the mean for each participant, condition and measure were excluded from the analyses, as well as responses containing misspellings and those in which an inter-letter pause was not produced. In total, 11.85% of the data were removed from the analysis. Stimuli considered as errors for more than a half of the subjects (*cosido* and *nevada* in the high syllable-frequency condition and *balido* and *casada* in the low-frequency condition) were also excluded, and so were their counterparts in the other condition (*batido* and *camada*; *cogido* and *negada*). Table 7 shows the means and standard deviations for latencies, inter-letter intervals (ILI1, ILI2, and ILI3), and the duration of the four initial letters (LD1, LD2, LD3, and LD4).

Response latencies, inter-letter intervals (ILIs), and letters durations (LDs) were submitted to separate analyses of variance (ANOVAs), with the frequency of the second syllable (high vs. low) as a within-participants factor. A significant difference between both conditions was obtained in the ILI3, $F_1(1, 28) = 9.55$, $MSE = 632.63$, $p < .005$; $F_2(1, 30) = 4.2$, $MSE = 301.32$, $p < .05$), being this ILI shorter in the HF condition than in the LF condition. The difference between both conditions was also significant in the LD3, but only in the analysis by participants, $F_1(1, 28) = 65.7$, $p < .001$; $F_2 = 1.22$; $MSE = 14{,}247.35$, $p = 0.278$, $1 - \beta = .188$). No other differences were significant.

We conducted additional post-hoc analyses to test whether or not we were able to obtain a syllabic boundary effect in the ILIs within each experimental word. Based on evidence reported in previous studies, it seems reasonable to expect that inter-syllabic intervals will be longer than intra-syllabic intervals. Therefore, the durations of the first three inter-letter intervals for the whole set of experimental stimuli were submitted to an analysis of variance (ANOVAs) with the position of the interval (ILI1, ILI2 and ILI3) as a within-participants factor. The type of interval was significant, $F_1(2, 56) = 5.89$, $MSE = 9{,}508.53$, $p < .005$; $F_2(2, 30) = 6.42$, $MSE = 5{,}824.09$, $p < .005$. Post-hoc comparisons showed that the ILI2 (the inter-syllabic interval) was significantly longer than ILI1, $t_1(57) = 2.67$, $p = .01$; $t_2(31) = 3.05$, $p = .005$, and than ILI3, $t_1(57) = 3.44$, $p = .001$; $t_2$ $(31) = 3.64$, $p = .001$. The difference between ILI1 and ILI3 (both intra-syllabic intervals) was not significant. Moreover, there were no differences in this effect between high- and low-frequency words ($F < 1$).

In sum, a syllabic boundary effect was found in the ILIs durations. Longer times were observed for the inter-syllabic intervals than for the intra-syllabic intervals. More importantly, a syllable-frequency effect was observed in the interval between the two graphemes of the second syllable, and an effect only significant in the analysis by participants was obtained in the duration of the first letter of the critical syllable. This evidence supports the idea that syllable-size motor units are retrieved during handwriting. Specifically, our findings show that high-frequency syllables compared to low-frequency syllables yielded longer durations of their first letter and shorter durations for the inter-letter interval between their constitutive letters. This pattern of results suggests that high-frequency syllables are processed as whole units in the moment the first grapheme is being produced, leading to shorter durations in the subsequent pause. These effects can be accounted for if a sort of repository including only the hand-movements corresponding to the most frequent syllables is assumed. A more detailed description of such a mechanism is given in the general discussion of the present chapter. However, we first wish to untangle these syllabic effects from potential bigram-frequency effects. As mentioned, some authors claimed that syllabic effects can be due to factors related to pure orthographic redundancy, such as letter cluster frequency (Seidenberg, 1987, 1989). Even though this hypothesis has been ruled out by evidence from visual word recognition studies (Conrad et al., 2009; Carreiras et al., 1993), Kandel and colleagues (2011) observed an impact of bigram-frequency in the course of the written response. Our results were obtained with stimuli matched by bigram-frequency, but it is possible that a small difference between conditions in this variable is enough to produce differences in the writing durations. Moreover, even if our results were truly generated by differences in syllabic frequency, it would be interesting to know what is the nature of the influence of bigram-frequency, in order to isolate both effects. If bigram-frequency produces an effect independent from syllable-frequency, then we might be able to distinguish between both of these. For example, Conrad et al. (2009) observed an inhibitory syllable-frequency effect but a facilitatory bigram-frequency effect using the lexical decision task. This means that, at least during the reading process, syllable-frequency and bigram-frequency effects can be independently obtained. To test whether this dissociation can also be observed in handwriting, we conducted Experiment 7, whose procedure and experimental controls were identical to Experiment 6, but in this case the frequency of the bigram forming the second syllable was manipulated, while the frequency of this syllable was controlled across conditions.

**3. Experiment 7**

The goal of this experiment was to study the effects of bigram-frequency as a measure of orthographic redundancy during the writing process. A bigram is a sequence of two letters, regardless of their syllabic status. For example, the Spanish word *batido* contains five bigrams: *ba, at, ti, id,* and *do* and just three syllables (*ba*, *ti* and *do*). It is reasonable to think that bigram-frequency could be especially relevant in handwriting. It is possible that two letters that have frequently been written together in the same order are faster recovered than two letters which rarely appear together. However, this possibility has not been empirically tested. Some writing studies have controlled the mean frequency of the bigrams of the word (Delattre et al., 2006), but this control could be not ideal if one is searching for sublexical effects. For example, in their study, Delattre and colleagues manipulated the sound-to-spelling regularity of words. It is more than likely that irregular words contain less frequent bigrams than regular words. Although the mean bigram-frequency was controlled, the frequency of the critical bigram was not kept constant. Because a rough measure such as the whole-word durations of the written response was used, it could be a confounding factor in their results, due to the lack of control at a more local level. In order to establish whether bigram-frequency does influence handwriting speed, in this experiment we controlled the frequency of the second syllable and manipulated the frequency of this bigram (in *batido*, the bigram *ti*). In the stimuli used in this experiment, the critical bigram is also the second syllable. We predicted two potential outcomes: a) an effect of the bigram-frequency in the interval within the critical bigram (the third bigram in the word) similar to that observed for syllable-frequency, but due to the influence of the distributional properties of letter clusters; or b) a null effect of bigram-frequency in both letters and ILIs duration.

*3. 1. Method*

Participants. Twenty-seven right-handed students from introductory psychology courses at the Universidad de La Laguna took part in the experiment to fulfill a course requirement. All were native speakers of Spanish. They all had normal or corrected-to-normal vision and reported no hearing or motor impairments.

Materials. Forty-three trisyllabic words with a CV.CV.CV structure, all of them consisting of six graphemes, were selected for this experiment according to LEXESP Spanish database (Sebastián et al., 2000). For a half of the stimuli, the second syllable of the word was a high-frequency bigram (mean: 430) and in the other half this bigram was a low frequency bigram (mean: 161). Stimuli were selected in pairs so they shared all the graphemes but the first letter of the second syllable (e.g., *maceta* vs. *maleta*). As in Experiment 6, this letter appeared in both experimental conditions; for example the grapheme *s*, is embedded in a high-frequency bigram in the stimuli *vasija* and in a low-frequency bigram in the word *reseca*. Both conditions were matched by logarithmic word frequency (means: 5,12 and 5,28, for words with a high-frequency bigram and for words with a low-frequency bigram, respectively); frequency of the second syllable (mean for HFB: 132,8; for LFB: 139,15); orthographic neighborhood, (means: 4,4 and 4,9); and frequency of the previous bigram: in *vasija*, the bigram *as* (means: 390,45 and 344,04). T-tests showed no statistical differences between both conditions in the mean values for these controlled variables. Forty extra words which shared length and syllabic structure with the target words served as fillers, and four additional words were used for practice. All the auditory stimuli were recorded by a male Spanish speaker with SoundEdit on a Macintosh computer.

Procedure. The procedure was identical to that used in Experiment 7.

*3. 2. Results*

Written latencies, letter durations (LD1, LD2, LD3, and LD4) and ILIs durations (ILI1, ILI2, and ILI3) more than 3.0 standard deviations above or below the mean for each participant, condition and measure were excluded from the analysis, as well as responses containing misspellings and those items in which a pause was not produced in an inter-letter interval. In total, the 12.34% of the data were removed. Stimuli considered as errors by more than a half of the participants (*latino* and *valija* in the HF condition and LF condition respectively) were also excluded from the analyses, as were their counterparts in the opposite condition (*vasija* and *ladino*). Table 7 shows the means and standard deviations for latencies, inter-letter intervals and letter durations for each condition. For the written latencies, the effect of bigram-frequency was marginally significant in the analysis by participants ($F_1(1, 26) = 3{,}494$, $MSE = 9{,}065.29$, $p = .07$), but non-significant in the analysis by items ($F_2 = .78$, $MSE = 6{,}543$, $p = .38$, $1 - \beta = .138$). Words with high-frequency bigrams showed shorter latencies than low-frequency bigrams. There were no other significant differences.

| | Experiment 6 (syllable-frequency) | | Experiment 7 (bigram-frequency) | |
|---|---|---|---|---|
| | HF | LF | HF | LF |
| Latencies | 1086 (248) | 1051(244) | 1045 (208) | 1071 (236) |
| LD1 | 379 (45) | 384 (39) | 414 (44) | 418 (51) |
| ILI1 | 110 (37) | 114 (46) | 119 (60) | 120 (55) |
| LD2 | 382 (43) | 382 (43) | 401 (47) | 403 (48) |
| ILI2 | 128 (54) | 123 (42) | 120 (43) | 122 (42) |
| LD3 | 352 (44) | 302 (49) | 322 (40) | 315 (34) |
| ILI3 | 105 (27) | 112 (31) | 110 (28) | 113 (30) |
| LD4 | 436 (51) | 420 (66) | 434 (50) | 433 (52) |

**Table 7.** Mean and standard deviation (in milliseconds) for latencies, letter durations (LD1, LD2, LD3 AND LD4) and inter-letter intervals (ILI1, ILI2 and ILI3) for words with high-frequency (HFS) and with low-frequency (LFS) second syllable in Experiment 6, and with high-frequency (HFB) and with low-frequency (LFB) third bigram in Experiment 7.

## 4. Discussion

In this chapter we tried to shed some light on the role played by the syllabic frequency during handwriting. Our goal was to test if syllable-frequency (and secondarily, bigram-frequency as a measure of pure orthographic redundancy) affected letter and/or ILI durations.

An effect of the frequency of the second syllable was found in the ILI between the two letters that formed that syllable (ILI3), being shorter when the syllable was a high-frequency one. The reverse effect was also observed in the duration of the first letter of the syllable, with longer durations for high-frequency syllables. Our results show that the distributional properties of syllables affect the execution of the writing hand-movements. As mentioned, in speech production research it has been assumed that syllabic frequency effects reflect the existence of some kind of store, a *mental syllabary* that would be a sort of library including routines which would contain the articulatory programs for at least the more frequent syllables in the language (Levelt, 1989; Levelt, Roelofs, & Meyer, 1999; Levelt & Wheeldom, 1994; but see Dell, 1986; 1988, for a different position about the role of the syllable in speech production). Of course, we cannot confirm or reject the existence of such a repository based only in the evidence collected here. However, the inhibitory effect of the syllabic frequency on the first letter of the critical syllable and the facilitatory effect on the subsequent inter-letter interval suggest that high-frequency syllables, but not low-frequency syllables, are processed like whole motor programs. From this point of view, the motor program retrieved when writing the first letter of a high-frequency syllable is more complex, because it includes the pattern of hand-movements required to produce the whole syllable. In consequence, the following interval is shorter than in the case of low-frequency syllables because central processing of the second letter of the syllable has already occurred during the execution of the first letter. In contrast, the written production of a low-frequency syllable would involve the retrieval of the individual motor program corresponding to each letter. Thus, the second letter of the syllable would be processed at the central levels while the prior segment (ILI3) is being produced. If low-frequency syllables were also stored in a syllabary, then a mere facilitatory effect of the syllabic frequency would have been observed, reflecting faster access to high-frequency syllables than to low-frequency syllables. Instead, the evidence gathered in the present chapter suggests that only high-frequency syllables are stored like whole motor programs.

Furthermore, our results also confirm that central processes are engaged even after the initiation of the written response. As commented in Chapter 2, if spelling central processes were completed before the movement started, no manipulation at the central levels of processing would affect writing durations. Since it is unclear to us what kind of conflict could cause such a pattern, we consider that the present results are difficult to conciliate with the assumption that effects obtained in writing durations are due to the presence of a conflict which cascade from the central levels of processing. Instead, the effects reported here seem to reflect the fact that central processing of sublexical units occurs simultaneously to the peripheral processing of preceding segments (Van Galen, 1991, Kandel et al., 2011; Kandel, Soler et al., 2006).

These results fit those reported by Kandel, Soler et al. (2006). In a study with children, these authors found longer durations for the first letter of the second syllable than for other letters in the word, suggesting a preparation of writing movements for that syllable during the execution of its first letter. In another study, Bogaerts and colleagues (1996) also reported an increase in stroke durations for the first letter of the second syllable in Dutch adults. We extend these previous findings by testing words in which other variables that could have affected writing durations were strictly controlled. However, it is noteworthy that we were able to control the identity of the target letter only in a general manner, since matching across conditions was obviously impossible.

Additionally, post-hoc analyses conducted on the ILI durations in Experiment 6 revealed that intervals were longer at the syllable boundary (ILI2, the interval between *a* and *l* in *ma.le.ta*) than at intra-syllabic positions (ILI1 and ILI3, in *maleta* the intervals between *m* and *a* and between *l* and *e* respectively, without significant differences between them). There seems to be a supplementary cost of processing associated to the syllabic boundary, as reported in previous studies (Kandel, Álvarez et al., 2006; Álvarez et al., 2009). In these earlier studies, the variability in the structure of the first and the second syllable was considerable, so it was difficult to affirm that the observed effects were not due to syllabic structure or syllable length. For instance, Álvarez and colleagues (2009) found that the ILI between *a* and *n in dan.za* (intra-syllabic) was shorter than in *da.nés* (inter-syllabic). In *danza*, the first syllable is a CVC syllable, whereas in *danés* this syllable has a CV structure, and the opposite is true for the second syllable. Since all the syllables in the words used in Experiment 6 were CV syllables, an explanation in terms of syllabic structure cannot account for our data.

It can be argue that if only high-frequency syllables are retrieved as whole motor units, then we should have obtained a reduced (or absent) syllabic boundary effect for those stimuli in the low- frequency condition. However, the interaction between syllabic boundary effect and syllabic frequency did not reach significance. Although this fact could seem contradictory, it is worth noting that both effects probably originate at very different stages of processing. Some authors have claimed that orthographic representations include separate levels corresponding to CV representations and syllabic structure (see Buchwald & Rapp, 2006 for a revision of this issue). If this were the case, a to-be-written word would be retrieved from the lexicon and maintained in the graphemic buffer segmented in syllable-size units, leading to syllabic boundary effects. The syllable-frequency effect would arise later on, when the appropriate motor program has to be selected. A long-term store for motor programs would contain not only the specifications to produce the different allographic forms for each letter, but also the hand-movements needed to produce the most frequent syllables in the language. Obviously, more evidence must be collected in order to replicate and/or to extent the present findings.

Experiment 7 revealed that bigram-frequency does not produce reliable differences in the duration of the handwriting movement. Previous writing studies addressing phonological factors have attempted to control the bigram-frequency (Álvarez et al., 2009, in Spanish; Delattre et al., 2006; Kandel, Álvarez, et al., 2006; Kandel & Spinelli, 2010, in French), because this variable is thought to affect the time-course of the written response. In those studies, experimental words were usually controlled for the mean frequency of all the bigrams within the word (Delattre et al., 2006). However, this control strategy might be ineffective in excluding an account of the results in bigram-frequency terms. A difference between experimental conditions in the frequency of a particular bigram could have more dramatic effects on writing times than a difference in the mean frequency of all the constitutive bigrams (see Kandel & Spinelli, 2010 and Kandel et al., 2011). For this reason, in Experiment 7, in order to detect potential local bigram-frequency effects, we chose the frequency of the critical bigram instead of the mean bigram-frequency as the independent variable. The strict control exerted over the stimuli in Experiment 6 allowed us to that the observed syllabic effects were not due to the frequency of letter clusters (measured by the bigram-frequency). Nevertheless, bigram-frequency could have produced independent effects. The results have, however, ruled out this possibility, and have shown that frequency of the third bigram only affected the duration of written latencies, but not the duration of letters or inter-letter intervals. The effect observed in writing latencies cannot be undoubtedly attributed to spelling processes, since it could be related to uncontrolled lexical characteristics of the words or other factors related to input decoding. These results indicate that, unlike syllable-frequency, pure orthographic redundancy does not have a relevant impact during the writing process.

In sum, the present findings offer empirical support for the notion of syllables as programming units in handwriting. Nevertheless, crucial questions remain unsolved concerning both syllabic boundary and syllabic frequency effects. Some authors have argued that “orthographic representations include information regarding orthographic syllable structure” (Buchwald & Rapp, 2006, p. 312). Do the syllabic effects obtained in writing tasks originate at a phonological level or are they orthographic in nature? Because it is virtually impossible to manipulate the frequency of a phonological syllable while keeping constant the orthographic syllable-frequency, we cannot answer such a question with the present evidence. According to Jónsdóttir, Shallice, & Wise (1996), basic phonological information about a word influences the syllabic structure of the spelling response. The fact that a syllable-frequency effect was found in writing durations (Experiment 6) but not a bigram-frequency effect (Experiment 7) suggests that orthography by itself cannot account for the obtained evidence, but it does not preclude the possibility that grapho-syllables are responsible for this effect. Although phonological syllables seem to be responsible for the syllabic effects observed when reading in Spanish (Álvarez et al., 2004; Conrad et al., 2007), other authors have provided evidence about the orthographic nature of the syllable-size units involved when writing in French (Kandel et al., 2011; Buchwald & Rapp, 2003). Of course, the possible phonological nature of the syllabic units involved in spelling might depend on the characteristics of the language and this needs to be explored in more depth.

Finally, a methodological conclusion can be extracted from Experiment 6 that could be crucial for forthcoming handwriting production studies. The evidence presented in this chapter follows a complex pattern of results. Syllabic frequency led to two consecutive effects operating in opposite directions: first, an inhibitory effect of the syllabic frequency was observed in the duration of the first letter of the syllable, and then a facilitatory effect in the following pause. This pattern of results suggests that some local effects may pass undetected if a rough measure, such as writing times for whole words, is used as dependent variable. We propose that finer measures should be collected in handwriting production studies, especially if sublexical factors are being studied.

# 6

# Grapheme complexity in handwriting

As commented in Chapter 5, increasing evidence supports the idea that units more complex than letters are processed during handwriting. We have already shown that syllables are units of programming during written production (Álvarez et al., 2009; Kandel, Álvarez et al., 2006; Kandel & Valdois, 2006; Weingarten et al., 2004; Kandel et al., 2011). However, it is possible that other sublexical units are also functional in writing. Van Galen (1991) claimed that there may be not a fixed unit of processing in handwriting. Instead, he proposed that there are multiple units of programming, each of which is typical for a level of processing. Evidence indicates that this might be the case. Letter identity and letter doubling information have been observed to be dissociable (Miceli, Benvegnú, Capasso, & Caramazza, 1995). The patient FM, a case reported by Tainturier & Caramazza (1996), showed better-preserved information of letter doubling than of letter identity. Consistently, FM often replaced a double-letter with another double-letter. This means that orthographic representations are non-linear internally complex representations.

Among those units larger than letters that might be functional during writing, graphemes are probably one of the most present in the spelling literature. As we have previously mentioned, a grapheme is the orthographic equivalent of a phoneme. We have shown in Chapter 4 that the relationship between phonemes and graphemes affects writing times, at least in the case of one-letter graphemes (simple graphemes). But graphemes can be formed by more than one letter (complex graphemes). For example, the sequence *CR* corresponds to two simple graphemes in English, because they represent two different phonemes (/k/+/r/). Whereas, the sequence *CK* is a complex grapheme because it corresponds to a single phoneme (/k/). Evidence of the functionality of graphemes has been repeatedly observed in reading and visual word recognition. Rey, Ziegler, & Jacob (2000) found that a given letter took longer to be detected in a word when it formed part of a complex grapheme (e.g., letter *C* was faster detected in the word *DECREASE* than in *ROCKET.* Henceforth, the graphemic unit appears underlined). Furthermore, it has been reported that words are recognized more slowly when a graphemic unit is experimentally disrupted than when the disruption affects other letters of the word (Pring, 1981; Martensen, Maris, & Dijkstra, 2003). For example, Martensen and colleagues (2003) observed that a word like *BREAD* was recognized and named faster when it was presented “br//ead” than “bre//ad”, because in the latter form the graphemic unit *EA* (/e/) is disrupted. Additional evidence has supported the claim that graphemes are functional units in reading (Dickerson, 1999; Rastle and Coltheart, 1998; Plaut, McClelland, Seidenberg, & Patterson, 1996; Spinelli, Kandel, Guerassimovitch, & Ferrand, 2012). Encoding of the graphemic status might be especially useful in order to successfully read in opaque languages, since phoneme-to-grapheme correspondences are more transparent than phoneme-to-letter correspondences.

Similarly, graphemes have been proposed to play an important role in spelling. Houghton and Zorzi (2003) proposed that letters representing the same phoneme are processed as whole units. Thus, the word *SET* would be composed of three graphemes, S+E+T, but the word *SEA* would be composed of two graphemes, S+EA. The authors observed that their spelling simulations were more accurate and plausible when such a grapheme level was included in the model besides a letter level. From the dual-route perspective, the graphemic level has been claimed to be the locus of integration of the outputs produced by both spelling routes. Thus, graphemes have been considered to be at the basis of the phonological effects generated by assembled routes. In their model of handwriting, Kandel and colleagues (2011) proposed that the letter module, along with knowledge about bigram frequency, stocks information about the relationship between phonemes and graphemes. They claimed that complex graphemes are not processed like other bigrams "because complex graphemes are frequent bigrams and are directly associated to phonology" (Kandel et al., 2011, p 1319). Some neuropsychological studies have reported striking evidence consistent with the idea of complex graphemes having a special status in spelling. Caramazza and Miceli (1990) found that the Italian patient LB produced more errors in the sequence *SC* (which in Italian can represent one or two phonemes) when represented two than one phoneme. In a more recent study using better controlled materials, Tainturier & Rapp (2004) observed that patients with graphemic buffer deficit produced less "broken sequences" in complex graphemes than in other similar letter clusters. That is to say, when patients made an error they were more likely to produce correctly only one of the two letters in the context of two simple graphemes than in a two-letter complex grapheme. This result seems to indicate that complex graphemes were processed as whole units, so this unit could be preserved (both letters would be correctly produced) or affected (both letters would be absent), but rarely partially affected.

Experimental studies on normal written word production have also reported evidence confirming that grapheme complexity affects writing, and more specifically writing durations (Kandel, Soler et al., 2006; Kandel & Spinelli, 2010; Spinelli et al., 2012). In a study conducted in French, Kandel, Soler et al. (2006) observed that children learning to write were influenced by grapheme complexity. They compared words in which the initial syllable consisted of two complex graphemes (*CH+AN.SON*) with words in which the first syllable was constituted by four simple graphemes (such as *C+R+I+S.TAL;* Experiment 1), and with words with an initial syllable starting with a simple grapheme followed by a complex three-letter grapheme (*P+EIN.TRE;* Experiment 2). Mean stroke duration percentages revealed a movement time peak in complex graphemes at letter 2 (this is, the last letter of the first complex grapheme) but not in the conditions with initial simple graphemes. The authors concluded that in the case of words with two complex graphemes (*CH+AN.SON)* children prepared the first grapheme before the written response was initiated, and that the second grapheme was prepared while local parameters of the previous letter (i.e., letter 2) were processed. However, this study compared writing durations produced for different letters. More recently, Kandel and Spinelli (2010) asked adult participants to copy words that included the same letter (*A* or *E*) and that differed in graphemic complexity. For example, letter *A* in *CLAVIER*, *PRAIRIE* and *PLAINTE* (*keyboard*, *meadow*, and *complaint*) was embedded in a simple grapheme, a two-letter complex grapheme and a three-letter complex grapheme respectively. The idea was to test not only the effect of grapheme complexity, but also the potential effect of gradient of complexity indicated by means of the number of letters included in a given grapheme. The results revealed shorter writing durations for the first letter of the target sequence (letter *A* in our examples) for simple than for both complex graphemes. Additionally, effects of complexity and of gradient of complexity were obtained in the mean stroke durations obtained for the letter preceding the target grapheme (*L* in *CLAVIER*, *R* in *PRAIRIE* and *L* in *PLAINTE*). Because the letter located at this position was not the same in all the experimental conditions, this effect could have been due to differences in letter form (see Chapter 2 of the present dissertation). Spinelli and colleagues (2012) have also reported effects of graphemic cohesion in both reading and writing. In their writing experiment (Experiment 2), they found longer mean stroke durations for weakly cohesive graphemes (such as *ON*, that can be parsed as a single grapheme or as two simple graphemes) than for strongly cohesive graphemes (as *OU*, which is always parsed as a complex grapheme). Again, different sequences of letters were used.

In all these studies mean stroke durations were observed to be longer for complex than for simple graphemes. It has been claimed that complex graphemes might represent an advantage or a disadvantage compared to simple graphemes in spelling. The maintenance in the graphemic buffer of complex graphemes might be less demanding than in the case of simple graphemes. Since the graphemic buffer is known to be sensitive to word length, keeping only two units in the buffer (like in $S_1EA_2$) should be easier than keeping three units (as in $S_1E_2T_3$). However, identity and order at the letter level must be determined later in the process, so the appropriate motor program can be activated. Consequently, some sort of "unpacking" might be necessary for complex but not for simple graphemes (Tainturier & Rapp, 2004). A digraph, for example, may simultaneously activate both letters at a processing module following the grapheme level (namely, a letter level). Thus, increased writing times would be observed during the production of the first letter of the digraph. Of course, these two hypotheses are not mutually exclusive, and different patterns of results could be observed depending on the task and/or on the dependent variable taken into account. For instance, when assessing the performance of patients with graphemic buffer deficit, it is crucial to establish which components of the orthographic working memory are specifically affected (activation, selection), since different pattern of errors are expected. In the case of word copy performed by adults, the minimal demands of the task on the graphemic buffer should lead to little or null advantage for complex graphemes. However, effects of unpacking would be detectable in an analysis of writing durations, because the simultaneous activation of both letters would affect the retrieval of the individual letters that constitute a grapheme, as well as their order (see Tainturier & Rapp, 2004 for a similar proposal).

We aimed to test whether graphemes are functional in French during copy, and to establish at which level of processing grapheme complexity might affect the writing process. Differently from previous studies, we compared the same sequence of letters in both simple and complex graphemes conditions. Specifically, we used weakly cohesive sequences (Spinelli et al., 2012) such as *AN*, which can correspond to two phonemes (/a/+/n/) or to a single phoneme (/ɑ̃/). In Experiment 8 we matched the experimental stimuli by the identity of their first three letters (e.g., B<u>*AN*</u>ANE vs B<u>*AN*</u>DIT). By doing so, we made sure that whether an effect in L1 (letter *B* in our example) was observed, as it was in previous studies (Kandel & Spinelli, 2010; Kandel, Soler et al., 2006), this could not be attributed to differences in letter identity. We predicted longer writing times for complex than for simple graphemes in the first letter of the target sequence (L2, in our examples, the letter *A*) or in the interval preceding that letter (ILI1), due to the fact that the graphemic units must be unpacked in their constituent letters.

**1. Experiment 8**

*1. 1. Method*

<u>Participants.</u> Thirty-seven students from Psychology introductory courses at the Université Pierre-Mendés-France took part in this experiment to fulfill a course credit requirement. All of them were native French speakers, right-handed and with no known motor or perceptive disorders. Some of them had participated in Experiment 6a or 6b two or three weeks earlier.

<u>Materials.</u> Seventy-two French words including the sequences *AN*, *AM*, *EN*, *IN*, *IM*, *ON* or *OM* were selected to serve as experimental stimuli. For half of these words the critical

sequence corresponded to two different phonemes (/a/, /e/, /i/ or /o/ + /n/ or /m/; for example, *BANANE*). For the other half, the target sequence represented only one phoneme (*AN*, *AM* and *EN* were pronounced /ɑ˜/; *IN* and *IM* represented /ɛ˜/, and *ON* and *OM* were pronounced /ɔ˜/; for example, *BANDIT*). This means that the critical sequence corresponded to two simple graphemes in the former condition and to a complex grapheme (specifically, a digraph) in the latter condition. The experimental words were paired so they shared their first three letters. Both conditions were closely matched by number of letters. Mean values of orthographic neighborhood, number of syllables, lexical frequency, and frequency of the third bigram according to Lexique 2 (New, Pallier, Brysbaert, & Ferrand, 2004) were controlled between-conditions. T-test showed that both conditions did not significantly differ in the mean value of these controlled measures (all $t$s < 1). A full list of the experimental words and their mean values for these variables are given in Appendix E.

Procedure. Participants were asked to copy on a digitizer in uppercase the words that appeared in the screen in lower case. The stimuli presentation, general characteristics of administration, and data collection procedures were identical to those described in Chapter 4.

*1. 2. Results*

Writing latencies, writing durations for the first three letters of each experimental word (L1, L2, L3) and durations of the first two inter-letter intervals (ILI1, ILI2) were submitted to separate ANOVAs. Grapheme complexity (simple graphemes, complex grapheme) was a within-participants variable in the analysis by participants ($F_1$) and a between-participants variable in the analysis by items ($F_2$). Scores above and below 2.5 standard deviations from the mean by participant and stimulus were considered extreme outliers and they were removed from the analysis. Misspellings, hesitations and trials in which a recording error occurred were removed from the statistical analysis Overall, 2.15% of the observations for letters were removed, and a

4.4% for intervals. Table 9 shows the mean and standard deviations for writing durations and errors for each condition.

| | Simple graphemes | Complex graphemes |
|---|---|---|
| Writing latencies | 1142 (209) | 1143 (207) |
| L1 | 402 (144) | 402 (135) |
| L2 | 434 (136) | 439 (138) |
| L3 | 439 (86) | 441 (86) |
| ILI1 | 113 (36) | 115 (36) |
| ILI2 | 111 (39) | 108 (38) |

**Table 9.** Mean values and standard deviation (in brackets) for writing latencies and durations, and inter-letter intervals durations for simple and complex graphemes (in ms), in Experiment 8.

Writing latencies were unaffected by grapheme complexity ($F < 1$). Regarding writing durations, the main effect of grapheme complexity was significant in the L2 durations in the analysis by participants, $F_1(1, 36) = 4.73$; $MSE = 426.05$; $p < .05$, but not in the analysis by items, $F < 1$. This letter was faster produced in the simple graphemes condition than in the complex grapheme condition. Significant differences in ILI2 durations were found only in the analysis by participants, $F_1(1, 36) = 4.47$; $MSE = 118.79$; $p < .05$; $F_2(1, 70) = 2.04$; $MSE = 125.97$; $p = .16$; $1- \beta = .23$. Opposite to the effect obtained for L2 durations, ILI2 durations were longer in the simple graphemes condition. No effects were observed in the analysis of L1 durations ($F < 1$), LD3 ($F_1(1, 36) = 1.21$; $MSE = 69.24$; $p = .28$; $1 - \beta = .19$) or ILI1 durations ($F_1(1, 36) = 2.19$; $MSE = 112.4$; $p = .15$; $1 - \beta = .3$).

*1. 3. Conclusions*

The effects of grapheme complexity obtained for L2 and ILI2 durations were significant, but only in the analysis by participants. We attribute this pattern of results to the large variability between items caused by the use of different letters as target. Experimental words included the target sequences *AN*, *AM*, *EN*, *IN*, *IM*, *ON* or *OM.* Obviously, mean durations for letters *A* (493 milliseconds in the present experiment), *E* (543 ms), *I* (290 ms) and *O* (276) ms) are very different. In this regard, it is worth noting that mean standard deviations for L2 durations were 106 and 104 milliseconds for complex and simple graphemes respectively. Because experimental stimuli were paired across condition by the identity and position of the critical sequence, this fact should not have a remarkable impact on the results of the analysis by participants. However, the analysis by items would be very unlikely to reach significance given the large variability among the durations of the hand-movements associated to different letters. In order to obtain comparable values regardless letter identity, we standardized the writing times obtained for L2 and ILI2. By converting each observation to z-scores we are now able to compare the values obtained for different letters which previously had different means and standard deviations (i.e., different distributions). Thus, we subtracted from each observation the mean duration of the specific letter being produced, and then we divided the outcome by its standard deviation. For example, given a 547-ms writing duration produced by a particular participant for the target letter *A* in the word *BANDIT*, the mean duration obtained for letter *A* in the whole experiment (493 ms) was subtracted, and the outcome was divided by the standard deviation for all the *A*s' durations (18 ms). This, the z-score for *A*'s duration = (547-493)/18 = 0.3).

Two separate ANOVAs were conducted on the z-scores obtained for the observations collected in Experiment 8 for L2 and ILI2. A significant effect of grapheme complexity for L2 durations was found in the analysis by participants, $F_1(1, 36) = 5.14$; $MSE = .17$; $p < .05$, and in the analysis by items, $F_2(1, 70) = 4.07$; $MSE = 4.28$; $p = .05$. Writing durations for this letter were longer when the critical sequence formed a complex grapheme. This fact seems to support the claim that grapheme complexity affects the duration of the first letter of the complex grapheme, and that the absence of an effect in the by items analysis in Experiment 8 was probably due to differences in letter identity across experimental trials. The difference between conditions in ILI2 durations were also significantly in both analyses, $F_1(1, 36) = 5.34$; *MSE*

= .21; $p < .05$; $F_2(1, 70) = 8.31$; $MSE = .34$; $p = .01$). The interpretation of the effect obtained in ILI2 is far from being straightforward. As occurred in Chapter 4, we were not able to match both conditions by the position of the syllabic boundary. ILI2 was always intra-syllabic in the complex grapheme condition (e.g., *BAN.DIT*), and always inter-syllabic in the simple graphemes condition (*BA.NA.NE*). This was unavoidable since the sequences included in Experiment 8 are pronounced as two separate phonemes almost exclusively when they belong to separate syllables. We think that the effect found in ILI2 durations is due to the position of the syllabic boundary for several reasons.

First, we predicted an effect in this position based on the evidence obtained in previous syllabic-boundary studies (Kandel, Álvarez et al., 2006; Lambert et al., 2007; Álvarez et al., 2009). Second, an effect in this interval was not reported by Kandel and Spinelli (2010) or Kandel, Soler et al. (2006). Although it is true that these studies involved the comparison of different letters per condition, this fact would not have had a dramatic impact on intervals durations. Kandel and Spinelli (2010) obtained grapheme complexity effects in the duration of the letter previous to the target sequence (our L1) and in the first letter of the target sequence, which is the first letter of the complex grapheme (L2). However, graphemic complexity had no effects in the ILI located at the within the complex grapheme (ILI2). In our opinion this is due to the fact that the stimuli used in these previous studies (unlike ours) did not differ systematically across conditions in the position of syllabic boundary. Nonetheless, we acknowledge the possibility that divergences between studies have been caused by other differences in the characteristics of the materials, since our experimental manipulation is different to that included in those studies. Third, we found the opposite effect in L2 durations: writing times were *shorter* for simple graphemes than for complex graphemes. However, ILI2 durations were *longer* for simple graphemes, as expected in the case of a syllabic boundary effect. Of course, a facilitatory effect of graphemic complexity could be accounted for by assuming a mechanism similar to that proposed in Chapter 5. An advantage in this interval for complex graphemes could be attributed to the fact that both letters are processed like a whole unit in this condition, but not in the simple grapheme condition. From this point of view, L3 would be partially retrieved during the processing of local parameters for L2 (the grapheme complexity effect obtained L2 might be reflecting this fact), so it would be accessed faster subsequently. This fact would have led to shorter durations for the inter-letter interval before L3 (i.e, ILI2). In order to confirm or rule out the hypothesis that the position of the syllabic boundary underlies the effect obtained in Experiment 8 in ILI2 durations, we carried out Experiment 9 in Spanish.

## 2. Experiment 9

In Experiment 9 Spanish words including the same sequence of letters used in Experiment 8 were selected, choosing cognates of those French stimuli when this was possible. In one condition, ILI2 was always an intra-syllabic interval (*BAN.DI.DO*), whereas in the other condition ILI2 was always inter-syllabic (*BA.NA.NA*). Since in Spanish these target sequences never constitute a complex grapheme (they always represent two different phonemes), those effects associated with grapheme complexity should be absent. Thus, if the effect observed in French in ILI2 durations was actually due to graphemic complexity, it would not be found in Experiment 9. In contrast, if this effect was due to the position of the syllabic boundary, then an effect similar to that observed in Experiment 8 in this position is expected. Because we interpret the differences obtained in Experiment 8 for L2 durations as a genuine grapheme complexity effect, we predict that this effect will vanish in Experiment 9. On the contrary, if the effect observed in L2 was related to the position of the syllabic boundary, then a similar effect should appear in Spanish.

*2. 1. Method*

Participants. Twenty-three students from introductory courses of Psychology participated in this experiment to fulfill a course credit requirement. They were all native Spanish speakers and they reported not to speak French.

Materials. Sixty-eight Spanish words containing the same sequences considered in Experiment 8 were selected. They were chosen in pairs, so each pair shared the first three letters (*BANANA*-*BANDIDO*). In one member of the pair, the second and the third letter belonged to the same syllable, and to different syllables in the other member. The same variables considered in Experiment 8 were controlled (all *t*s < 1). The complete set of stimuli is shown in Appendix E.

*2. 2. Results*

Separate ANOVAs were carried out on the writing latencies, and L1, L2, L3, ILI1 and ILI2 durations, with the syllabic status of ILI2 (inter-syllabic versus intra-syllabic) as a within-participants variable in the analysis by participants ($F_1$) and a between-participants variable in the analysis by items ($F_2$). A 2.35% of the observations for letters and a 5% for intervals were removed from the analysis following the same criterion that in Experiment 8. Mean and standard deviations are given in Table 10.

| | Inter-syllabic interval | Intra-syllabic interval |
|---|---|---|
| Writing latencies | 1120 (201) | 1131 (200) |
| L1 | 325 (127) | 322 (126) |
| L2 | 349 (117) | 347 (116) |
| L3 | 375 (76) | 373 (75) |
| ILI1 | 92 (36) | 91 (37) |
| ILI2 | 90 (34) | 88 (34) |

**Table 10.** Mean values and standard deviation (in brackets) for writing latencies and durations, and inter-letter intervals durations for inter-syllabic and intra-syllabic intervals (in ms), in Experiment 9.

A significant effect of syllabic status of ILI2 was observed in ILI2 duration only in the analysis by participants, $F_1(1, 22) = 4.44$; $MSE = 80.81$; $p < .05$; $F_2(1, 66) = .93$; $MSE = 79.55$; $p = .34$; $1 - \beta = .16$. ILI2 was shorter when this interval was intra-syllabic. There were no other significant differences (all *F*s < 1). Again, we failed to observe a significant effect in the analysis by items. Following the same reasoning as in Experiment 8, we standardized the observations for ILI2 and conducted a new analysis of variance. A significant effect was obtained in the analysis by participants, $F_1(1, 22) = 4.1$; $MSE = .13$; $p < .05$, and it was marginally significant in the analysis by items, $F_2(1, 66) = 3.34$; $MSE = .2$; $p = .07$. ILI2 took longer in the inter-syllabic (*BA_NA.NA*) than in the intra-syllabic condition (*BAN_DI.DO*).

*2. 3. Conclusions*

As predicted, an effect of syllabic status was found in ILI2 durations, suggesting that the effect observed in this position in Experiment 8 was due to differences between conditions in the syllabic status of this interval. Again, we have replicated the syllabic boundary effect previously reported in the literature (Kandel, Álvarez et al., 2006; Lambert et al., 2007; Álvarez et al., 2009). Importantly, the fact that the effect for L2 durations found in Experiment 8 was not obtained in Experiment 9 seems to confirm that this effect was actually due to the grapheme complexity manipulation.

**3. Discussion**

Two experiments addressing the functionality of graphemic units during handwriting are reported in this chapter. In Experiment 8, the same sequence of letters was compared when representing simple to complex graphemes. Significant differences between both conditions were obtained for L2 and ILI2 durations. Complex graphemes yielded longer writing durations for L2 (*B<u>AN</u>.DIT* versus *B<u>A</u>.NA.NE*), and shorter durations for ILI2 (*BA_NDIT* versus *BA_NANE*) than simple graphemes. The effect found in L2 is similar to that reported by Kandel and Spinelli

(2010). These authors observed that the duration of letter *A* was shorter when embedded in a one-letter grapheme (a simple grapheme, like in *CLAVIER*) than in a two- or three-letter grapheme (*PRAIRIE* or *PLAINTE*). This effect would be equivalent to the effect observed in Experiment 8 for L2 durations, a position which represents the first letter of the complex grapheme. However, some differences between the results from our study and those obtained by Kandel and Spinelli (2010) must be pointed out. First, they reported that letter durations for the letter previous to the target grapheme were shorter for one-letter than for two-letter graphemes, which, in turn, were shorter for than for three-letter graphemes. Differently, grapheme complexity did not affect the duration of the letter preceding the target grapheme in our study (L1, *B* in *BAN.DIT* versus *BA.NA.NE*). Furthermore, the effect obtained here for ILI2 was absent in Kandel and Spinelli's study. We claimed that the two effects reported here (effects in L2 and ILI2 durations) were due to different factors. Whereas we interpreted the effect observed in L2 durations as reflecting processing differences between complex and simple graphemes, we suggested that the effect in ILI2 durations is a syllabic boundary effect. Results from Experiment 9 were in line with this distinction. When Spanish writers produced the same sequences of letters used in Experiment 8, longer durations were obtained in ILI2 for inter-syllabic than for intra-syllabic sequences, but effects in L2 durations were not observed. We predicted this pattern of results. Since these sequences did not differ in grapheme complexity in Spanish, only syllabic boundary effects should be found in this experiment.

The evidence reported here suggests that graphemic complexity affects the execution of the first letter of the complex grapheme (i.e., L2). This letter takes more time to be produced when is embedded in a complex grapheme, indicating that complex graphemes are kept in orthographic working memory (or graphemic buffer) as units, and that they have to be "unpacked" in some way to determine letter identity and order. In the case of simple graphemes, this process would not occur, leading to shorter writing durations. Thus, it seems that complex graphemes do not produce a detectable processing advantage based on the maintenance of fewer elements in the graphemic buffer, at least in the copy task. Instead, grapheme complexity would affect writing durations at a later stage of processing, in which the digraph would have to be segmented into two letters. The precise locus of the effect is uncertain. On the one hand, complex graphemes might have been stored as in the case of high-frequency syllables, leading to a similar effect. From this point of view, the effect observed in ILI2 might reflect syllabc boundary effects and grapheme complexity effects. On the other hand, letters within a complex grapheme may have a more distributed pattern of activation, which would produce competition and interference between both letters (i.e, the fan effect, Anderson, 1974), especially during the retrieval of the motor pattern of the first letter of the digraph (our L2). Alternatively, our pattern of results could be explained by proposing that complex grapheme have to be "unpacked" in some way, and that increased movements times in this position reflect the fact that an additional step of processing is required in this case. The evidence reported here does not distinguish between these potential explanations, so they need to be further tested in future studies.

The same effect obtained in Experiment 8 in ILI2 durations was obtained in Experiment 9 conducted with Spanish materials. Like both experimental conditions in Experiment 8, stimuli in Experiment 9 differed in the position of the syllabic boundary with respect to the critical letters. In Experiment 8, ILI2 was intra-syllabic in all the words included in the complex grapheme condition (*BA_N.DIT*) and inter-syllabic in all the words with simple graphemes (*BA._NANE*). Results showed longer durations for the simple graphemes condition, as expected in the case of a syllabic boundary effect. In Experiment 9 a similar effect was observed with Spanish words in which the critical sequences always represented simple graphemes (*BA_N.DI.DO* versus *BA._NA.NA*). Altogether, these results may indicate that the effect observed in ILI2 durations in

French was a syllabic boundary effect, and not a grapheme complexity effect.

In comparison to the evidence reported by Kandel and Spinelli (2010), our study did not reveal an effect of grapheme complexity in L1 durations. We believe that this effect could have been due to differences in letter identity among conditions in the study conducted by Kandel and Spinelli, and that it may not be related to grapheme complexity. Although these authors normalized the writing durations in order to enable the comparison of different letters, we have claimed that this procedure does not produce fully comparable measures, so effects obtained with this methodology must be taken with caution. At least, evidence obtained by comparing the same letter sequence at the same position would be more reliable. Additionally, given the pattern of results observed in the analysis by items for L2 durations in Experiment 8, it seems that writing durations are dramatically affected by differences in letter identity, even if they exist only within-condition. In this case, effects might be difficult to reach significance effects in the analysis by items.

Although further research is necessary to clarify the origin of the differences between our study and that of Kandel and Spinelli (2010), we suggest that grapheme complexity effects arise during the processing of local parameters of the first letter of the complex grapheme rather than during the execution of the previous letter, as claimed in earlier studies.

# Part III: Summary and discussion

# 7

# General discussion

The main goal of the present dissertation was to investigate the involvement of phonological sublexical information during the writing process performed by adults. For many years, forceful evidence has been reported supporting the claim that orthographic lexical representations can be directly accessed via the semantic system (Miceli et al., 1997; Rapp & Caramazza, 1997; Rapp et al., 1997). This evidence has led to general acceptance of the idea that phonological information has little opportunity to come into play during the lexically mediated writing process. Although there is extensive agreement about the existence of lexical (orthographic) processes and sublexical (phonological) processes, these two spelling routes are thought to have very different scopes. According to early proposals, the so-called lexical route would provide the spelling for well-known words by means of the retrieval of the appropriate orthographic word-form from an output lexicon; in contrast, the sublexical route would produce phonologically plausible spellings for nonwords or low-frequency words. That is to say, the assembled route would be functional when a lexical representation is not available. In spite of this fact, phonological manipulations at the sublexical level have been observed to affect word writing (Bonin, Peereman et al., 2001), so it has been proposed that both routes would be simultaneously activated in normal spelling circumstances, and that the relative influence of each route on the writing process would largely depend on the experimental material and task. In the present PhD dissertation we contribute to this debate with considerable evidence obtained with a methodology based on strict control of the experimental material and analysis of chronometric measures.

**1. Summary of the results**

In Chapter 3, three experiments using the odd-man-out variant of the implicit priming paradigm were reported, aimed at determining the role played by phonological information during the handwriting process. Participants were asked to write a small set of words learned in response to prompts. Within each block, response words could share initial segments (constant homogeneous) or not (heterogeneous). Also, two variable homogeneous blocks were created by including a response word that did not share orthographic onset with the other responses (odd-man-out). This odd-man-out could be phonologically related to the target words (*banana*, *balada*, *baraja*, *vacuna*) or not (*banana*, *balada*, *baraja*, *tarima*). Experiment 1 showed a preparation effect in the constant homogeneous condition, which disappeared (spoil effect) in the variable condition non-phonologically related. However, no spoil effect was found when the odd-man-out shared the phonological initial segment with the target. In Experiment 2, we obtained a spoil effect in the variable phonologically related condition, but significantly smaller in the variable non-phonologically related condition. The effects observed in Experiment 2 vanished in Experiment 3 under articulatory suppression, suggesting that they originated at the sublexical level.

Chapter 4 aimed to establish whether or not the grapheme-to-phoneme (G-P) probability of a mapping affected the production of the grapheme. We manipulated the relative frequency of two phonemes related to the same polyvalent grapheme, which was embedded in to-be-copied French (Experiments 4a and 4b) and Spanish words (Experiment 5). Experiment 4a *(vicTIme-marTIen*) failed to observe significant differences between both frequency conditions. In Experiment 4b we used the polyvalent French grapheme *E*, which allowed us to increase the differences in G-P probability between conditions. In this case, writing durations revealed that the ILI located before this letter was shorter and that the letter itself was faster executed. Similar effects were found in Spanish in Experiment 5. An inhibitory effect was also obtained in Experiment 4b in the ILI following the target letter. This effect was absent in Experiment 5, so we claim that it is unlikely to be due to relative phoneme-frequency. Altogether, these results confirm that phonology is retrieved also during copy, and reflect that the strength of the connection between a phoneme and a grapheme is increased whenever activation spreads from one to another.

Chapter 5 included two spelling-to-dictation experiments aimed to disentangling the influence of syllable (a unit of phonological origin) and bigram (an orthographic terms) frequency in writing production. In Experiment 6 we manipulated the frequency of the second syllable of Spanish words while keeping the frequency of the bigram constant. Longer durations for the first letter of the syllable and shorter durations for the subsequent ILI were observed for high-frequency compared to low-frequency syllables. In Experiment 7 the frequency of the third bigram (the second syllable) was manipulated and the syllable frequency kept constant. In this case, we observed shorter written latencies for high-frequency bigrams than for low-frequency bigrams (only in the analysis by participants), but no differences were obtained in writing times. We interpreted these findings as a reflection of the fact that syllable-size abstract motor patterns are stored for high-frequency but not for low-frequency syllables.

In Chapter 6 we addressed the involvement during handwriting of graphemes, another sublexical unit defined by its relation with phonology. We compared writing times produced for the same sequence of two letters when they represented a complex two-letter grapheme (*bANdit*) versus two simples graphemes (*bANane*). Results revealed that the duration of the first letter of the sequence was longer in the complex grapheme condition than in the simple graphemes condition. Additionally, the subsequent ILI was shorter in complex than in simple graphemes. Given the characteristics of the stimuli, the latter effect was consistent with an account in terms of the position of the syllabic boundary. A similar effect in ILI2 was found when the same sequences were tested in Spanish, so we cannot be sure whether this effect is due to grapheme complexity. This pattern of results indicates that graphemic units are encoded at some point of the spelling/writing process.

**2. Conclusions**

The evidence reported in the present dissertation has revealed that phonological information is consistently retrieved when skilled writers produce well-known words. Our findings indicate that phonology affects handwriting at a sublexical level of processing. The individual phonemes of the to-be-written words are activated during the writing process, and these phonemes activate, in turn, their related graphemes. Thus, both the lexical (orthographic) route and the sublexical (phonological) route integrate information, presumably at the grapheme level (Bonin, Peereman et al., 2001; Folk & Rapp, 2004). As commented, several of the theoretical proposals presented in Chapter 2 are models of the processes involved in specific writing tasks (e.g., spelling-to-dictation), so it is not immediately obvious what effects are predicted for other tasks. In any case, we consider that the mechanism proposed by Bonin, Peereman et al., (2001) for written picture naming could account for the results obtained in Chapter 3.

Moreover, results obtained in Chapter 3 are in line with the hypothesis that a phoneme activates all the graphemes related to it (Martin & Barry, 2012), and not only the most frequently associated grapheme (Barry & Seymour, 1988; Baxter & Warrington, 1987). Similar results were observed regardless of the identity of the target grapheme. In fact, results from Chapter 4 suggest that phonology-to-orthography mappings are graded based not only on phoneme-grapheme probability (Barry & Seymour, 1988), but also on the grapheme-phoneme probability. Altogether, the results reported in Chapters 4, 5 and 6 indicate that multiple phonological units are functional during handwriting, and suggest that there may be more than one programming unit (Van Galen, 1991).

The effects reported in this manuscript were clearly detected in those segments previous to the location of the experimental manipulation or in the duration of the critical segment itself. We interpreted this fact as evidence in favor of the anticipatory theory of writing production introduced by Van Galen (1991), and supported by other authors (Kandel et al., 2011). Writing durations are affected by manipulations at the central level, contrary to the claim that central processing must be finished before the written response is initiated (Damian & Stadthagen-González, 2009). Instead, our findings are consistent with the idea that increased writing times are due to the concurrent engagement of different modules of processing with different parts of the response. While one unit is produced, forthcoming segments of the response are processed at higher-order levels, so increased times can result from: a) increased demands exerted at the motor levels by the segment actually being produced, or b) increased demands exerted at more central levels by the following element(s) in the response. This anticipatory hypothesis seems to provide a better account of the effects reported here than an explanation based on the existence of a conflict between competing graphemes which remains unsolved during several seconds (Delattre et al., 2006). Our findings cannot be explained by the mere presence or absence of a conflict between the outputs from the lexical and the sublexical route. If the consequences of such a conflict cascaded from the central levels of processing to affect writing durations, then increased times should have been observed for all the letters of the word, at least until the conflict had been solved. Differently, sublexical manipulations affected the writing times produced for the critical segment and/or the immediately previous segments. Although in Chapter 3 writing durations were not affected by the phonological manipulation, this does not rule out the anticipatory theory of handwriting. In that case, the critical segment was the initial segment of the target words, so from the anticipatory perspective only an effect on the written latencies was expected in this series of experiments. Furthermore, the anticipatory theory fits the findings of previous studies. For example, from this point of view, a manipulation affecting the writing durations is expected to affect any replication of the stimulus (and not only in the first replication, as assumed by Delattre et al., 2006), since the processes responsible for the effect are necessary for the ordered production of the sublexical elements of the word. As we have already commented, evidence seems to confirm this prediction.

As mentioned above, models of handwriting have focused on different aspects of the process. Some of them have been designed to account for results coming from a particular task (see Figures 5 and Figure 6), and more inclusive theoretical proposals have been largely unspecific about the mechanisms that could be involved in each processing module (see Figure 2 and Figure 8). Furthermore, some of the phenomena investigated in this manuscript had never been experimentally addressed, so current models have not made predictions about them (e.g., syllable-frequency, relative phoneme-frequency). For this reason, we propose a tentative model of handwritten word production which describes the minimal processing modules that we consider necessary to account for our results and for some of the most important findings reported in the literature. This model, depicted in Figure 9, also includes some intuitions about the writing process that have not yet been experimentally tested, aiming to stimulate debate about some concepts that have not received very much attention. Although other architectures might explain some of the results, and some mechanisms will probably have to be added in order to reflect the complexity of the writing process (for example, feedback connections may be necessary in order to account for how the writing system from one sublexical unit to the next sublexical unit), we think that this model includes some levels of processing and some assumptions about the flow of activation that are fundamental to understanding the dynamics of the writing process in general and the influence of phonological information in particular. Our model has been developed with specific interest in the sublexical processes to which the elements held in the orthographic working memory (OWM) have to be submitted. For this reason, these processes are commented in special detail.

We propose a hierarchical model in which component processes are engaged in parallel. Input processes are represented in yellow and output processes appear in blue. Squared and circular shapes correspond to long-term and short-term stores respectively. Arrows express the fact that the output from one component process is the input for the next process. The horizontal organization of the more peripheral levels has been chosen to stress the fact that these processes have to be applied in a left-to-right manner over the sublexical units kept in the OWM.

The first processes depicted in the model are the input lexicons. Because this architecture aims to reflect the word writing process, routes that are considered to be engaged exclusively during nonword spelling (or when a real word fails to activate a lexical representation) are not included in the model[5]. Once a to-be-written word has been accessed in an input lexicon, either orthographic or phonological, a semantic representation is retrieved. This representation sends

5 Obviously, additional mechanisms (not semantically mediated) should be included to account for nonword written production. However, a thorough description of these mechanisms is beyond the scope of the present work.

activation in parallel to both output lexicons, so the corresponding orthographic word-form can be retrieved in the orthographic output lexicon without any phonological mediation (Miceli et al., 1997; Rapp & Caramazza, 1997; Rapp et al., 1997). However, in normal writing conditions both the phonological and the orthographic word-forms are activated. These lexical forms activate their constituent sublexical elements, which are deposited in the corresponding buffer/working memory. Processes beyond this point (in Figure 9, marked with *) are explained in more detail in Figure 10. The information held in the phonological working memory encodes information about phonemes and phonological syllables, while the orthographic working memory maintains information about graphemes and syllables. Both buffers are interconnected, with phonemes sending activation to the corresponding graphemes, and with syllables activating syllable-size units in the orthographic working memory. These sublexical units are processed by the following modules in a left-to-right manner, presumably syllable-by-syllable.

First, the graphemes within the first syllable are activated/deposited in the letter level (letter level may be a long-term storage or a buffer) according to their order. Figure 10 depicts the lower levels of the handwriting process for the Spanish word *bala* (*bullet*), assuming that *ba* is a high-frequency syllable and *la* is a low-frequency syllable. In the case of *ba*, the pattern of activation generated by the individual letters at this level of processing would trigger the activation of a more complex whole-syllable motor pattern at the next level. This would produce longer writing times during the production of the first letter. During the interval after the production of this first syllable, the letters of the second syllable are activated (at the letter level).

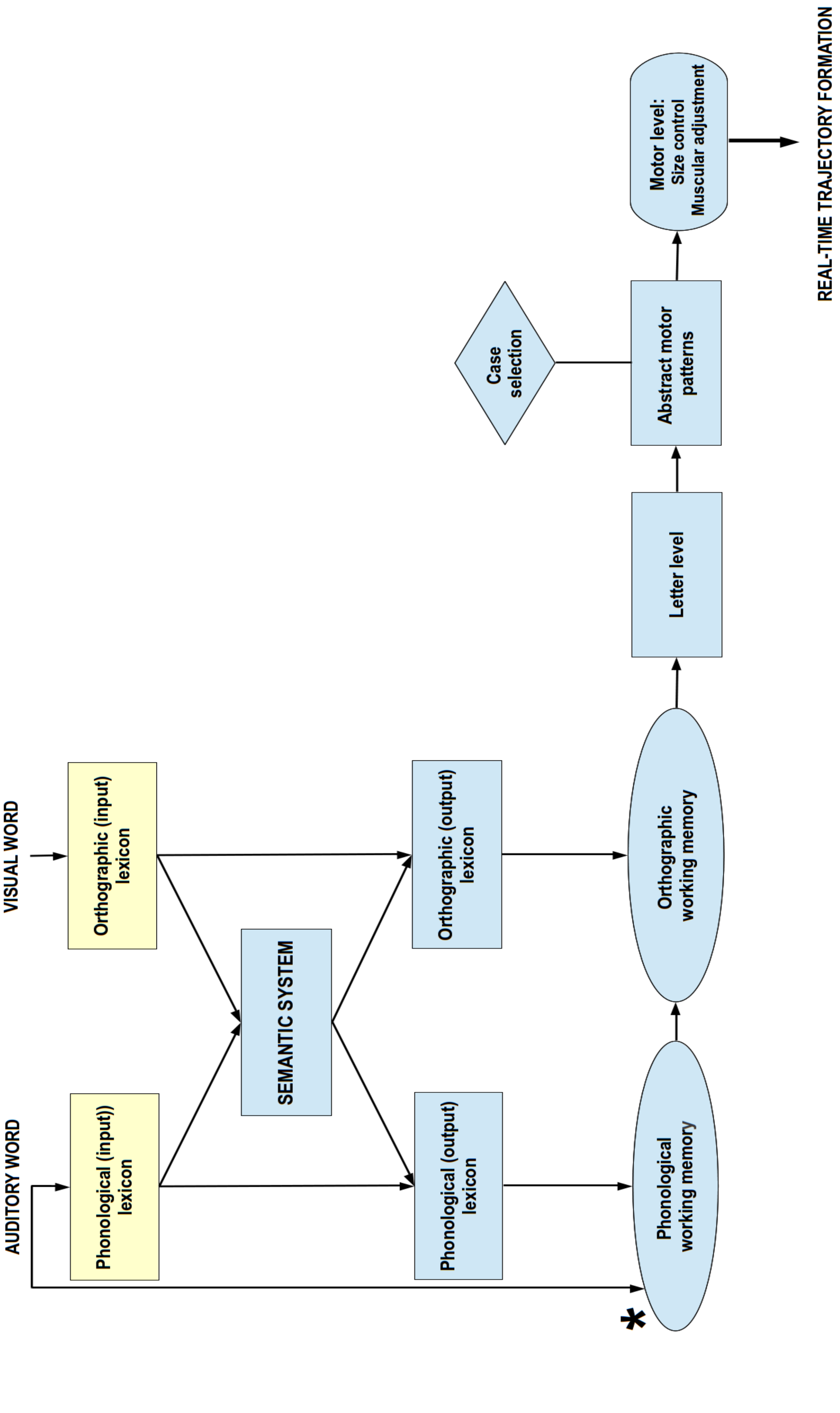


**Figure 9.** Working model of handwritten word production.

In our example, we can see that in the case of a low-frequency syllable (*la*) a holistic motor pattern is not stored, so the motor program for the first letter is individually executed. Only when this letter has been finished can the motor pattern for the second letter be retrieved, leading to the syllable-frequency effect observed in Chapter 5. Thus, abstract motor patterns corresponding to upper-case and lower-case forms of each letter and of the most frequent syllables are stored. Once the writer decides which case to use, the appropriate motor program is retrieved. A motor program is understood here as an abstract representation, which includes the minimal specifications needed to execute a movement. As we commented in Chapter 6, the locus

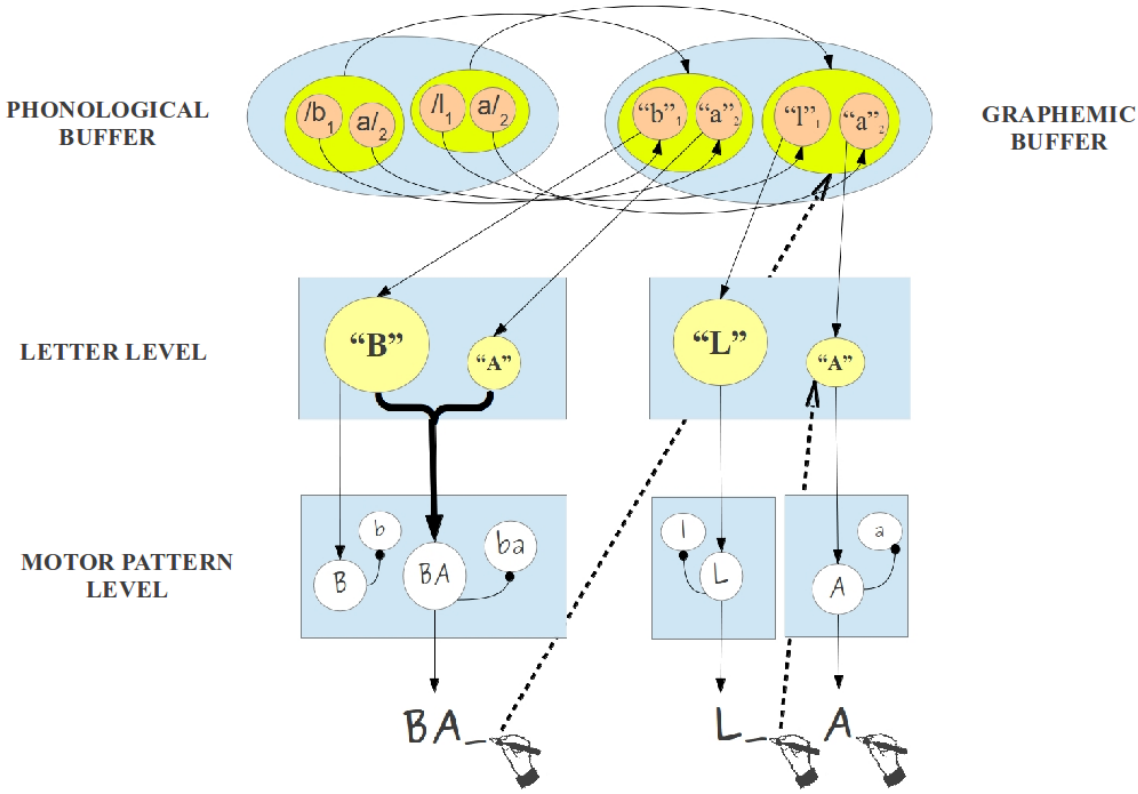


**Figure 10.** Visual representation of the post-lexical levels involved in the handwriting production of the Spanish word *bala*, in which *ba* is a high-frequency syllable and *la* is a low-frequency syllable. Both the phonological and the orthographic working memory are represented, and also the letter and the motor pattern level. Solid arrows express the flow of activation, and dotted arrows point to the units being processed at more central levels concurrently to the real-time response.

of the observed grapheme complexity effect is unclear, and it could be situated at the letter (e.g., due to unpacking or fan effect) or at the motor pattern level (due to the storage of motor programs corresponding to complex graphemes). Then the motor level would be in charge of controlling the size and the specific muscles involved, and also the particular slope necessary to produce, for example, cursive script. These processes are extremely dependent on the biophysical context, so they vary considerably across repetitions of the same segment.

Summing up, the evidence reported in this PhD dissertation reveals that, at least in Spanish and French, sublexical phonological information plays an important role during the course of adult handwriting. A phonologically mediated route of spelling seems to be active even when writing well-known words. Graphemes and syllables, two units of phonological origin, are encoded and used to retrieve the motor programs for each letter. Effects in writing durations seem to emerge from the fact that resources are limited, and that component processes of spelling can be concurrently engaged by different sublexical units (Van Galen, 1991). Thus, handwriting seems to be based on the anticipation of the forthcoming segments to be produced. This seems rather intuitive considering the speed with which all the information necessary to produce a written response is retrieved. To successfully handwrite a word, linguistic, motor and spatial information have to be accessed. It is unlikely that handwriting skill has been acquired by humans without the possibility of anticipating the processing of the following segments. If this were the case, handwriting would be slower.

Finally, we want to stress that experimental control in handwriting research should be increased. Special attention has to be paid to an issue that has been largely ignored: the identity of the target letters. Different letters clearly have different writing durations, and these differences might be determinant for results. We acknowledge the fact that to find stimuli that meet every experimental requirement is not easy, but we consider that new paradigms and methodologies such as those we have described may help to achieve this. We have demonstrated that it is possible to exert such strict control. Moreover, we have seen that at least the sublexical effects reported here were observed in segments preceding the experimental manipulation. This means that keeping constant the identity of the critical letter(s) and the immediately previous letter might suffice to obtain reliable results. In the context of psycholinguistic research, experimental material has to be se lected with the utmost care, especially in younger disciplines in which the effects of many variables remain unknown.

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# Appendices

# Appendix A

Response (in uppercase) and prompt words (in lowercase) used in Experiment 1. Experimental words appear in boldface.

| **Set of words** | **Constant homogeneous** | **Variable phonologically related** | **Variable phonologically unrelated** | **Heterogeneous** | | |
|---|---|---|---|---|---|---|
| "Ba-" | poema-**BALADA** | poema-**BALADA** | blusa-CAMISA | poema-**BALADA** | plátano-**BANANA** | naipes-**BARAJA** |
| | plátano-**BANANA** | plátano-**BANANA** | poema-**BALADA** | señora-MUJER | señora-MUJER | señora-MUJER |
| | naipes-**BARAJA** | naipes-**BARAJA** | plátano-**BANANA** | diario-PERIÓDICO | diario-PERIÓDICO | diario-PERIÓDICO |
| | suciedad-BASURA | inyección-VACUNA | naipes-**BARAJA** | memoria-RECUERDO | memoria-RECUERDO | memoria-RECUERDO |
| "Ve-" | próximo-**VECINO** | hermosura-BELLEZA | llegada-REGRESO | señora-MUJER | señora-MUJER | señora-MUJER |
| | reunión-**VELADA** | próximo-**VECINO** | próximo-**VECINO** | diario-PERIÓDICO | diario-PERIÓDICO | diario-PERIÓDICO |
| | poción-**VENENO** | reunión-**VELADA** | reunión-**VELADA** | memoria-RECUERDO | memoria-RECUERDO | memoria-RECUERDO |
| | calor-VERANO | poción-**VENENO** | poción-**VENENO** | próximo-**VECINO** | reunión-**VELADA** | poción-**VENENO** |
| "Bo-" | claxón-**BOCINA** | claxón-**BOCINA** | claxón-**BOCINA** | claxón-**BOCINA** | entrada-**BOLETO** | farmacia-**BOTICA** |
| | entrada-**BOLETO** | entrada-**BOLETO** | entrada-**BOLETO** | señora-MUJER | señora-MUJER | señora-MUJER |
| | farmacia-**BOTICA** | farmacia-**BOTICA** | farmacia-**BOTICA** | diario-PERIÓDICO | diario-PERIÓDICO | diario-PERIÓDICO |
| | cúpula-BÓVEDA | náusea-VÓMITO | dolor-CÓLICO | memoria-RECUERDO | memoria-RECUERDO | memoria-RECUERDO |

# Appendix B

Response (in uppercase) and prompt words (in lowercase) used in Experiments 2 and 3. Experimental words appear in boldface.

| Set of words | Constant homogeneous | Variable phonologically related | Variable phonologically unrelated |
|---|---|---|---|
| "Ba-" | poema-**BALADA** | poema-**BALADA** | poema-**BALADA** |
| | plátano-**BANANA** | plátano-**BANANA** | plátano-**BANANA** |
| | naipes-**BARAJA** | naipes-**BARAJA** | naipes-**BARAJA** |
| | descenso-BAJADA | jarrón-VASIJA | plataforma-TARIMA |
| "Bo-" | claxón-**BOCINA** | claxón-**BOCINA** | claxón-**BOCINA** |
| | entrada-**BOLETO** | entrada-**BOLETO** | entrada-**BOLETO** |
| | farmacia-**BOTICA** | farmacia-**BOTICA** | farmacia-**BOTICA** |
| | cúpula-BÓVEDA | náusea-VÓMITO | dañino-TÓXICO |
| "Ve-" | próximo-**VECINO** | hermosura-BELLEZA | parcela-TERRENO |
| | reunión-**VELADA** | próximo-**VECINO** | próximo-**VECINO** |
| | poción-**VENENO** | reunión-**VELADA** | reunión-**VELADA** |
| | calor-VERANO | poción-**VENENO** | poción-**VENENO** |
| "Vi-" | existencia-**VIDA** | barril-BIDÓN | serpiente-PITÓN |
| | poste-**VIGA** | existencia-**VIDA** | existencia-**VIDA** |
| | tinto-**VINO** | poste-**VIGA** | poste-**VIGA** |
| | abrigo-VISÓN | tinto-**VINO** | tinto-**VINO** |

# Appendix C

Experimental stimuli used in Experiment 4a.

| Experiment 4a | |
|---|---|
| **Higher G-P probability** | **Lower G-P probability** |
| Centime | Action |
| Comptine | Ambition |
| Cultivé | Caution |
| Destiné | Diction |
| Émotif | Dotation |
| Entier | Édition |
| Fertile | Fiction |
| Hématite | Fixation |
| Identité | Initial |
| Intime | Initié |
| Légitime | Initier |
| Litige | Lotion |
| Maritime | Martial |
| Mitigé | Martien |
| Notice | Motion |
| Obstiné | Mutation |
| Patine | Nation |
| Platine | Notion |
| Ratatiné | Nuptial |
| Routine | Option |
| Satiné | Ponction |
| Solstice | Potion |
| Ultime | Ration |
| Ventilé | Relation |
| Vestige | Section |
| Victime | Taxation |

# Appendix D

Experimental stimuli used in Experiment 4b.

| Experiment 4b | |
|---|---|
| **Higher G-P probability** | **Lower G-P probability** |
| Averti | Bedaine |
| Berceau | Bedeau |
| Bercer | Belote |
| Berline | Besace |
| Berlue | Besogne |
| Cerque | Brebis |
| Fievre | Brevet |
| Mercure | Cerise |
| Permis | Crever |
| Persan | Devenir |
| Persil | Devise |
| Pervers | Grenat |
| Pester | Menacer |
| Presto | Mesurer |
| Segment | Pelade |
| Seigle | Pelage |
| Sergent | Pelote |
| Sermon | Peluche |
| Serpent | Pelure |
| Serveur | Penaud |
| Service | Regain |
| Servir | Repris |
| Ternir | Secouer |
| Trèfle | Secret |
| Verger | Semaine |
| Vermeil | Sevrage |
| Verser | Tenable |
| Vertige | Tenant |
| Veston | Velours |

# Appendix E

Experimental stimuli used in Experiment 5.

| Higher G-P probability | Lower G-P probability |
|---|---|
| Buenazo | Quedada |
| Consuelo | Burguesa |
| Cuero | Queja |
| Cuidarse | Quitasol |
| Duelista | Quebrado |
| Expuesto | Orquesta |
| Fortuito | Manguito |
| Gratuito | Lánguido |
| Huesuda | Quemar |
| Inmueble | Juguetón |
| Jueves | Quedar |
| Mueble | Quejido |
| Mueca | Gueto |
| Noruega | Ceguera |
| Pescuezo | Carguero |

# Appendix F

Experimental stimuli used in Experiment 6.

| High-frequency syllable | Low-frequency syllables. |
|---|---|
| Balada | Bajada |
| Batido | Balido |
| Botero | Bolero |
| Cabaña | Calaña |
| Cadera | Cajera |
| Camada | Casada |
| Canilla | Capilla |
| Casero | Cajero |
| Cometa | Coleta |
| Cosido | Cogido |
| Debate | Delate |
| Dopado | Dorado |
| Nevada | Negada |
| Novato | Nonato |
| Pavada | Pagada |
| Pesado | Penado |
| Recato | Rebato |
| Remato | Relato |
| Robado | Rosado |
| Rogado | Rozado |

# Appendix G

Experimental stimuli used in Experiment 7.

| High-frequency bigram | Low-frequency bigram |
|---|---|
| Boceto | Boleto |
| Capilla | Canilla |
| Careta | Cateta |
| Casado | Calado |
| Chalado | Chapado |
| Cocido | Cogido |
| Gamada | Ganada |
| Latino | Ladino |
| Maceta | Maleta |
| Monada | Mojada |
| Papada | Patada |
| Pesado | Pecado |
| Picado | Pirado |
| Ramera | Ratera |
| Rebeca | Reseca |
| Remate | Rogate |
| Retazo | Regazo |
| Rosado | Rodado |
| Vasija | Valija |
| Venado | Vedado |

# Appendix H

Experimental stimuli used in Experiment 8 and Experiment 9

| Experiment 8 | | Experiment 9 | |
|---|---|---|---|
| **Complex grapheme** | **Simple graphemes** | **Intra-syllabic** | **Inter-syllabic** |
| Banane | Bandit | Banana | Bandido |
| Canari | Canton | Camilla | Campeón |
| Canicule | Candidat | Camino | Campo |
| Canine | Cancer | Canario | Cansar |
| Canular | Cantina | Canasta | Candidato |
| Chamelle | Champion | Canela | Cantina |
| Clameur | Clamper | Canónico | Cangrejo |
| Conique | Confort | Cenefa | Censor |
| Cramer | Crampe | Cinética | Cincel |
| Domicile | Dompteur | Comino | Compacto |
| Granite | Grandor | Cónico | Cóncavo |
| Grimace | Grimper | Limar | Limbo |
| Manier | Mandat | Limitar | Limpio |
| Manitou | Manchot | Lineal | Linterna |
| Manucure | Mansarda | Manejar | Mandato |
| Manuel | Manger | Manicura | Mandril |
| Menacer | Mendier | Manivela | Mancebo |
| Meneur | Mental | Manual | Mango |
| Menuisier | Mensonge | Memorable | Membrana |
| Minable | Minceur | Menaje | Mendigo |
| Mineur | Mincir | Menor | Mensual |
| Monocle | Monstre | Monarquía | Monstruo |
| Nominal | Nombril | Moneda | Monja |
| Panier | Passer | Panorama | Pancarta |
| Panorama | Pancarte | Penal | Pensar |
| Penaud | Pensif | Penalti | Pendiente |
| Planeur | Planche | Pomelo | Pompa |
| Ramonage | Rambarde | Ponente | Poncho |
| Sonate | Sonder | Siniestro | Sinfín |
| Tamiser | Tambour | Sonata | Sondeo |
| Tenace | Tendon | Tamaño | Tambor |
| Timide | Timbre | Tenaza | Tendón |
| Tonique | Tondeur | Tímido | Timbre |
| Vanille | Vandale | Tonelaje | Tontería |

# Summary

# Summary

Writing is a motor and cognitive skill. It is acquired only through extensive practice, and it is thought to be the basis of the ability to manipulate symbols. It provides a long-lasting support for linguistic messages, and it allows for long-distance communication. Although the relevance of handwriting has been considered to have decreased during the last decades, it seems to be renewed interest in this process, in part due to the fact that tablets are gaining in importance. However, the cognitive study of handwriting production has been largely neglected in comparison to other linguistic processes, such as speech production or language comprehension. In the present PhD dissertation we present a series of nine experiments devoted to obtain empirical evidence about the processes involved during the written production of well-known words, and specifically about the potential role that phonological information may play during this process. In spite of the fact that phonology was proposed to be retrieved only when writing nonwords, recent evidence suggests that phonological information might be retrieved even when producing familiar words. However, the studies addressing this issue are very scarce, and a method for the quantitative analysis of the written response has not been unanimously accepted. Thus, cognitive models of handwriting production have been proposed to account for a given writing task, and the role ascribed to phonology is usually circumscribed to nonword writing or spelling-to-dictation.

In the present manuscript, we provide striking evidence about the involvement of phonology in a range of writing tasks (copy, spelling-to-dictation, associated-pairs) when adult writers produce known words. Interestingly, multiple phonological units seem to be functional during handwriting, as syllables, graphemes and letter. Furthermore, we demonstrate that he frequency of a phoneme have an impact in the duration of its corresponding grapheme.

Altogether, the evidence presented here also confirms the impact of central high-order (phonological) variables in the duration of a written response. This fact supports the idea that writing starts as soon as the initial segments of the response have been processed, and rules out the affirmation that a word does not begin to be produced until the whole word has been processed at the central (abstract) levels.

In Chapter 3, we describe three behavioral experiments conducted with an adaptation of the odd-man-out version of the implicit priming paradigm, in which participants have to produce words in response to previously learned prompts. In Experiment 1, participants produced the same set of words in three different contexts: (1) a constant homogeneous block in which all the responses shared the orthographic and phonological initial segment (*balada*, *banana*, *baraja*, *basura*), (2) an heterogeneous block in which the response words did not share neither the orthographic nor the phonological initial segment (*balada*, *mujer*, *recuerdo*, *periódico*), (3) a variable homogeneous block with an *odd-man-out* non-phonologically (or orthographically) related to the target words (*balada*, *banana*, *baraja*, *camisa*), and (4) a variable homogeneous block with an *odd-man-out* phonologically (but not orthographically) related to the target words (*balada*, *banana*, *baraja*, *vacuna*). Results revealed a preparation effect (target words were faster produced in the constant homogeneous set than in the heterogeneous set) and a spoil effect in the case of an *odd-man-out* non-phonologically related (absence of preparation effect). However, the variable block with a phonologically related *odd-man-out* did not showed a significant preparation or spoil effect. This pattern of results could points out to the fact that the phonological information provided by the *odd-an-out* was used by the participants to prepare the written response, but also might indicate that our experiment lacked of the experimental power necessary to detect a significant difference between these two groups. In Experiment 2 we modified some aspects of the design used in Experiment 1 aimed to increase the statistical power. In this case, a significant difference was observed between the constant homogeneous set and the variable phonologically related set (spoil effect). However, the spoil effect obtained in this condition was significantly smaller than the spoil effect observed in the case of the variable non-phonologically related block. We interpreted these findings as evidence of the retrieval of phonological information during the production of the writing response. Participants were faster when they were still able to prepare the phonological onset of the response, although they could not predict the orthographic form they had to produce. Experiment 3 showed that the effects observed in Experiment 2 vanished under articulatory suppression, suggesting that they originated at a sublexical level.

Chapter 4 was devoted to test whether or not the execution of a given grapheme was influenced by the frequency of its corresponding phoneme. Two experiments using the copy task were conducted. In Experiment 4 French participants copied words which contained the sequence *ti* and *e*, each of them with two different pronunciations, one more frequent than the other. Results revealed that both conditions differed from each other in the case of *e* but not in the case of *ti*. While differences in distribution between the pronunciations of *ti* were small, the frequencies of the pronunciations used for grapheme *e* were more extreme. Results from Experiment 5, conducted in Spanish, showed the same effect with a grapheme highly-biased toward one specific pronunciation (*u*). These results suggest that links between phonemes and graphemes are weighted according to the frequency with which they appear together.

In Chapter 5 two experiments addressing the influence of syllable frequency (Experiment 6) and bigram frequency (Experiment 7) on the spelling-to-dictation task were conducted in Spanish. In Experiment 6, the frequency of the second syllable was manipulated, and the bigram-frequency was kept constant. In Experiment 7, the frequency of the third bigram of the word (the second syllable) was manipulated and its syllable-frequency was controlled. Results revealed that only syllable-frequency produced an effect in writing durations. The first grapheme of the critical syllable was faster produced in the context of a low-frequency syllable than in the context of a high-frequency syllable. Furthermore, the following inter-letter interval was faster in high than in low-frequency syllables. Together, these results suggest that the motor pattern corresponding to a high-frequency syllable was retrieved as a whole, so the specifications to produce the second grapheme of the syllable are partially retrieved during the execution of the first letter. Consequently, the interval produced before the second grapheme is shorter in high-frequency syllables. Differently, low-frequency syllables would be produced grapheme-by-grapheme.

In Chapter 6 the same sequence of letters (*an*, *en*, *in* and *on*) was embedded in to-be-copied French words. The critical sequence constituted two different phonemes (*bANane*) or one complex grapheme (*bANdit*). The first letter of the sequence was produced faster in the simple graphemes condition than in the complex grapheme condition. Moreover, the interval located after this letter was shorter in the complex grapheme condition. In Experiment 9, the same sequences were copied in the context of Spanish words which differed in the position of the syllabic boundary, in order to establish whether or not the effects observed in Experiment 8 were due to systematic differences between conditions in this variable. We found an effect of the position of the syllabic boundary only in the duration of the interval between both critical letters. This fact suggests that although the effect observed in French for that ILI could have been cause by the position of syllabic boundary, the effect observed during the production of the critical vowel is better accounted for by grapheme complexity. The first letter of a complex grapheme it takes longer to be produced than when the same letter is a simple grapheme. This fact might reflect that complex graphemes have to be unpacked in their constituent letters, or that a more complex motor pattern is retrieved when a complex grapheme is produced.

Evidence obtained in these experiments strongly support the claim that phonology is systematically retrieved during the normal handwriting process, even when writing well-known words. Phonology is retrieved during handwritinga, and it is used at a sublexical level to strengthen the orthographic (lexical) information kept in the orthographic working memory. Later on the process, the written response is produced syllable-by-syllable, indicating that the phonological loop plays a role in the response segmentation. In the case of low-frequency syllables, which lack of a holistic motor pattern, the motor programs for individual letters have to be retrieved. This process produces an increase of the cognitive load demanded by complex graphemes. More studies are necessary to establish how these effects vary when complex graphemes are embedded in high-frequency syllables. However, we have been able to confirm the involvement of at least two different units of phonological origin during handwriting production: syllables and graphemes. Multiple units seem to be used to program the writing movements, in line with Van Galen's (1991) proposal. Finally, this pattern of results fits a model of written production in which levels of processing are simultaneously active, but engaged with different segments of the response. When processing demands are increased at a certain level of processing, concurrent processes can be also affected. We propose a psycholinguistic model of handwriting production which integrates the evidence reported here and most of the previous literature.