Toward a Parallel and Cascading Model of the Writing System: A Review of Research on Writing Processes Coordination

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Abstract: Efficient coordination of the different writing processes is central to producing good-quality texts, and is a fundamental component of writing skill. In this article, I propose a general theoretical framework for considering how writing processes are coordinated, in which writing processes are concurrently activated with more or less overlap between processes depending on their working memory demands, and with the flow of information cascading from central to peripheral levels of processing. To support this view, I review studies that investigated effects of handwriting skills on concurrent activation of higher order processes, and research on word production that explored how information cascades between levels of processing in the writing system. I argue that a parallel and cascading model makes it possible to combine different findings in a common integrated framework and thus constitutes a heuristic for further understanding coordination of the different levels of processing involved in writing.

Keywords: Writing processes, processes coordination, incremental and cascading processes.

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1. From ideas to graphical signs: coordinating levels of processing when writing

Researchers have regularly attempted to model the written language system (for a review, see Alamargot & Chanquoy, 2002; Hayes, 2012). However, none of these models provides a detailed description of how the writing processes they postulate are coordinated. Efficient coordination of the writing process is nevertheless central to producing good-quality texts, and is a fundamental component of writing skill. This relationship between a writer's performance and the way he or she coordinates these writing processes arises out of the considerable demands that writing places on working memory (Berninger & Swanson, 1994; Gathercole & Alloway, 2008; Kellogg, 1996; McCutchen, 2000; Olive, 2004, 2011). To avoid overloading their limited working memory capacity, writers have to decrease demands writing processes place on working memory, particularly processes such as handwriting and spelling and to orchestrate - or juggle - the demanding writing processes (Fayol, 1999). It is generally assumed that writing processes can be orchestrated concurrently as long as their processing demands do not exceed writers' working memory capacity (Kellogg, 1996; Hayes, 2012), but how these processes are actually orchestrated and how information flows between levels of representation still remains opaque.

Although the different models of the writing processes cannot be regarded as equivalent, it is possible to establish an overview that is compatible with almost all these models, wherein writing is conceived of as engaging conceptual, linguistic, motor and evaluation levels of processing for manipulating concepts, deciding what to say, how to say it, for tracing the text and evaluating it. Additionally, executive functions are needed for evaluating operations at all levels of representation and for orchestrating these cognitive operations in the written language system.

At a conceptual level, cognitive processes operate on semantic information found in the environment or retrieved from long-term semantic or autobiographic memory. Writers select the ideas they want to include in their text, and structure these ideas into a plan that fits the textual genre and communicative goals of their writing task. Activation then spreads to a linguistic level of processing which converts the conceptual message into a linguistic structure by creating syntactic frames, selecting items in the mental lexicon, and finding the correct spelling of words[1]. For handwriting to take place, the graphemes selected by spelling have to be stored in orthographic working memory. Caramazza, Miceli, Villa, and Romani (1987) have proposed that graphemes are maintained in the form of syllables in a graphemic buffer until they can be transcribed (the debate about the phonological or orthographical nature of the syllables involved in writing is outside the scope of this article but resolution of these issues may vary across specific languages and orthographies). However, syllable processing mainly occurs in novice writers, and with more knowledge of letter co-occurrence, advanced writers may process bigrams (or n-grams, Kandel, Peereman, Grosjacques & Fayol, 2011). The abstract letters maintained in orthographic memory have to be converted into subtle and complex finger movements (for a review, see Graham & Weintraub, 1996). Converting these graphemes into movements first requires selecting their allographic characteristics (e.g., upper or lower case, cursive or print, etc.), then programming movements that will adjust to the allograph size, and finally producing the handwriting movements with agonist and antagonist muscles (Ellis, 1982; van Galen & Teulings, 1983). These conceptual, linguistic and motor levels of processing are hierarchically organized (van Galen, 1991), with higher-level processes expected to process larger units of language than lower level ones. For example, conceptualization operates on ideas or groups of ideas, formulation transforms those ideas into syntactical structures, then into words, morphemes, and graphemes that are finally written down.

The permanent nature of the written trace allows writers to assess whether the text they are writing optimally fulfils their communicative goals. A revision component is thus also engaged to assess outputs at the different levels of processing and to revise the text produced so far. However, when producing a piece of written language, only conceptual, linguistic and motor levels of processing are truly essential. Not only can revising the text be postponed until long after it has been written, but it can even be optional. This is not to say that revising is not important for writing. On the contrary, it is of fundamental importance if the text is to meet its communicative goals and correspond with its intended audience. But the fact remains that revision is not part of the minimum requirement in terms of levels of processing for producing a piece of text.

The different processes engaged in writing can be characterized as either low- or high-level (or peripheral vs. central). The peripheral vs. central distinction generally refers to sensorimotor processes and to processes involved in elaborated cognition and thinking (problem solving reasoning, planning, assessing, etc.) respectively. In writing research, central levels of processing refer to the processes involved from text conceptualization to spelling and include revision, while peripheral processes refer to the processes involved in the transcription of the text (e.g., handwriting or typing). The central vs. peripheral distinction is supported by studies of acquired dysgraphia following neural injury that show that spelling processes are preserved when handwriting is not. It is also supported by functional neuroimagery studies that show that different brain regions, and particularly cortical ones, are involved in handwriting and in spelling (for a meta analysis, see Purcell, Turkeltaub, Eden & Rapp, 2011; see also Magrassi, Bongetta, Bianchini, Berardesca & Arienta, 2010).

In sum, producing written language requires converting ideas into well-elaborated language before transforming it into visual signs via hand and finger movements. From a cognitive point of view, three levels of representation are needed to perform these cognitive operations: a conceptual or semantic level, a linguistic level and a motor one. It is notable that this broad definition of the main cognitive levels of processing involved in writing is similar to those used in speaking (Caramazza, 1997; Levelt, 1989; Bock & Levelt, 1994). Research in speech production has led to sophisticated theories and models of speaking, which are much more advanced than the models used in writing. Of course, this might be explained by the fact that the constraint imposed by writing differs from that imposed by speaking. Nevertheless, in order to better comprehend writing, there is now a need for writing research to investigate the timing of cognitive processes. In this article, I address precisely this issue by proposing a theoretical account of how the different levels of processing involved in writing are coordinated.

2. Toward a Parallel and Cascading model of the Writing Processes

Cognition has long been conceived of as relying on sequential or serial processing steps. In a sequential perspective, the processing steps involved in a cognitive task occur in strict succession, one after the other; the output of a level of processing being the input of the immediately following one. Moreover, transmission of information is discrete; processing at one level must finish before processing at the next level can begin. In this view, because levels of processing are encapsulated, they do not interact.

Given the high compositional fluency observed in skilled writing, a strictly sequential conception with no overlap between processing of different segments of texts does not appear plausible. If writing processes were sequentially coordinated, then writers would first plan a segment of text, next transcribe it, and they would not be able to prepare the following segment of text until the handwriting of this segment of text was finished. Thus, language preparation would only occur during pauses. In general, when skilled writers compose a text, they do so in frequent fluent phases made up of short pauses and longer bursts of language that can combine different clauses or sentences (Cislaru & Olive, in press). Furthermore, if it were necessary to attend to the different writing processes in a linear and sequential order, then this strict order would reduce the opportunity for rapid interactions between planning and translating. Yet, such interactions are fundamental in skilled writing (McCutchen, 1988), and interactions between central and peripheral processes have been reported (see later in this article). Finally, the slow pace of handwriting could also facilitate the simultaneous activation of higher order levels of processing.

It seems therefore more realistic to consider that levels of processing may operate concurrently, and particularly with handwriting in skilled writers, with more or less parallel processing depending on the availability of resources. I suggest that a parallel and cascading model of writing is not only more plausible; it also permits integrating in a common theoretical framework the findings of most of the studies that investigated writing process coordination. In this view, text production is incremental because the text is constructed segment by segment, from left to right in many orthographies (Kempen & Hoenkamp, 1987) and right to left in others such as Hebrew. However, different segments are processed in *parallel* when sufficient cognitive resources (or working memory capacity) are available. Parallel processing allows for flexible overlap of the cognitive operations to adapt to writing demands and to maintain fluency.

Information is described as *cascading* because it continuously flows or spreads from central to peripheral processes, resulting in possible top-down effects between levels of processing with feedback from peripheral to central processes. This cascading view is opposed to a discrete view in which one level of processing has to be completed before the next begins (McClelland, 1979). Additionally, limited- vs. full-cascading processing may be distinguished. In full-cascading models, information automatically flows between levels of processing as soon as a concept is activated (e.g., Humphreys, Riddoch, & Quinlan, 1988; Dell, 1986). In limited-cascading systems, information flows only within a level of representation, as in Levelt, Roelofs, and Meyer's (1999) model where information flows only at the lexical level for a single active concept. Other models have posited that a selection procedure interrupts the automatic flow of information through the language production system (Kuipers & La Heij, 2009).

Figure 1 represents cascading levels of processing in skilled and unskilled writers composing the sentence "*I am trying to explain what a cascade is*" based on preparation of two segments of the sentence. As can be seen in Figure 1a, when a skilled writer composes this sentence, each segment of it (i.e., Segments n, n+1 or n+2) is sequentially processed from conceptualization to execution, but the various levels of processing operate simultaneously.

The horizontally striped 'a' boxe indicates that buffering is required until the following process is ready to operate. The diagonally striped 'b' boxe indicates a pause in handwriting owing to the fact that the previous level of processing has not completed its operations and nothing has been sent for execution. Figure 1b represents the sequential activation of the levels of processing in an unskilled writer. Here, the two text segments are sequentially processed one after the other, each one from conceptualization to execution. The striped 'b' box indicates a lengthy handwriting pause owing to the fact that the writer has to prepare the forthcoming piece of text before embarking on transcription.

To sum up, in the proposed parallel and cascading conception of writing, each segment of text is sequentially processed from central to peripheral processes, and different levels of processing operate simultaneously on different segments of text. Because information cascades between levels of processing, operations at a particular level may interact with a subsequent level of processing. Because several levels of processing operate simultaneously, operations at low levels of processing may affect higher levels.

Finally, arguing for parallel processes supposes that the accumulated demands of the activated levels of processing do not exceed the limited capacity of working memory. As such working memory, and especially, the executive function of working memory, mediates writing processes coordination. Writers with low-demanding operations and with high executive skills can better coordinate the flows of information between the different levels of processing. However, a cascading account of writing cannot be equated with a model of working memory in writing for several reasons.

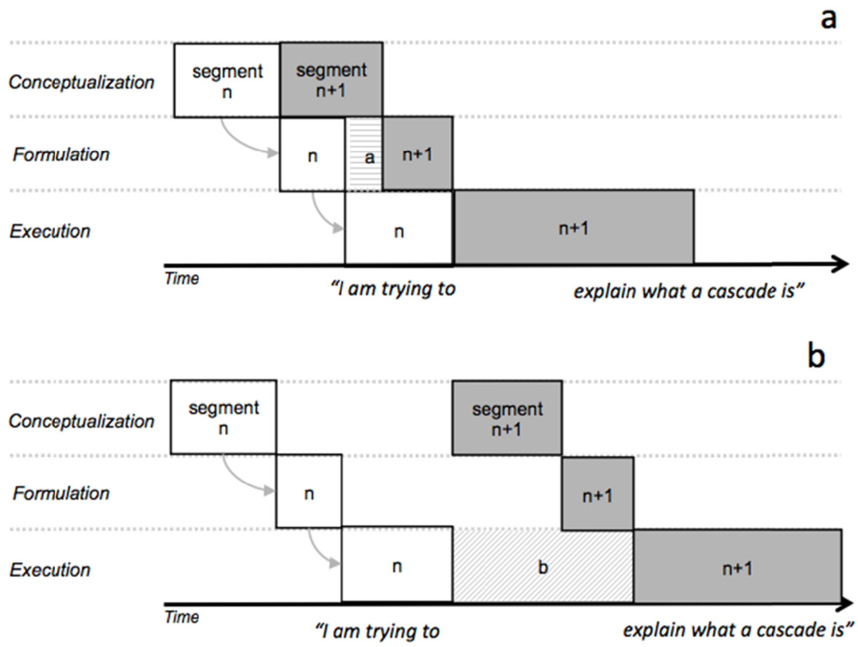

Figure 1. A schematic representation of writing processes coordination when producing a sentence. The parallel coordination of the writing processes when composing the sentence "*I am trying to explain what a cascade is*" is illustrated in (a), while (b) represents the sequential coordination of the writing processes when composing the same sentence. NB: The striped 'a' boxe represents a period where buffering is necessary while the following processes get ready to operate. The striped 'b' boxe indicates a pause in handwriting.

First, a parallel and cascading conception of writing is domain-specific, whereas working memory is domain free. As a result, different questions may be asked: for example, which levels of representation cascade? To what extent is a cascade between levels of processing x and y limited? Finally, properties of cascading models apply to all levels of processing, independently of their processing demands (to the extent that the theoretical model of the processes allows it). Of course, writing processes coordination is assumed by the executive functions of working memory, and so it is another fundamental facet of process coordination with inter-individual differences in working memory affecting how levels of processing are coordinated.

3. Arguments in favour of parallel and cascading writing processes

From a theoretical point of view, writing shares many cognitive operations with speech production, particularly some of the levels of processing involved in linguistic formulation (Fayol, 1991). The idea that spoken language is prepared simultaneously at different levels of processing is now well established (Damian, 2003; Kello, Plaut, & MacWhinney, 2000). Power (1985) was among the first to demonstrate cascading when producing sentences during speaking. He asked individuals to perform a tracking task while producing sentences composed of two clauses. He showed that participants systematically made more tracking mistakes while articulating the first clause of a complex sentence than while producing the second one. Assuming that tracking errors reflect the participants' attentional effort, Power (1985) interpreted his results in terms of parallel coordination of formulation and articulation: when planning a complex sentence made up of different clauses, one clause is planned during the articulation of the one that immediately precedes it (see also Ford & Holmes, 1978). Can we apply this idea to writing?

Beyond its realistic plausibility, verifying validity of a parallel and cascading model requires showing 1) that the architecture of the writing system allows for parallel processing; and 2) that the flow of information cascades between levels of processing. In this section, I review studies that suggest that handwriting is concurrently activated with central levels of processing, and experiments on word production that explored how information cascades between levels of processing in the writing system.

3.1 Parallel writing processes

Various empirical findings support the idea of parallel processing in writing, at least between handwriting and central levels of processing. Some findings come from studies that investigated the effects of different handwriting skills on compositional fluency and quality, with the underlying assumption that bottom up effects would indicate that the different levels of processing concurrently shared working memory capacity at a given moment and so would provide evidence of parallel processing. Other findings come from studies that analysed the effects of different handwriting skills on how handwriting is coordinated with central processes.

3.1.1 Effects of handwriting skills on compositional fluency and quality

If central and peripheral levels of processing are simultaneously activated, in other words, if they pose concurrent demands on working memory capacity, handwriting skills are expected to interact with higher order levels of processing. Bourdin and Fayol (1994) provided a direct experimental demonstration that the high demands of handwriting hamper higher order cognitive processes. They found that the cost of handwriting reduced performance on a written serial recall task compared with an oral recall task. In a first experiment, they compared adults and children recalling lists of words either orally or in writing. They observed a modality interaction, in that the adult writers recalled the same number of words whether they were speaking or writing, whereas children recalled more words when speaking than when writing. Because writing is much slower that speaking, Bourdin and Fayol then tested the hypothesis that children's inferior written recall could be due to the slowness of their handwriting. Indeed, it might have taken the children so long to write the words that they forgot the words they had memorized. They compared fixed or free recall rates and observed again the modality effect in children only without interaction with rate of recall. In another experiment, they compared adults' recall performance when speaking or writing in an unfamiliar style (cursive uppercase). As they hypothesized, adults recalled fewer words when they used the cursive uppercase than when they used their familiar and automatized handwriting. As this series of experiment shows, handwriting demands affected recall performance, which according to the authors suggests that central and peripheral levels of processing were concurrently activated in working memory and so were operating in parallel.

Major studies carried out by Berninger and colleagues (e.g., Berninger, Yates, Cartwright, Rutberg, Remy, & Abbott, 1992), and summed up in Berninger and Swanson (1994), examined how transcription skills (i.e., transcription and spelling) modulate the developmental constraints imposed on writing acquisition. Berninger and her collaborators showed that these transcription skills (assessed by orthographic coding, orthographic-motor integration and finger movements) make the greatest contribution to the fluency and quality of composition in primary schoolchildren (66% and 25%, respectively). The contribution to fluency decreases in children in intermediate grades, and continues to decrease in junior high grades (41% and 16%, respectively), giving way to constraints related to linguistic skills. More specifically, handwriting skills contribute more substantially to fluency than to compositional quality, but only in the primary grades (for evidence that handwriting contributes to written production in kindergarten children, see Puranik & Alotaiba, 2012). In addition, they showed that orthographic coding and orthographic-motor integration impose independent constraints. For their part, Christensen and Jones (2000) found that orthographic-motor integration accounted for most of the variance (67%) in the quality of written texts produced by children in their second year of formal schooling. However, unlike Berninger and Swanson (1994) they reported that these correlations remained fairly consistent across grade levels (from .74 in Grade Three to .62 in Grade Eight). This difference may come from the fact that Jones and Christensen included typing in the higher grades whereas Berninger and Swanson focused on handwriting only.

Recently, Limpo and Alves (2013) also confirmed that handwriting development interacts with the acquisition of high-order writing skills. They statistically modelled the contributions of transcription (handwriting and spelling), planning, revision, and self-efficacy to writing quality in children (Grades 4-6 vs. 7-9). In the lower grades, transcription contributed directly to text generation. In the higher grades, however, transcription contributed to text generation through planning and self-efficacy. The authors suggested that high automatization of transcription contributes to the acquisition of self-regulatory skills, which in turn positively influence the quality of text generation.

There is also evidence that handwriting skills continue to contribute to writing performance in adult writers. Connelly, Dockrell, and Barnett (2005) investigated the relationship between handwriting and writing performance in undergraduates producing a class essay and writing an examination paper. First, the undergraduates were found to be very slow writers, with a writing speed equivalent to that of 11-year-old children. Second, compared with the class essay, the essay produced in an examination setting was constrained by the students' handwriting fluency. More specifically, handwriting fluency was correlated not with the introduction of the essay but with its conclusion. Connelly et al. (2005) suggested that the students had sufficient time to produce the introduction and so were not constrained by their handwriting fluency. However, because of their low handwriting speed, they did not have enough time to write a conclusion and so, at that point in the composition, they were constrained by their poor handwriting skill. This was confirmed by measures of text organization, which showed that text quality suffered from the impoverished content of the conclusion. A relationship has also been observed between the handwriting fluency of undergraduates and the quality of their lecture note taking (Peverly & Sumowski, 2012).

Given that low handwriting skills negatively affect high-level processes, interventions that increase handwriting skills would enhance both the quality and fluency of composition. Christensen (2005) showed that an intervention consisting of daily handwriting practice for eighth and ninth graders increased their handwriting efficiency, which was correlated with the length and quality of their texts (see also Jones & Christensen, 1999). Interestingly, Christensen (2004) had previously observed an even stronger relationship between typing skill and the length and quality of computer-based texts. However, although an intervention targeting handwriting and typing increased both types of skills, it only had an impact on typing and typewritten texts.

Effects of handwriting on composition have also been evidenced by removing the demands of handwriting altogether, by comparing writing with dictation (to an adult or to a tape recorder)[2]. Bereiter and Scardamalia (1987) reasoned that handwriting might affect the quality of composition in two ways: first, the different writing processes might interfere with each other (e.g., in terms of the attentional resources allocated to transcription); second, the time taken to physically write it down might cause the writer to forget. To test these hypotheses, they removed the burden of transcription by asking intermediate grade children (Grades 4 and 6) to compose a text either in a normal condition or else by dictating it to an adult. However, because dictating is faster that handwriting, it may also increase text generation demands. To counter this constraint, the authors included a slow dictation condition in the study, in which the rate of production was comparable to that of writing. Children produced around 85% more words in slow dictation, and 160% more words in normal dictation. Text quality tended to be higher in slow dictation than in normal dictation, and in normal dictation than in writing, but the differences were not significant. Additionally, transcription demands and speed of transcription independently affected quality. Similarly, Hidi and Hildyard (1983) found that students produced more text in an oral composition than in a written one, and did not observe any effect on text quality, at least when assessed on cohesion at the sentence and text levels. Scardamalia, Bereiter and Goleman (1982) conducted a further study by matching the rate of the slow dictation condition to the rate of written composition. As in the first experiment, children in Grades Four and Six who dictated at a normal rate produced more text than children in the slow dictation condition, followed by the writing condition. Overall quality of composition was again affected by dictation. For his part, Gould (1980) failed to observe any superiority of composition when adults dictated their texts, although dictation appeared to be faster than writing (20-25%). One likely explanation is that the adult writers who took part in the experiment had high skilled transcription processes that did not interfere with higher order writing processes.

As shown, a large body of evidence now confirms that handwriting skills affect higher levels of processing. This bottom-up interference comes from the simultaneous demands that are placed on the limited capacity of working memory by parallel central and peripheral levels of processing. In the next section I report on studies that showed that these effects are mainly changes in how central writing processes are coordinated with handwriting.

3.1.2 Effects of handwriting skills on writing processes coordination

Relatively few studies have investigated on-line writing processes coordination. Nevertheless, all these studies confirm that writing processes coordination is affected by handwriting skill. For example, Chanquoy, Foulin, and Fayol (1990) asked 8-year old children and adult writers to complete stories under different constraints of complexity and predictability. They found that when the events being written about in the story were unpredictable, the adults (but not the children) increased the duration of their prewriting and between-clause pauses, and slightly slowed their within-clause writing rate. The adults coordinated the writing processes in part by slowing the pace of the low-level motor processes in order to accommodate high-level processing demands. Similarly, Foulin (1995) asked children and adult participants to produce a sentence with two clauses. Among the adults, the duration of intra-clause pauses decreased in the second clause, and the rate of production accelerated at the end of the sentence, as the conceptual and linguistic demands waned. No such variations were observed among the children, because transcription was demanding and its pace inflexible. Fayol and Stephant (1991) also showed that adult writers are able to plan part of their future text while handwriting. In their experiment, adult and children were asked to complete and to recall sentences by handwriting. Fayol and Stephant found that the adult writers composed the end of the sentence as fast as when recalling. By contrast, the children did not increase their composing rate when producing the sentence. These results are particularly convincing because pauses and writing speed when recalling were subtracted from pause duration and writing speed in composition thus minimizing the influence of transcription and essentially reflecting the implementation of high-level writing processes. More specifically, the children preferentially adopted a step-by-step strategy for producing their texts, that is, they paused in order to plan a short segment of text, then transcribed that segment, then paused again in order to plan the next segment of text, then transcribed it, and so on. By contrast, the adults preferred a more distal strategy that consisted of preparing long text segments while transcribing. Taken together, these findings strongly suggest that the preparation of a segment of text takes place at least partially during the transcription of the previous one.

A related question is whether process overlap is an all-or-nothing occurrence, or whether the amount of overlap is flexible and depends on the demands of the writing processes. Olive and Kellogg (2002) provided direct evidence in support of this assumption when they asked children, adults using their familiar handwriting, and adults using cursive uppercase handwriting to compose a text and then copy it. They predicted that, like the children writing in their standard handwriting, the adults writing in an unpractised handwriting would have difficulty concurrently activating a high-level process with handwriting. Secondary reaction times were used to measure the processing demands of high-level writing processes only (pausing), and handwriting only (handwriting while copying), and handwriting while composing. For the adults who used their familiar handwriting, the processing demands associated with the periods of handwriting during composition were greater than processing demands of either handwriting only or high-level processing only. Olive and Kellogg (2002) interpreted the high level of processing demands when transcribing as a sign of the concurrent activation of handwriting and high-level writing processes. Conversely, for children and for adults writing in an unfamiliar style, handwriting was as much effortful when composing as when copying, indicating the absence of concurrent activation. Presumably, they were unable to activate high-level writing processes while handwriting, and therefore had to suspend their handwriting to think about their texts. Interestingly, the findings also suggested that adults are able to adapt the coordination of the writing processes according to their varying demands. For instance, when they were instructed to use an unpractised cursive handwriting, the adults in the study adopted a sequential strategy, whereas when their handwriting was less demanding, they coordinated the writing processes so that they ran concurrently. Thus, the strategy for coordinating the writing processes may shift from sequential to more or less concurrent activation, with more or less advance planning (or overlap between processes). Similar changes in word preparation during text composition have been reported by Maggio, Lété, Chenu, Jisa, and Fayol (2012), who observed that grade level affected how different words are processed in parallel.

Flexibility in process coordination has also been observed for syllable processing in relation to handwriting demands. Sausset, Lambert, Olive, and Larocque (2012) asked writers to copy out two- and three-syllable words three times in a row, using four different handwriting modes: lowercase, uppercase, large uppercase, and large uppercase with no visual feedback. Latencies, as well as interletter intervals both at syllable boundaries and before and after those boundaries were analysed. An effect of syllable number was observed when handwriting was the least demanding (lowercase condition) but disappeared when handwriting demands increased. In addition, the duration of the interletter intervals at the syllable boundaries increased relative to intrasyllabic ones when graphomotor constraints increased. Sausset et al. (2012) interpreted these findings as evidence that all the syllables in the words were processed prior to execution in the low handwriting constraint condition, whereas each syllable was sequentially processed at the syllable boundary in the high handwriting constraint condition. In the usual handwriting condition, therefore, orthographic planning took place in advance, before the onset of execution. However, when handwriting constraints were high, orthographic processing was postponed and took place during execution, at the syllable boundaries.

Since the high demands associated with poor handwriting skills prevent unskilled writers from concurrently activating the high-level writing processes, we would expect the length of transcription periods to be affected, too. If high-order writing processes can be implemented concurrently with handwriting, writers can presumably keep on handwriting for as long as the high-level processes keep on providing content for transcription. By contrast, if the high demands of poor handwriting skills result in a more sequential strategy, then writers presumably have to alternate between phases of constructive thinking and phases of transcription. This should be evidenced by longer pauses (to prepare content) and shorter transcription periods than with good handwriting skills. The way in which differences in children's handwriting skills affect transcription periods was investigated by Alves, Branco, Castro, and Olive (2012). Fourth graders were first screened for their handwriting ability and divided into three groups (low, average and high handwriting skills). First, text quality differed between the three groups, as the children with good handwriting skills produced the best and the longest texts, and were more fluent when composing. Second, although there was no effect of handwriting skill on pauses, the better the handwriting skills, the higher the number of words produced per transcription period (high = 6.44 words; average = 4.64; low = 4.33). The children were also asked to dictate a story to the experimenter. Although the highly skilled children produced longer texts, the quality of these texts did not benefit from the removal of handwriting demands with dictation. This study clearly showed that children with high handwriting skills are able to maintain their handwriting for longer periods than children with low handwriting skills.

Alves, Castro, Sousa, and Strömqvist (2007) examined how differences in undergraduates' typing skills affected the length of transcription periods. First, they found that the undergraduates could sustain typing for about 10 seconds before pausing (for more than 2s). Moreover, when participants were divided into groups according to their typing speed, a reliable difference between slow and fast typists emerged in the length of these transcription periods. The slow typists had mean transcription periods of about 8 seconds, and produced about three words in each one, whereas the fast typists had mean transcription periods of 12 seconds, during which they produced twice as many words as the slow typists. This finding led Alves et al. (2007) to argue that typing skill contributes to the ability to sustain typing over longer periods of time.

It is possible to move one step closer to understanding writing processes coordination by analysing how handwriting skills influence the implementation of the writing processes during pauses and during handwriting. Alves, Castro, and Olive (2008) addressed this issue in adults' typing. To distinguish between pauses and transcription periods, Alves et al. recorded all the participants' keystrokes while they composed a narrative on a keyboard. To identify the writing processes that occurred during the pauses and the transcription periods, participants were regularly asked to report which writing process they were using (for a description of the technique, see Kellogg, 1987; Piolat, Olive, Roussey, Thunin, & Ziegler, 1999). The authors found that translating occurred mostly during handwriting, whereas revising and planning were mainly activated during the pauses. However, none of the writing processes could be described as being typical of pauses, as translating occurred to a similar extent as the other two processes. Surprisingly, writing process coordination was not affected by the participants' level of typing skill. Olive, Alves, and Castro (2009) addressed the same issue with the handwriting of argumentative texts, which are more demanding to compose than essays. A similar design and methods were used, but half the participants were asked to use their familiar handwriting, and half used cursive uppercase handwriting. Results indicated that translating took place during handwriting, rather than during pauses, while planning, translating, and revising were divided fairly evenly between pauses and transcription periods. Translating dominated planning and revising. Writing in an unfamiliar format affected how the writing processes were coordinated with handwriting. In the unfamiliar handwriting condition, translating was activated just as much during pauses as during handwriting. Interestingly, the cognitive effort of the writing processes was greater in the uppercase condition, suggesting an impact of the unfamiliar handwriting. A reduction in sentence length, as well as in text quality, in the unfamiliar handwriting condition confirmed this interaction. These experiments suggest that translating is closely linked to handwriting. Translating is indeed more likely to be executed during handwriting than during planning and revising, both because it is the least demanding process, and because it immediately precedes handwriting.

All the studies presented in this section demonstrate how handwriting skills affect central writing processes. In sum, concurrent activation of central and peripheral processes can only be achieved if motor output releases sufficient working memory capacity for allowing concurrent activation of high levels of processing. One important finding is flexibility in process coordination. The writing system is able to adapt to the various demands of the writing processes by modulating how many processes operate in parallel. In the next section, I review studies that have shown that information cascades between levels of processing.

3.2 Cascading processes

Whether information cascades from higher to lower order writing processes has been studied mainly in word production tasks. For example, Roux and Bonin (2013) examined how information cascades within the lexical system. In a series of experiments, they asked writers to write the names of objects represented on pictures. A target picture was presented with a superimposed interfering picture the name of which did or did not share phonological or orthographical characteristics with the target word. Roux and Bonin (2012) showed that writing fluency was greater when the target and the interfering picture shared orthographic and/or phonological characteristics. They concluded that the interfering pictures activated their corresponding concepts at the semantic level of representation and that information cascaded to the orthographical representations of the names of the picture.

Information also cascades between the semantic and orthographic levels of processing in written word production. Bonin, Roux, Barry and Cannell (2012) asked adult writers to write the name of an object presented on a picture. In Experiment 3 and 4, each picture was preceded by a semantically high or low predictable sentence. They found that the semantic constraints interacted with word frequency, a lexical variable. More specifically, initiation times were faster with frequent words in the low predictable condition, but the effect of word frequency disappeared when the sentence preceding the picture was semantically highly predictable. Interestingly, the authors showed that information at the perception level did not flow to lower levels of processing as indicated by the absence of interaction with word frequency (Exp. 1 & 2). Because the high semantic constrains only disregarded the effects of word frequency, Bonin et al. (2012) concluded that information flows between the semantic and the orthographic levels of processing, supporting a limited cascading account.

Cascading processes have also been observed between lexical and handwriting levels of processing. For instance, Delattre, Bonin, and Barry (2006) demonstrated that the amount of orthographic information that cascades onto handwriting varies according to lexical specificity. They showed that spelling processes begin before the actual writing of the word, but while they are completed prior to execution in the case of regular words, they continue during transcription in the case of irregular words, as though they were occurring sequentially for each grapheme. The authors concluded that the processing difficulties related to spelling irregular words carry over and affect the time it takes to produce the handwritten responses. As well as overlapping with the execution of the word in question, the spelling processes may also begin while the previous word is still being written. In a task requiring several words to be copied at a time, Lambert, Alamargot, Larocque, and Caparossi (2011) observed that the processing of target words (captured through writers' eye movements) was triggered at different junctures, depending on their lexical features. Frequent and regular target words were processed while the end of the previous word was still being transcribed. The findings of these two studies confirm that spelling processes cascade onto execution, and can start earlier when processing is facilitated, as it is with regular or frequent words.

Finally, it has been shown that spelling and handwriting interact, supporting the idea that higher level of processing are still active during lower level processing and therefore moderate them. Roux, McKeff, Grosjacques, Afonso, and Kandel (2013) examined how lexical and sublexical levels cascade on handwriting. Participants had to copy regular and irregular words and pseudowords presented on a screen of a computer. They had to copy the words using capital letters, affording the authors to analyse the writing duration of the first five letters of the words the participants wrote. They indeed postulated that the cascading effects would appear during handwriting, i.e., that orthographic retrieval should still operate at the initiation of the writing movements. They reasoned that duration of the initial letters should be longer for words than for pseudo words if lexical retrieval is still active when the physical writing of the words starts. As expected, the results indicated that the lexical and sublexical variables affected the kinematics of letter production but on different letters. The authors thus concluded that lexical and sublexical information cascade differently onto the peripheral processes of handwriting.

4. Perspectives

In this article, I presented an integrated model or framework for understanding writing processes coordination. This model is supported by several findings already published in the literature but which were not put together in a single framework. More precisely, I set out to argue that conceptual, formulation, and handwriting levels of processing are concurrently coordinated and that information may spread between the levels of processing even when operation at a specific level of processing is not yet achieved. In this framework, a text is composed by incrementally processing different segments of a text at different processing levels. These levels of processing are organized hierarchically, from central to peripheral processes, and operate in parallel. It is important to note that the framework suggests that parallel processing is flexible. Levels of processing can overlap to a greater or lesser degree, depending on the demands they place on working memory. Accordingly, when peripheral levels of processing are sufficiently automatized, enough working memory capacity is available for concurrently activating central writing processes. As a consequence, low-levels of processing may affect higher levels. In addition, information cascades between different levels of representation with feedback from peripheral to central processes. This cascading view is opposed to a discrete and encapsulated view in which one level of processing has to be completed before information flows to the next one. Finally, cascading systems allow for top-down effects: operations at a level of processing may affect lower levels.

There is now converging evidence that at least the peripheral and central levels of processing engaged in writing operate concurrently. Moreover, although more scarce, there is evidence that degree of overlap between levels of processing is flexible and depends on their processing demands. Cascading has been observed at different levels of processing. For instance, semantic processing has been shown to cascade onto formulation processes, formulation sub-processes cascade onto each other, and central processes cascade onto peripheral ones. Of course, I do not argue that all levels of processing always operate in parallel. As shown, levels of processing are more or less parallel depending of the processing demands they place on working memory capacity. Thus, it is likely that during fluent writing phases conceptual, formulation and handwriting levels of processing can operate concurrently. By contrast, in more hesitant writing phases, i.e., when writers are faced with a particular need at a particular level of processing, they can focus on a specific level of processing and adopt a more sequential coordination of the writing processes. For example, in integrated reading-writing activities, when writers need to consult a source document for example for generating new content, they stop the operations engaged in formulating and handwriting language by focusing on the conceptual level of processing.

Future research on writing process coordination should therefore examine precisely how the different demands of the various writing processes affect their coordination, and how this coordination changes in more or less fluent writing phases. Relative automatization of handwriting is crucial in this framework. Indeed, poor handwriting skills interfere with higher level writing processes that are activated in parallel to transcription because the writer does not possess sufficient resources to allocate to these processes, which then function inefficiently. One solution for avoiding such overload consists of reducing overlap between processes by adopting a more sequential coordination style. This results in more proximal preparation of the text and less integration and interaction between the writing processes. By contrast, writers with good handwriting skills can sustain their handwriting for longer, and prepare the next text segments concurrently. Writing fluency is thus closer to the rate of thinking, and this creates less opportunity for forgetting ideas or pieces of text that have already been prepared but are not yet written. From a developmental point of view, in the light of Luria's (1973) research on neurological restructuring over the course of development, Berninger (1999) argues that "*reorganization has major implications for working memory, which is not only a work space but also a temporal mechanism for coordinating the automatic and non-automatic construction processes*" (p. 106). Taking a closer look at the effects of handwriting and of typing skills on the extent of overlap in the written production system will be of major interest since these peripheral processes play an important role in writing acquisition. Investigating writers' executive skills will also be of major importance. Cascaded functioning indeed requires a high degree of executive control for monitoring not only process switching, but also information flow and the related processing and short-term storage demands. These high executive demands of skilled cascading coordination certainly explain why self-regulation techniques are beneficial for writing and learning to write (Graham, McKeown, Kiuhara, & Harris, 2012).

One other issue that needs to be addressed is the unit of language preparation. As shown earlier in this article, language preparation mainly occurs simultaneously to handwriting, and the higher the handwriting (or typing) skills, the longer handwriting can be sustained. Thus, skilled composition results in frequent fluent phases made up of short pauses and long bursts of language. However, little is known about such language bursts. Although some studies have delineated their global characteristics, very few have analysed what is produced during such bursts. Only Kaufer, Hayes, and Flower (1986) analysed the linguistic structures of bursts. These authors showed that text segments tend to correspond to clauses, since they showed a strong tendency to end at clause boundaries, and less so at phrase boundaries. Accordingly, writers would compose sentences by first selecting a topic, and then by producing and evaluating sentence parts that fit grammatically with the part of the sentence that has already been prepared. Pause studies seem to confirm the clause as a candidate for the unit of preparation (Foulin, 1995, 1998; Schilperoord, 2002). However, recent analyses of bursts' content showed that bursts rarely coincide with grammatical forms. Cislaru and Olive (in press) even found that a large number of bursts combine several identical or different grammatical forms. Discovering the unit of preparation of writing will contribute to a detailed comprehension of how writing processes are coordinated. Addressing this issue from a developmental point of view will be fundamental since acquiring writing skills may not only result in changes in the units of processing but also in changes in process coordination.

Finally, one other issue to address is whether information spreads in limited vs. full cascading. At least two questions can be raised: First, at a given level of processing, does information cascade within the different processes that are active? For example, does information cascade at a linguistic level of processing between syntactic and lexical processing? Second, does information cascade between levels of processing? For example, does semantic processing cascade onto linguistic processing? Such questions will need to be investigated in writing tasks that require different units of language to be produced, asking writers to produce words, as well as sentences and texts.

To conclude, approaching a more detailed and functional account of writing is now possible thanks to the increasing use of on-line sophisticated paradigms in writing research which have revived interest and underline the necessity for on-line studies of writing. Different tools (keylogging technologies, recording of handwriting) are now available for analysing handwriting speed, pauses, and eye movements (for typing, see Leijten & Van Waes, 2013 and Wengelin, Torrance, Holmqvist, Simpson, Galbraith, Johansson, & Johansson, 2009; for handwriting, see Alamargot, Chesnet, Dansac, & Ros, 2006). However, studying the degree of overlap between levels of processes and information flow will also require investigating writing with different writing tasks (text or sentence composition, word production, copy, dictation, etc.) that are designed to tap specific levels of processing.

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Footnotes

1. Whether or not spelling is one of the transcription processes is not discussed here. For a discussion, and evidence, see Abbott, Berninger, and Fayol (2010), who investigated the longitudinal interrelationships between levels of language in writing.

2. It is important to stress that asking writers to dictate a text does not solely remove handwriting constraints. Talking into a tape recorder also prevents writers from rereading and revising their text, and from constructing a visuospatial representation of what they have written so far (Olive & Passerault, 2012). This may result in higher planning, translating and reviewing demands. As suggested by De La Paz and Graham (1995), equating dictating with writing requires, at the very least, making the advancing text visible to writers.

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