Working Memory in Written Composition: An Evaluation of the 1996 Model[1]

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Abstract: A model of how working memory, as conceived by Baddeley (1986), supports the planning of ideas, translating ideas into written sentences, and reviewing the ideas and text already produced was proposed by Kellogg (1996). A progress report based on research from the past 17 years shows strong support for the core assumption that planning, translating, and reviewing are all dependent on the central executive. Similarly, the translation of ideas into a sentence does in fact require also verbal working memory, but the claim that editing makes no demands on the phonological loop is tenuous. As predicted by the model, planning also engages the visuo-spatial sketchpad. However, it turns out to do so only in planning with concrete concepts that elicit mental imagery. Abstract concepts do not require visuo-spatial resources, a point not anticipated by the original model. Moreover, it is unclear the extent to which planning involves spatial as opposed to visual working memory. Contrary to Baddeley's original model, these are now known to be independent stores of working memory; the specific role of the spatial store in writing is uncertain based on the existing literature. The implications of this body of research for the instruction of writing are considered in the final section of the paper.

Keywords: written composition, working memory, sentence generation.

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Composing a written text, whether it is a single paragraph or a lengthy document of many pages, entails far more than language production. Ideas must be generated and organized in planning the text. Decisions about what to say must be made while simultaneously thinking about the rhetorical problems of how to express them. Once the complex linguistic processes of sentence generation yield a grammatical string of words, the writer must at some point read and edit the sentence to make certain it adequately conveys the author's intended meaning. Such monitoring may also be applied to the purely conceptual representations of ideas and their organization during planning. It is imperative that the text as written accurately expresses what the author meant to say and, of equal importance, that the author be able to see how the reader might interpret--rightly or wrongly--the words on the page. Although planning and reviewing are also involved in spoken language, the written text must stand on its own before the reader, exacerbating the demands for careful thinking as well as lucid language. The words as they appear in the text are all that the reader has to go on in understanding the author's ideas. Unlike in spoken discourse, there is no dialogue between the author and reader to gradually shape a shared understanding. Thus, written composition is as much a thinking task as it is a language task and this is as true for the production of a tightly wrought paragraph as for a book length manuscript.

A model of how working memory supports the planning of ideas, the translation of ideas into written sentences, and the reviewing the ideas and text already produced was proposed by Kellogg (1996). In writing as well as other complex cognitive tasks, working memory provides a means for transiently holding knowledge in an accessible form so it can be effectively used. For example, knowledge about the writing topic and the specific language in which the text will be written must not only be available in long-term memory, but also must be retrieved and accessible for use in solving the content and rhetorical problems at hand. The model specified the demands of planning ideas, translating ideas into sentences, and reviewing ideas or sentences on the central executive, phonological loop, and visuo-spatial sketchpad based on the evidence then available. It thus integrated Baddeley's (1986) model of working memory with the seminal Hayes and Flower (1980) model of written composition.

The overarching goal of the present paper is to provide a progress report from the past 17 years of research on working memory and writing. As will be seen, some of the core assumptions of the model have been confirmed whereas others must be rejected on the basis of the growing literature. The paper will begin with a summary of the model's assumptions. The logic of the methodologies used to test these assumptions will then be explained. One approach assesses individual differences in the capacities of working memory components and relates these to writing performance. Another approach employs secondary tasks to either index working memory usage or to deplete the working memory resources available for writing. After summarizing the implications of past research for the model, some new experimental tests of the model are outlined for future research. Finally, the implications of the model for writing instruction will be addressed.

1. Assumptions of the Model

The model differentiated six basic processes. Planning referred to the generation and organization of ideas that is logically prior to the linguistic processes involved in sentence generation. Thus, when looking at the production of a single sentence, planning can be viewed as a stage of processing that precedes the stage of grammatical encoding and subsequent linguistic processes. In the speech production literature, the focus is on this sentence level production. For example, in the standard model of oral language production developed by Bock and Levelt (1994), grammatical encoding is then followed by a stage of phonological encoding. For written output, this would further require a stage of orthographic encoding. Bock and Levelt proposed that planning the message, grammatical encoding, and phonological encoding during speech production unfolded as serial steps that cascaded from one to the next in piecemeal fashion. That is to say, once a small package of content was planned, such as a phrase or a clause, it was immediately grammatically encoded, even though the next package of content was still being formulated. It was not necessary to plan an entire sentence before grammatical encoding began, in other words. In similar fashion, once the package was grammatically encoded, the phonology for its constituent words was retrieved, readying it for spoken output.

In the writing literature, the focus is on entire paragraphs and larger units of text structure rather than on a single sentence. In this context, it is clear that planning and sentence generation should not be viewed as serial stages of processing. Instead, planning, sentence generation, and even reviewing of ideas and text are recursive operations that occur in complex patterns through text production (Flower and Hayes, 1980). As Kellogg (1994) noted, it is possible to think of a text as moving through serial stages of development from prewriting, to producing a first draft, and later revising it in subsequent drafts. Thus, the *product* moves through serial stages. Yet, the *process* of writing involves recursive operations of planning, sentence generation, and reviewing during the drafting of a text. Similarly, in revising a text to create a second, third, or fourth draft, the same recursive pattern reoccurs. Even during the prewriting stage of product development, writers may plan ideas at a conceptual level and then attempt a preliminary translation into mental sentences or possibly written notes of phrases or even whole sentences. These may later find their way into the first draft of the text as the writer moves out of the prewriting stage. Similarly, reviewing of preliminary mental sentences or even conceptual plans may occur during the prewriting stage as part of a recursive pattern of writing processes.

Hayes and Flower's (1980) seminal model on text production distinguished planning ideas, translating ideas into sentences, and reviewing ideas and the text produced thus far. The latter kind of reviewing necessarily entails reading. The Kellogg (1996) model adopted this structure by distinguishing among planning, translating, reading, and editing, where the latter two were sub-processes of reviewing thought to make different demands on working memory. Sub-processes of planning were also differentiated by Hayes and Flower (namely, generating versus organizing ideas), but

Kellogg proposed that both make the same kinds of demands on working memory. The linguistic sub-processes of grammatical encoding, phonological encoding, and orthographic encoding were likewise collapsed in the model and identified as translating. Because these sub-processes of sentence generation were assumed to make the same kinds of demands on working memory, there was no need to differentiate them in the model.

In addition to the four cognitive processes derived from Hayes and Flower (1980), two other motor processes were examined. The motor output of the writing – like any kind of motor output – requires both a programming and an execution process. For example, in handwriting, the letter formation in either cursive or block print styles requires a motor program that must then be executed by the muscles of the hand and arm (Van Galen, 1990). Similarly, in typing the location of finger movements is spatially programmed and then executed as ballistic movements of the fingers across the keyboard. These motor output processes are assumed to make minimal and highly constrained demands on the working memory system and stand in contrast to planning, translating, reading, and editing.

Table 1. The Resources of Working Memory Used by the Six Basic Processes of Writing

	Working Memory Resource		
Basic Process	Visual-Spatial Sketchpad	Central Executive	Phonological Loop
Planning	X	X	
Translating		X	X
Programming		X	
Executing			
Reading		X	X
Editing		X	

As shown in Table 1, all processes with the exception of motor execution are assumed to make at least some demands on the central executive. These demands are posited as substantial for the four cognitive processes. On the other hand, motor programming makes little if any demands when the writer is highly practiced with the mode of output. An adult, for example, may be highly skilled at handwriting and typing so that these activities are fully automatic. For a young child, however, the programming aspect of motor output can be still effortful and demanding of the resources of the central executive (Bourdin and Fayol, 1994). The burdensome demands of the mechanics of handwriting and the orthographic processes of spelling place major constraints on the composing ability of young children (Graham, Berninger, Abbott, & Whittaker, 1997). Until they learn to automate to some degree these lower level processes, insufficient resources of the central executive are available to the higher order demands of planning ideas, generating text, and reviewing the work produced thus far.

In contrast to the pervasive involvement of the central executive in writing, the two storage components of Baddeley's (1986) model were envisioned to play a limited and highly specific part. The visuo-spatial sketchpad presumably was needed for planning when ideas were visualized prior to being put into words. Other aspects of planning that tapped the sketchpad included the mental visualization of organizational schemes, supporting graphics, orthographic styles, and the spatial layout of text and graphics. Similarly, drawing diagrams, sketches, networks and related forms of externalized plans would presumably also require the visuo-spatial sketchpad to create, understand, and modify them. According to the model, then, planning was the only aspect of written composition that placed a demand on the visuo-spatial sketchpad, but there were a variety of ways that it might be recruited to support the writer's cognitive work.

Translating ideas into sentences in theory demanded the phonological loop. The inner speech that accompanies text composition reflects this transient storage of the phonologically encoded phrases of a sentence. Whole clauses and even complex sentences might be held in the phonological loop for several seconds as a way of trying out the sentence mentally before execution processes are initiated. Or, individual words and phrases might be only very briefly retained in the loop and immediately cascaded to motor programming and execution. In the latter case, the inner speech accompanying sentence generation would be subjectively experienced as closely tracking in time the output of either handwriting or typing.

The linguistic encoding of ideas into sentences is multi-faceted. It includes grammatical, phonological, and orthographic processing that translate activated concepts into the words of a sentence. Syntactic information needed in grammatical encoding, phonological word forms used in both spoken production and the covert speech that accompanies writing, and orthographic word forms needed in written spelling must be retrieved and used in production. Existing theories of sentence production differ on the details of how these operations unfold (Bock & Levelt, 1994; Caramazza, 1991). One possibility is that phonological and orthographic representations are retrieved independently and fed forward to grammatical representations (Caramazza, 1997). In this case, the inner voice of the writer maintains words in the phonological loop during translation and these phonological word forms are retrieved early in the process.

The temporal dynamics of such a mechanism could unfold in either a purely serial or a cascaded manner (Bock & Levelt, 1994). That is to say, it might be done in a two-step series with grammatical encoding beginning only after the phonological/ orthographic encoding stage is completed for the entire sentence; or it may occur in a piecemeal fashion with the initial phrase of the sentence encoded in terms of phonology or orthography and then cascaded this unit forward immediately for grammatical encoding, before the processing of the next phrase of the sentence is initiated. On either view, such storage in the phonological loop can be regarded as a support for grammatical and orthographic encoding processes that take place in written production.

For example, the syntactic features of words must be retrieved and maintained during the positional processing that creates the sentence's phrase structure. These grammatical processes could be mediated by the transient activation of the activated phonological word forms. Similarly, orthographic encoding can in some cases be aided by phonological mediation, with the orthographic word forms computed using sound to written letter conversion rules for regular English words.

Writing can proceed, of course, without phonological mediation by direct retrieval of orthographic word forms (Caramazza, Miceli, Villa, and Romani, 1987). Indeed, this direct route is necessary for irregular words in English that do not allow the computation of orthography from phonology. Even so, the immediate retrieval of phonology is likely automatic from ingrained habits with speech production. That orthographic representations are also retrieved independently does not necessarily eliminate the transient phonological storage in working memory.

The upshot of the model is that the generation of a single sentence places substantial demands on the phonological loop of working memory. A key prediction of the model is that all forms of sentence generation place a continuous demand on the transient storage of words in a phonological form. As a result, irrelevant speech that intrudes into the phonological loop ought to have some negative impact on the translation of ideas into sentences. Similarly, totally committing the phonological loop to the continuous production of a word unrelated to sentence generation, such as “tap, tap, tap…” ought to seriously impair sentence generation. This form of dual task methodology is known as articulatory suppression, because it prevents participants from engaging in silent articulation. For example, in memory experiments it prevents the use of inner speech to rehearse the material to be learned. It would also prevent the inner voice of the phonological loop from being engaged in the linguistic encoding processes of translation.

Reading a sentence, as well as producing one, also implicates the inner voice of the phonological loop. Although reading can be done directly from orthography, it often invokes the temporary storage of phonological representations during comprehension. In the case of reviewing one’s own writing, however, the reading process may be less demanding than normal because of all the planning and translating that preceded it. This may be one reason why it is difficult to catch mistakes in one’s own text, because the reading process proceeds from the top down without the usual level of working memory involvement in understanding the text (Daneman & Stainton, 1993).

Editing refers to the detection of mistakes, that is, some mismatch between the writer’s intentions and output of another writing process. Often mistakes occur in the linguistic encoding of a sentence (e.g., poor word choice, grammatical errors, or spelling errors). However, it might involve a programming error during motor execution, such as typing *hte* even though the output from orthographic encoding specified *the*. The editing process was regarded in the model as the evaluation function that detects and diagnoses problems in a text in the revision model proposed by Hayes, Flower, Shriver, Stratman, and Carey (1987). However, editing could also take place on the output of planning – at a purely conceptual level – before words were selected and sentences generated.

A key and controversial assumption of Kellogg's (1996) model is that editing makes demands solely on the central executive. These demands are thought to be heavy for adults who devote significant degrees of effort to revising their conceptual plans and drafts of a text in progress. For young children for whom the mechanical demands of handwriting and spelling overwhelm the capacity of the central executive, little effort is even given to editing. The central point from the model is that editing makes a highly specific and constrained demand on the working memory system. Although editing can take numerous forms, ranging from the detection of a motor programming error to the revision in the organization of ideas in a text, it targets solely the central executive, according to the model.

2. Constraints on the Model

An important theoretical challenge to the Baddeley (1986) model emerged in the form of Cowan's (1995) embedded-process model that viewed working memory as a transiently activated subset of long-term memory. This alternative architecture of memory contended that the phonological loop and the visuo-spatial sketchpad were not separate short-term storage mechanisms mediated by neurological regions independent of long-term memory. Rather, short-term memory is embedded within long-term memory, in Cowan's model. Similarly, the focus of attention is an embedded subset of the total information held in short-term memory. Both models nevertheless posit a central executive component that directs attention and controls processing of information within the short-term stores, however they may be realized within the brain. With respect to the working memory demands of writing, it is possible to adopt either Baddeley's or Cowan's view regarding the relation of short-term and long-term memory. What each view stresses is the functional importance of keeping mental representations active on a transient basis during written composition. Whether the mechanism involves transient activation of structures in long-term memory or transfer to a separate short-term store makes no difference for the assumptions of Kellogg's (1996) model.

A second theoretical challenge to Baddeley's conceptualization of working memory came from neuroimaging work (Smith & Jonides, 1997). Brain images are taken while participants perform a task requiring the short-term maintenance of either verbal, visual, or spatial information. For example, in the verbal condition, they tried to retain a set of four letters using the phonological loop by silently rehearsing the digits. For visual information, the participants had to retain the shape of objects while not worrying about their spatial location. By contrast, for spatial information, to respond correctly the participants had to retain the location of the objects rather than their shapes. It was discovered that the phonological loop involves brain mechanisms in the left hemisphere that are distinct from those mediating the visuo-spatial sketchpad, as contended by Baddeley's model. The verbal condition revealed neural activation in left frontal cortex associated with Broca's area and a motor area. These regions support speech production and reflected the covert speech of the phonological loop as the participants rehearsed silently the letters. A region in the left posterior parietal lobe was also activated. Based on other findings in the literature, this posterior region in the left hemisphere is known to be involved in the storage of phonological representations of verbal material. Thus, the phonological loop could be witnessed at work in the left hemisphere as the silent articulation of the letters kept active their phonological representations.

However, Smith and Jonides (1997) further showed that the visuo-spatial sketchpad must be fractionated into two separate components based on the neuroimaging results. Maintaining visual objects activated regions in the left hemisphere that were distinct from those involved with verbal information. However, when the spatial location of the objects had to be retained in working memory, it was the right hemisphere that showed distinctive regions of activation, not the left. Thus, one component of working memory keeps active the visual shape of objects while a separate component in the opposite cerebral hemisphere maintains their spatial locations. Through introspection, the subjective experience of visual imagery involves a seamless combination of shape and location information. They are bound together in awareness even though separate components located in entirely different hemispheres serve as the neural mediators.

Throughout the remainder of the paper, the visuo-spatial sketchpad will generally be broken down into a component of visual working memory (WM), on the one hand, and spatial WM on the other. For parallelism, the phonological loop will often be referred to as verbal WM.

The central executive postulated by Baddeley (1986) has also been fractionated into different subcomponents. For example, the central executive provided a means for switching back and forth between multiple processes or tasks. This time-sharing function is distinct from the role it plays in the effortful retrieval of representations from long-term memory, including the selection of appropriate retrieval strategies (Baddeley, 1996). Another distinct executive function is the capacity to attend selectively to one stimulus or element in working memory while ignoring another. A key development in the fractionation of the central executive has been the isolation of three distinct means of cognitive control. Once information is retrieved from long-term memory and maintained in working memory, what functions are critical in using the activated information to guide behavior? Miyake, Friedman, Emerson, Witzki, Howerter, and Wagner (2000) established that three independent executive functions work together to achieve cognitive control: updating representations in working memory, the capacity to switch between tasks, and the ability to inhibit responses. Although these are distinct subcomponents of the central executive they jointly contribute to the ability to control the contents of working memory and provide for flexibility in behavior.

A limitation of the Kellogg (1996) model is that it leaves unspecified the specific functions of the central executive that permit the writer to assert cognitive control during composition. As noted in Table 1, some or all of the three functions outlined by Miyake et al. support planning, sentence generation, and reviewing. Clearly, the coordination of all three processes during composition depends on task-switching. It is further necessary to inhibit some ideas that enter planning, so as to focus on others. Similarly, inhibition of alternative lexical representations or grammatical structures is central to selecting a particular set of words and phrase structure during sentence generation. Lastly, updating the contents of working memory as the writer's thoughts develop and the text emerges on the page is unavoidable in composition. An important future line of investigation would entail drawing on the work of Miyake et al. (2000) to specify in detail how updating, task switching, and response inhibition contributes to planning, sentence generation, reading, editing, and motor programming. Is one executive function more important for planning, whereas another largely determines the outcome of editing, for example? To what extent do individual differences in task switching versus inhibition versus updating contribute to overall writing performance? In short, the 1996 model could be profitably extended by fractionating the central executive into specific executive functions.

Another clear boundary condition on the 1996 model was its failure to address the possibility of a semantic WM that temporarily stores purely conceptual representations. Studies with brain injured patients have documented that different regions of the brain provide transient storage of semantic representations (i.e., the meaning of a concept) compared with phonological representations (Martin, Shelton, & Yaffee, 1994; Martin & Freedman, 2001). The meaning of a concept is held in a semantic store of working memory independently from phonological store that holds the sound of the name for the concept. Hayes (1996) in fact theorized that the planning of conceptual content in writing tasks might often require the use of semantic WM. Although this is an important aspect of writing, it is difficult to use dual task methods to interfere with the semantic component in isolation. That is to say, it is not obvious how to design a concurrent task that occupies only the semantic component without also impinging on the verbal, visual, or spatial components, as either a word or picture would do. Further, despite wide agreement on the importance of semantic working memory in a variety of cognitive tasks, it has been difficult verify that semantic information can be temporarily stored and retained for short periods of time independent of other mechanisms, such as the extended duration of the priming of concepts stored in long-term memory (Shivde & Anderson, 2011).

A further limitation of the original model was its failure to consider the role of domain expertise. Writers with a high degree of disciplinary or domain-specific knowledge could avoid some of the demands made by composition on short-term working memory. Domain-specific knowledge appeared to allow experts to escape the severe constraints on working memory that hinder effective writing in novices (McCutchen, 2000). Writers must juggle multiple processes and representations in working memory as they compose (Flower & Hayes, 1980). Because attention and other components of working memory are limited in capacity, these demands can lead to failures in planning ideas, translating ideas into sentences, and reviewing ideas and the text already generated (Kellogg, 1996). However, expertise allows the rapid, facile, and effortless retrieval of representations from long-term memory as necessary, and eliminates the need to maintain everything actively in transient form in working memory (Ericsson and Kintsch, 1995). The ability of domain experts to use such long-term working memory could be the critical advantage they have over less knowledgeable writers in achieving fluent production (McCutchen, 2000; 2011). For example, expertise in the game of baseball enabled writers to respond to auditory probes as they composed narratives of a half-inning significantly faster than was observed for control participants with little knowledge of the game (Kellogg, 2001).

Finally, empirical investigations of the relationship between individual differences in working memory capacity and writing skill have established boundaries on the model's utilities. For example, studies of children in primary grades indicate that differences in overall working memory capacity reveal only weak to moderate relationships to writing skills (Swanson & Berninger, 1996a). Possibly for young children still devoting substantial attention to handwriting, relatively little working memory may be available for higher order writing processes of planning, translating, and reviewing. For older children with greater automaticity of motor output, working memory variations show stronger relationships to the higher order writing processes (Swanson & Berninger, 1996b). At the same time, it is important to recognize that the central executive is more important in predicting writing performance than are the two storage components (Vanderberg & Swanson, 2007). The Kellogg (1996) model can only be fruitfully applied in individual difference studies when there is a way to assess independently the resources of the phonological loop, the visuo-spatial sketchpad, and the central executive. Even taking into account the differential contributions of these components of working memory, it would be a mistake to expect that writing competence can be reduced to working memory alone. For example, Bourke and Adams (2011) explored the reasons why girls outperform boys in writing skill at a young age. They concluded that the difference arose from knowledge of language and skills spoken language comprehension, rather than from variations in the functioning of working memory.

3. Methodological Approaches

Two methodological approaches have dominated research on working memory and writing. The regression approach examines how individual differences in measurements in various capacities of working memory correlate with measures of writing performance. For example, overall working memory capacity as measured by the widely used test of reading span (Daneman & Carpenter, 1980) could be correlated with fluency of text production or the holistically rated quality of the resulting text.

Reading span and other tests of working memory capacity require both the processing of information in one task and the storage of information in a second task. By requiring the individual to perform two tasks concurrently, the executive component of working memory is assessed as well as capacity of short-term memory stores. Further measures of short-term memory storage without concurrent processing can also be administered with the objective of indexing individual differences in the capacity of the phonological loop and the visuo-spatial sketchpad as well as the central executive (Vanderberg & Swanson, 2007). For example, tests that measure the resources of central executive can be isolated from those that index the capacity of the phonological loop, using statistical techniques. Thus, the regression approach allows both an assessment of how individual differences in overall working memory capacity contribute to writing performance, and an analysis of the specific contributions of each of the three components of Baddeley's (1986) model.

The second approach is to apply dual-task methodology. When people perform two tasks concurrently, the central executive of working memory is called upon to coordinate the two tasks. Executive attention must be shifted from one task to the other and each shift requires time as well as effort. Multitasking thus stresses the resources of the central executive. The central bottleneck phenomenon illustrates this overload. When two tasks are done concurrently, the response to the first stimulus must be made before the response to the second stimulus can be programmed and executed. If the second stimulus occurs a few seconds after the first stimulus, then the first response can be completed and attention switched to the second stimulus without any problems. However, if the gap between the first and second stimulus is very brief, then responding to the second stimulus is abnormally delayed. There is a bottleneck within the central executive because its resources are needed to complete the first response before the second stimulus can be processed. Thus, by adding a second task to writing, one can examine how stressing the central executive disrupts the fluency or quality of written composition.

In a similar way, tasks can be designed that occupy the phonological loop or verbal WM. One example is the requirement to remember six random digits while composing. Another example is to listen to irrelevant speech that gains entry into the phonological loop. A third example is to require the concurrent articulation of an irrelevant word, such as "tap." In each case, a load is placed on the central executive, because two tasks are done concurrently, but also the storage component for verbal information is occupied and less available for use in written composition. In the same way, concurrent tasks that require visual or spatial information can be designed to occupy the visuo-spatial sketchpad. The logic is that specific concurrent tasks consume the resources of specific components of working memory. The investigator then examines how these concurrent tasks disrupt written composition.

As Levy and Ransdell (2002) pointed out, another use of dual task methodology is to reveal aspects of the composing process in a way that does not disrupt performance. For example, asking the writer to think aloud while composing is a widely used technique for revealing the planning, translating, and reviewing processes as they unfold (Flower & Hayes, 1980). An alternative approach is to interrupt the writer at random intervals and ask them to retrospect about the thoughts occupying working memory when the prompt occurred. By training the writers in advance to identify planning, translating, and reviewing, it is possible to examine the transitions from one process to another. This technique is called directed retrospection because it imposes specific categories rather than talking aloud in an unconstrained manner. With directed retrospection, it is also possible to assess the degree to which attention was engaged in the reported writing process by measuring response times to the signal that interrupted the writer. For example, while composing, a writer is instructed to say "stop" when an auditory "beep" is heard over headphones. The degree to which this response is delayed reflects how deeply attention was engaged in composition. Next, the writer presses a button to indicate whether his or her thoughts reflected planning, translating, or reviewing when the "beep" occurred, adding a third task. This triple-task method reflects another variant of the think-aloud protocol for understanding which processes are engaged and the degree to which they are engaged (Olive, Kellogg, & Piolat, 2002).

With the alternative use of dual-task methodology discussed by Levy and Ransdell (2002), the researcher is interested in the extent to which written composition disrupts the concurrent task rather than vice-versa. For example, responses might be delayed or accuracy impaired when performing the task while writing at the same time. Interference can be measured at the level of the individual participant by collecting control data on the task performed in isolation. For example, in recalling six random digits, a person may achieve an accuracy of 95% when the task is performed in isolation. Under dual task conditions, written composition might cause performance to drop to only 80% accuracy. The interference score of 15% reflects the degree to which working memory resources needed for digit retention were taken instead by composing processes.

4. Research Review

The 1996 model was developed on the basis of theory and empirical research available at that time. Over the past 17 years, a large number of studies on working memory and writing have been conducted. In the next section, a representative selection of this body of research will be presented. No claim is made for an exhaustive review. The purpose is to highlight which assumptions of the model have been well supported and which ones are questionable. To preview, a core assumption is that planning, translating, and reviewing are all dependent on the central executive and substantial evidence has accumulated in support of this view. Similarly, the findings of a key experiment using articulatory suppression as a tool for disrupting the phonological loop confirmed that the translation of ideas into a sentence requires verbal working memory as well as the central executive. However, the assumption that editing makes no demands on the phonological loop appears incorrect based on further research using articulatory suppression. The model assumed that planning would engage the sketchpad. Experiments using a 1-back visual secondary task confirmed this prediction, but showed it held only for the planning of sentences involving concrete words evoking imagery but not for abstract language. The spatial subcomponent of the sketchpad does not appear to be engaged by planning, but experiments using a 1-back spatial secondary task have yielded some conflicting results.

4.1 Central Executive as Critical

A key study using the correlational approach successfully indexed individual differences in the three components of Baddeley's (1986) model of working memory. Vanderberg and Swanson (2007) assessed short-term memory storage in a variety of ways using verbal materials, on the one hand, and visual materials on the other. They were able to identify tasks that index the capacity of the phonological loop independently from other components of working memory. Similarly, they were able to provide separate capacity estimates for the visuo-spatial sketchpad and the central executive. To illustrate the principle involved, a short-term retention task that requires participants to recall a set of random digits in the order they were presented measures the capacity of the phonological loop. By contrast, in a backward digit span task, the forward order must be inhibited, the digits must be manipulated and recalled in the reverse direction starting with the last item presented, and this novel order of recall must be carefully monitored for accuracy. The effortful activities of the backward digit span demand significant attention and so provide a measure of the capacity of the central executive.

Participants in the study were students in the 10th grade. Besides the battery of working memory tasks, they completed the story subtest of the *Test of Written English-2* (TOWL 2) and an Experimental Writing task requiring an analytical essay ("Write an essay about two characters facing a challenge. Discuss two or three ways in which the characters respond to the challenge."). Several measures of writing ability were taken from these composition tests and subjected to a factor analysis to separate specific traits of writing skill. For example, from the TOWL-2 researchers examined higher order writing skills, punctuation, spelling, and vocabulary. Next, regression analyses determined which component of working memory correlated with individual differences in these traits. The key finding was that the capacity variations in the central executive reliably predicted higher order writing skills, punctuation, and vocabulary in story composition. The only trait it could not account for was spelling. Neither the phonological loop nor the visuo-spatial sketchpad could explain variance in any of these performance traits. The same message came from the Experimental Writing essay task, with the central executive alone accounting for differences in vocabulary and text structure. Vandenberg and Swanson (2007; p. 170) concluded that "the central executive predicts the same skills and parts of writing regardless of the style of writing occurring."

The regression findings are consistent with 1996 model in pointing to the central executive as being most heavily involved in planning, translating, and reviewing. One would expect that individual variations in the capacity of the central executive would prove most informative in predicting an individual's overall writing ability. Both the writing of a creative story and an analytical essay revealed this pattern. The two storage components make only a limited contribution to specific writing processes (see Table 1); hence, it is not surprising that their contribution could not be detected by looking at quality of the product alone. To see their role in composition, dual task approaches ought to be more fruitful; a concurrent task can be used to reduce directly the resources of phonological loop or the visuo-spatial sketchpad and observe the consequences.

Ransdell, Levy, and Kellogg (2002) manipulated the kind of concurrent task required as college students composed an essay. Irrelevant speech—the kind of background noise one hears while composing in a coffee shop, for example—presumably enters and occupies the phonological loop (Baddeley, 1996). But it arguably does not implicate the resources of the central executive. Ransdell et al. used mean sentence length as an index of how effectively the sentence generation process in particular was functioning in the presence of a concurrent task. In Experiment 1, they found that irrelevant speech shortened sentence lengths by a small but reliable amount, about half a word, compared with a control condition.

In Experiment 2, the participants in the control condition who wrote without distraction wrote more than a full word more per sentence in comparison with a slight variation of the background speech. On occasion, the participants in the experimental condition had to press a button each time they heard a target word in the otherwise irrelevant speech. Making this decision about whether a target word had occurred made a minimal but important demand on the central executive. This speech plus decision task required that some attention be given to the background speech.

Finally, in Experiment 3, Ransdell et al. placed a large load on the central executive by requiring that the writers hold in mind six random digits while they composed. A set of six digits was presented, the subject composed awhile, and then tried to recall the digits. This sequence was then repeated with six new digits. Performing this highly effortful task required substantial resources of the central executive and reduced sentence length by about three full words relative to the control condition.

4.2 The Phonological Loop and Sentence Generation

The literature on language production has emphasized the issue of lexical access, retrieving the words to use in a sentence to express the planned conceptual content. The prevailing view is that lexical access involves two stages (Bock & Levelt, 1994; Cutting & Ferreira, 1999; Dell, 1986; Garrett, 1975). In the first stage, an abstract lexical representation (lemma) is selected to express a concept. Syntactic as well as semantic features are provided by the retrieved lemma. The first stage of grammatical encoding entails more than the retrieval of lemma representations of words and suffixes that mark grammatical distinctions in Bock and Levelt's (1994) symbolic speech production model. It further requires positioning these lexical elements in a phrase structure. Phonological encoding then follows as the second stage in lexical access by providing the sound structure or lexeme representation associated with the words and suffixes to be produced. Lexeme retrieval is both necessary for the motor execution of overt speech and seemingly typical for the inner speech that accompanies writing. Before motor execution can occur in speech, the phonemes that form syllables must be selected to drive articulation. In the case of written language production, orthographic encoding is required to specify the graphemes needed to spell each word (Caramazza, Miceli, Villa, & Romani, 1987; Caramazza, 1991).

The distinction between independent lemma and lexeme representations has been challenged, however. An alternative independent network of lexical access postulates the retrieval of modality specific lexeme representations prior to the processing of their syntactic features (Hillis & Caramazza, 1995; Caramazza, 1997). A phonological lexeme is retrieved for speech or an orthographic lexeme is retrieved for writing. Grammatical encoding then follows using these modality specific representations as inputs. This does not imply that phonological and orthographic encoding are necessarily discrete from grammatical encoding. Rather, these stages could be cascaded or even fully interactive during sentence generation as connectionist models contend.

The 1996 model stipulated an important role for the phonological loop in the translation of ideas into a sentence. This view is consistent with Caramazza's (1997) contention that phonological and orthographic representations are retrieved independently and fed forward to grammatical representations. On this view, the inner voice of the writer maintains words in the phonological loop throughout translation and these phonological word forms are retrieved early in the process. Such storage can be regarded as a support for grammatical and orthographic encoding processes that take place in written production.

Speeded picture naming of homophones clearly supports the view of early phonological processing. For example, in naming a picture of a ball used in a game, Cutting and Ferreira (1999) found that presenting the word "dance" 150 ms before the picture effectively speeded the production of the picture name "ball." This finding indicates that the phonological properties of "ball" were activated early in lexical access when semantic processing was also occurring (i.e., understanding that dance and ball are semantically related but inappropriate for naming the picture at hand). An early phonological effect rules out the possibility that lemma selection is discrete and complete prior to the start of phonological encoding and instead supports a cascaded or interactive model. The effect is also consistent with the view outlined earlier that phonological lexemes are retrieved directly from semantic activation of concepts early in the process of generating a word, as proposed by Caramazza (1997).

Research with the congenitally and profoundly deaf population also supports Kellogg's assumption that the phonological loop underpins written sentence production (Almargot, Lambert, Thebault, & Dansac, 2007). This population tends to commit specific kinds of spelling errors (Leybaert & Alegria, 1995) and grammatical errors (Volterra & Bates, 1989) in their written language production. Almargot et al. showed that both kinds of errors arose chiefly from deficits in the storage of phonological representations in verbal working memory.

College students who know the grammatical rules of French can nevertheless be induced to commit errors in subject-verb agreement. This is accomplished by requiring a concurrent task that distracts verbal WM from written production (Fayol, Largy, & Lemaire, 1994; Moretti, Torre, Antonello, Fabbro, Cazzato, Bava, 2003). Levy and Marek (1998) have shown that irrelevant speech causes errors in both number and tense during sentence generation. Importantly, they were able to show that same effects were observed with scrambled unattended speech as with words in a meaning order. Thus, it was the phonological rather than the semantic properties of the speech that made a difference.

In an especially revealing study, Chenoweth and Hayes (2003) used articulatory suppression to preclude the possibility of using inner speech as a support for linguistic encoding processes during translation. They asked writers to repeat an irrelevant word over and over again aloud as they composed ("tap, tap, tap…"). This suppresses the possibility of silent articulation. The number of words produced per second was reliably impaired by this concurrent task relative to a no-tap control condition. Importantly, the investigators included an additional condition in which the writers were asked to tap their foot at the same pace as was used in the articulatory suppression condition. Of great interest, the foot tapping as a concurrent task had no reliable effect on the words produced per second. Inclusion of this foot-tap condition allows one to rule out the central executive as the source of the impairment. Both conditions make demands on the central executive to coordinate the tap task with writing, yet only the articulatory suppression condition reduced the rate of sentence generation. The number of grammatical, typing, and spelling errors also increased in the voice-tap condition relative to the two control conditions.

As seen in Table 1, the phonological loop was proposed in the 1996 model to support reading during the review of the text already produced as well as during the translation of ideas into sentences. One might contend that it was reading that was impaired by articulatory suppression rather than sentence generation. The data from Chenoweth and Hayes (2003) allow one to rule out this alternative interpretation, because they replicated the experiment using invisible writing that did not allow the writer to read the evolving text. Once again, it was only the voice-tap condition that reduced the rate of sentence production and increased the error rate under conditions with invisible writing. Without being able to read the text, more grammatical, typing, and spelling errors were observed in all three conditions because reviewing the text was prevented compared with visible writing. Still, the voice-tap condition showed the highest number of errors for both visible and invisible writing, suggesting it directly affected the translation of ideas into sentences.

4.3 Editing and the Phonological Loop

The findings of Hayes and Chenoweth (2006), by contrast, seriously challenged the assumption of 1996 model with respect to its claim that editing involved only the central executive. They again asked college students to repeat aloud the word "tap" but this time while they concurrently performed a transcription and reviewing task. The participants transcribed through typing a text from one computer window to another (note that it was not a text that they had composed). By reviewing the transcribed text, they could edit the mistakes as they went. Of interest was the correction rate of any errors that were made during the transcription. Uncorrected errors represented a failure of the editing process. The results showed that articulatory suppression reliably increased the number of uncorrected errors relative to the no-tap control condition.

Levy and Marek (1999) found no effect of irrelevant speech on transcription and editing despite the effect it had on sentence generation. This pattern is consistent with the contention that the phonological loop is unaffected by editing, even though it affects translating. However, articulatory suppression clearly did impact the ability of writers to edit a text as they transcribed it. Thus, the phonological loop must be involved in either editing, reading, or the motor programming and execution required by typing. As Hayes and Chenoweth (2006) pointed out, it would be useful to test an additional control condition before concluding that editing in particular was disrupted by articulatory suppression. Would the uncorrected errors be worse in the voice-tap condition with invisible writing when reading the transcribed text was impossible? It could be that articulatory suppression impaired only the reading of the text rather than its editing. Although editing is less frequent overall when reading is prohibited, according to the findings of Chenoweth and Hayes (2003), it still occurs. For example, writers can certainly mentally edit word choice, spelling errors, or grammatical constructions prior to initiating any motor output. Thus, it would important to know from a future experiment whether articulatory suppression elevated the number of uncorrected errors when writing was invisible and reading impossible.

4.4 Planning and the Visual-Spatial Components

As can be seen in Table 1, verbal WM appears to be more critical to text production than is visual or spatial WM. Whereas the phonological loop supports both translation and reading, the visuo-spatial sketchpad was postulated to only aid with planning. Findings by Lea and Levy (1998) were consistent with the model. A concurrent task requiring the storage of phonological information disrupted composition more (21%) than one requiring the storage of visuo-spatial information (13%). It may have been the spatial rather than the visual demands that were most disruptive, according to the findings by Galbraith, Ford, Walker, and Ford (2005). They studied college students as they first generated ideas, next organized the ideas into an outline, and finally produced a text. A spatial tracking task affected the organization of ideas by reducing the quality of content and the integrity of the outline. By contrast, a visual noise task had no impact at all.

Olive, Kellogg, and Piolat (2008), on the other hand, found that writing reduced accuracy of performance reliably on a visual concurrent task and to the same degree as that of a verbal task (about 8%). By contrast, a purely spatial task was affected very little, if at all (less than 3%). The outcome raised important questions about whether visual WM and spatial WM make different contributions to written composition and which specific processes they support.

Moreover, further experiments showed that visual WM has an even more limited role in that it aids only the planning of concrete concepts. For concepts with a concrete referent that can be visualized (e.g., table or book), the imagery process requires the capacity of the visual WM store. By contrast, abstract concepts may not be linked to concrete referents that can be mentally imaged (e.g., liberty or philosophy). For such abstract language, the conceptual content of a sentence is presumably held in a semantic WM store (Hayes, 1996), as amodal propositions (Kintsch, 1998). Although the meaning of concrete concepts can be stored in semantic WM, their referents can also be visually imaged, providing the writer with a knowledge representation that goes beyond the propositional. Writers reported more imagery and produced more detailed language when defining concrete nouns compared to abstract nouns (Sadoski, Kealy, Goetz, and Paivio, 1997).

At a theoretical level, one can argue that spatial WM is necessary to support motor output, but not planning, in producing a single sentence. Granted, writers may develop a spatial representation of an extended text (Hayes, 1996) or in planning texts with spatial information (e.g., directions), but these observations are not generally true of isolated sentence generation. Conceivably, all concrete language processing could require spatial as well as visual WM (Sadoski & Paivio, 2001), but the mental images associated with words need not be spatially located as real objects are necessarily located in the physical world. Thus, it is reasonable to suppose that spatial WM has no mandatory role in planning the written production of concrete language in general—visual WM alone is sufficient.

With respect to motor output, however, it is clear that spatial parameters must be set in the motor programming of handwritten output (Van Galen, 1991), and in young children motor transcription is highly demanding of WM resources (Bourdin & Fayol, 1994; 1996; McCutchen, 1996; Olive & Kellogg, 2002). It is less clear that these effects can be observed in college students who have extensively practiced handwriting to the point that it is relatively automatic. It is also uncertain if the spatial parameters involved in motor programming make use of the spatial component of working memory. Conceivably, the visuo-spatial sketchpad as a resource for cognition is distinct from the motor system. A special form of transient spatial memory might be dedicated to storing the motor parameters required for handwritten output, for example. On the other hand, it appears that the central executive is involved in both motor and cognitive functions.

So, it is possible that a general form of spatial WM could be employed in motor programming as well as in the planning of concrete language.

Kellogg, Olive, and Piolat (2007) addressed the question of whether handwritten sentence generation alone depended more on visual versus spatial WM. As a concurrent task, they asked college students to detect changes in phonological, visual, or spatial information in a 1-back task of working memory. That is to say, a phonological segment was presented on a computer screen at random times during the sentence production (i.e., "BA"). If it matched the one presented last, then the participant ignore it. Whenever a new phonological segment appeared (i.e., "PA"), they pressed a button as rapidly as possible. In other conditions, visual objects (geometric shapes or shapes not readily named) were presented on either the left or the right hand side of the screen. To test visual WM, participants responded to the shapes, whereas to test spatial WM they ignored the shapes and decided if the location was new compared to the last time it appeared on the screen. The result suggested that visual WM, but not spatial WM, had an important role to play in planning. But, this occurred only when the writers were trying to incorporate concrete nouns into the sentences that they generated. For abstract nouns, there was no apparent involvement of visual WM.

The lack of any difficulties with spatial WM is intriguing but inconsistent with other evidence. Raulerson, Whiteford, and Kellogg (2010) reassessed whether the sentence generation task was impacted by spatial as well visual concurrent tasks using the 1-back task. They found that both had an impact, although the visual task was more disruptive. They also showed that a concurrent load on verbal WM using the phonological segments was far more disruptive to sentence production that either the visual or the spatial tasks. The difference in outcome of Kellogg et al. (2007) and Raulderson et al. (2010) is puzzling; in both studies handwriting was the means of motor output and the other procedures were similar in most respects. The only difference was that markedly more sentences were handwritten by participants in the 2010 study.

The sentences in Raulerson et al. as well as in the earlier study were generated in isolation rather than integrated into a single text. Hence, it is unlikely that participants relied on spatial WM for getting a sense of the text as a whole, as might well happen in composing coherent texts (Hayes, 1996; Olive & Passerault, 2012). Perhaps the spatial parameters needed to guide hand and arm movements during the handwritten output were drawing on spatial WM (Van Galen, 1990), but then it is unclear why spatial interference was not detected in Kellogg et al. (2007). One might speculate that spatial WM in fact supports motor programming by transiently maintaining the spatial parameters needed to trigger motor execution. With typed motor output, a similar demand could be hypothesized, if one assumed that the spatial arrangement of the keyboard must be held in spatial WM during the programming of the ballistic finger movements that strike the keys. However, future research is needed to clarify under what conditions demands on spatial WM can be reliably observed in the production of isolated written sentences, whether by handwriting or typing.

Another possibility is that the orthographic stage of linguistic encoding required when spelling words depends on spatial WM. For spoken language, phonological encoding is all that is required because the words are not spelled and graphemes need not be selected. However, spelling is required for handwritten or typed output and this aspect of linguistic encoding might draw upon spatial WM. Again, such a hypothesis cannot readily explain why some experiments detect spatial interference whereas others do not. As will be discussed in the next section, it would be helpful to test directly the hypothesis that spatial WM in fact plays a necessary role in written but not spoken sentence generation.

In sum, the literature on whether and how spatial WM is involved in written composition is mixed and confusing. It is difficult to trace the differences in outcomes to whether complete texts were composed or simply isolated sentences. Storing the spatial layout of a text as proposed by Hayes (1996), for instance, should not be found with isolated sentences and, yet, Raulerson et al. found evidence of demands on spatial WM. Possibly the specific kinds of planning required by the writing task are critical, as proposed by Passerault and Dinet (2000). They reported evidence that writing a descriptive text demands more resources of the visuo-spatial sketchpad than does an argumentative text. Just as concrete language invokes visual imagery, so too does the composition of a descriptive text, for much the same reason that it is rendered in concrete language. Passerault and Dinet found that holding geometric figures in mind disrupted the composition of a descriptive but not an argumentative text. However, it remains unclear whether this effect was driven primarily by disruptions of the component of visual WM rather than spatial WM per se.

All of these results show that the 1996 model was incomplete. Although planning invokes the visuo-spatial sketchpad, the specific demands matter importantly. For example, the high level process of idea organization depends heavily on spatial WM rather than visual WM (Galbraith et al., 2005). In planning ideas prior to sentence generation, it is visual WM rather than spatial WM that matters more (Kellogg et al., 2007). However, the planning process relies on visual WM only when the concepts are concrete rather than abstract.

5. Potential New Tests of the Model

To summarize, the findings from the past 17 years have been, for the most part, supportive of the assumptions of the model proposed by Kellogg (1996). The empirical evidence convincingly supported the supremacy of the central executive in writing, the important role of the phonological loop in linguistic process of sentence generation, and the visual-spatial sketchpad in the thinking or problem solving act of planning. However, an important restriction was uncovered in that active visualization occurred only in planning with concrete concepts but not with abstract ones. A more significant challenge to the model came from the finding that editing appeared to require the phonological loop as well as the central executive. There remains, however, the possibility that it was actually reading rather than editing that was disrupted by the concurrent task of articulatory suppression. Would articulatory suppression disrupt editing when reading was prohibited by the use of invisible writing? Such a new experiment would prove informative.

On balance, then, the model does not appear to be fatally flawed and continues to generate testable predictions. Does this imply that the role of working memory in writing is now reasonably well understood? Not necessarily. It could instead imply that the tests to which the model has been subjected are not stringent enough to cause it to fail. Perhaps the experiments conducted to date simply have not yet exposed the model's most serious weaknesses. In this section, several experiments will be sketched to illustrate new tests of the model's assumptions.

The first examines the claim that planning at times depends on visual working memory whereas grammatical encoding relies solely on verbal working memory. Based on past findings, the model assumes that planning with concrete concepts ought to make a demand on visual WM. It would, therefore, be of interest to manipulate the amount of planning that would be required as a way of creating either a relatively low demand on visual WM versus a high demand. If two nouns are given as prompts to compose a written sentence, it is known that unrelated nouns require more planning in comparison with related nouns. Strong semantic associations between the nouns (e.g., chair-table) minimize the amount of planning in the conceptual domain needed to create a proposition to be expressed in a sentence. It takes about a half second longer to initiate typing a sentence when the nouns are weak semantic associates (e.g., bride-eagle), because more conceptual planning is needed to form a proposition linking the two ideas (Kellogg, 2004). Once a proposition is created, however, the grammatical encoding demands ought to be the same for either related or unrelated items. This follows from the assumption that grammatical encoding is a stage of composition that follows the planning stage and is independent of it. According to the model, the grammatical encoding stage as well as other stages of written sentence generation (i.e., phonological and orthographic encoding) depend on verbal WM, not visual. Thus, in the first proposed experiment, unrelated concrete nouns would be expected to demand more visual WM during planning compared with related concrete nouns, but have no effect on verbal WM. Only concrete nouns would be used to insure that they make at least some demand on visual WM.

On the other hand, translating ideas into passive sentences ought to demand more verbal WM relative to active sentences, but leave visual WM unaffected. Passive structures presumably are more complex syntactically compared with active sentences. The justification for this assertion is in part theoretical and in part empirical. In terms of linguistic theory, Chomsky's (1965) transformational grammar and in his successive revisions the passive surface structure is derived from an active form of the sentence. In the original model, for example, an active deep structure had to be transformed to produce a passive surface structure. As an empirical fact, the evidence shows that passive sentences typically require more time to comprehend compared with active sentences (Gough, 1965). This is consistent with the linguistic analysis that the passive voice is the more complex of the two. Because grammatical encoding presumably requires verbal WM alone, composing a passive sentence ought to make greater demands on verbal WM compared with active sentences. This manipulation of grammatical structure ought to have no impact on visual WM, according to the model. In short, it should be possible to demonstrate a double dissociation between planning and grammatical encoding with respect to the demands that they place on visual versus verbal WM.

A second test of the idea that planning and grammatical encoding are independent stages with different support needs from working memory would employ a picture prompt for sentence generation rather than supplying two nouns to include in the sentence. This allows one to examine the lexical selection aspect of grammatical encoding rather than the positional aspect. The goal is to prompt using pictorial referents either a familiar or an unfamiliar noun. The rationale for the experiment is that retrieving and maintaining a noun that names a picture is more difficult when the noun is unfamiliar than when it is frequently used. Thus, the lexical selection process during grammatical encoding will be more demanding for pictures to elicit an unfamiliar noun compared with a common object. As in the previous experiment, the aim is to document a double dissociation between visual WM and verbal WM in the support of planning and linguistic encoding, respectively. The hypothesis is that verbal WM is necessary to linguistically encode concepts prior to motor output. Visual WM, on the other hand, is necessary only for imaging the referent of concrete nouns during sentence planning. A between-groups design would entail the manipulation of the secondary task (verbal versus visual) crossed with word frequency (familiar versus unfamiliar). The primary task is to write a simple sentence that includes the two nouns that name the pictures presented as prompts. The materials for the experiment would consist of pictures of pairs of nouns. The nouns themselves would be a moderate level of concreteness, imagery, and meaningfulness, with half high in printed frequency (familiar) and half low (unfamiliar). The predictions are that when writers select familiar lexical items for inclusion in the grammatical structure of a sentence, there should be less interference with the verbal WM concurrent task compared with unfamiliar nouns. By contrast, if it is accurate that lexical selection is independent of planning conceptual representations of the sentence and that planning requires only visual WM for concrete concepts, then familiarity should have no effect on the level of interference observed for the concurrent visual WM task.

According to Baddeley's conception, verbal working memory involves the temporary storage of phonological representations. It is also possible, however, that orthographic representations of spelled written words are involved instead of or in addition to phonological representations. This is an important distinction in the production of written language given that an orthographic stage of linguistic encoding necessarily is required for spelling the words of a sentence. Perhaps it is important to consider the role of an orthographic loop, as suggested by Richards, Berninger, and

Fayol (2012). Would such an orthographic stage of processing draw on spatial WM or would it instead by an alternative form of verbal WM that is not phonologically based?

To address whether verbal WM entails orthographic representations, the methodology of Kellogg et al. (2007) would be adapted. In the critical experimental condition, however, the *ba* and *pa* stimuli used in the concurrent task would be heard rather than read so as to minimize or even eliminate orthography. As a primary task, the participant might be asked to produce a written sentence from a picture depicting two objects. Again, the pictures could selected to elicit either familiar nouns or unfamiliar nouns. The other factor manipulated in the experiment would be the input modality of the concurrent verbal WM task. For half of the participants, the verbal task would be read whereas for others it would be heard. In the heard condition, it is possible to assess whether the interference arises from orthographic rather than from phonological processing. It is known that reading activates phonological and orthographic representations, whereas hearing typically activates only phonology in WM. Of interest, then, is whether writing interferes differently with the verbal WM task when it is read with visual presentation or heard with aural presentation. It is predicted that read and heard conditions would show exactly the same degree of interference with sentence production for both familiar and unfamiliar noun prompts, if verbal WM is phonological in nature. The alternative hypothesis that verbal WM at least in part involves orthographic storage would hold that the interference would be greater for the read compared with the heard condition. Taking this view a step further, if verbal WM were entirely orthographic, then interference for the heard condition ought to fall to zero.

To address the role of spatial WM in orthographic encoding, a verbal task could be compared with a spatial task. As in the experiments outlined above, the participants would either respond to the phonological segment read on the computer screen (*ba* versus *pa*), or they would respond to the location of the segment (*left* versus *right)*. In the 1-back task for spatial WM, participants would respond whenever the location was different from the previous presentation regardless of whether it was a *ba* or a *pa*. Conceivably, the orthographic stage of linguistic encoding depends on spatial WM rather than a verbal WM store based on orthographic or graphemic representations. This might be assessed by contrasting written sentence production with spoken production. On each trial, participants might be presented with two pictures or, alternatively, with two nouns that are equated in terms of familiarity, concreteness, and other lexical properties. In the written condition, they must type a sentence (or produce it through handwriting), whereas others do the same through spoken production where spelling is not required by the task. If it is correct that verbal WM is based on phonological representations, then the written and spoken production tasks should interfere equally for the verbal task. Of greatest interest is what will happen with the spatial task. On the view that the orthographic stage of linguistic encoding in fact draws on spatial WM, then the written form of sentence production should produce substantial interference. However, for those who speak sentences, thus avoiding the orthographic encoding stage, there ought to be no interference with the spatial WM task.

6. Implications for Writing Instruction

A substantial body of literature has both confirmed and modified assumptions of the 1996 model. Additional tests of the model are still needed as outlined in the preceding section. Even so, there are implications of the model as it now stands for understanding writing performance and writing difficulties. The assumptions of the model provide an account for why specific kinds of interventions ought to be most successful in educating effective writers.

Educational research has carefully documented the extensive range of knowledge that must be available in long-term memory for effective text composition. A large mental lexicon, heightened grammatical competence, a variety of discourse structures, and domain-specific knowledge of the topic are among these (Nystrand, 1982). Equally important, but perhaps less appreciated, is that writers must be able to retrieve their knowledge during composition and creatively apply it to decide what to say in the text and how to say it. Accessibility in working memory or through rapid, well-timed retrieval from long-term memory is necessary or else the writer's knowledge is inert during composition (Kellogg, 1994). McCutchen (1996) documented that children’s writing performance and development depends on the successful operation of planning, sentence generation, and reviewing. She reported that limitations in working memory capacity can impair each of these component processes, with ramifications for the level of writing skill shown. Indeed, what motivated the 1996 model in the first place was the need to provide an account of why written composition can be so cognitively effortful and how the juggling of planning, translating, and reviewing can overload working memory.

Only 3% of American students write at an advanced level, with less than one third of students in grades 8 and 12 performing at or above a proficient level on the National Assessment of Educational Progress (NAEP, 2011). If one accepts that such a mediocre level of achievement is not simply an illusion created by unrepresentative testing conditions or a single, limited sample of students' abilities, then it would appear that the vast majority of even graduating seniors are still struggling with written composition. This, by itself, does not necessarily imply that working memory failures are the main source of the problem. Instead, a deficit in the *availability* of linguistic knowledge and skills in long-term memory--as opposed to their *accessibility* in working memory--could account for the problem in its entirety. For example, in young children, boys do less well in written composition than girls on average precisely because of such knowledge and skill deficits and these effects persist even into secondary education (Bourke and Adams, 2011). Although working memory advantages for girls could account for their superior writing skills, this does not seem to be the case. Rather, it is the degree to which verbal knowledge is available in girls compared with boys that explains their edge in writing skills rather than the accessibility of such knowledge in working memory.

Even so, it is also possible that failures to maintain representations in working memory contribute significantly to problems in coherence, grammar, and spelling for both girls and boys. One contributor to the failure of 97% of high school seniors to exhibit advanced writing skills on the NAEP test could well be a lack of knowledge accessibility caused by working memory overload. Some of what the students know may remain inert because the demands of the composing process exceed the capacity of working memory. The high degree of mental effort observed in college students while composing relatively short texts is consistent with this perspective (Kellogg, 1994). Individual differences in working memory capacity, regardless of the students' sex, might account for variations in writing skill even when the availability of knowledge is held constant (McCutchen, 1996).

According to the 1996 model, working memory can be readily overwhelmed by the mental gymnastics required by planning, language generation, and reviewing. The relatively untrained student writer may be composing with the equivalent of a six digit concurrent load held in working memory, impairing his or her fluency and effectiveness as a writer. Accordingly, the model suggests that developing writers would benefit from reducing the overload on working memory during composition. There are three primary ways to achieve this goal through instructional design. The first is to avoid the demands on short-term working memory by composing on a topic that the writer knows extremely well. A high degree of domain-specific knowledge permits the relatively automatic retrieval of content from long-term memory and weakens the burden on the central executive of working memory. The second approach is to use strategies that focus attention on one process at time to help manage the coordination of planning, sentence generation, and the other essential writing processes. A third approach uses deliberate practice to reduce the demands of individual writing processes, rendering them less effortful than they would be otherwise. Consider each approach in turn.

6.1 Long-Term Working Memory

Gaining domain-specific expertise allows the writer to retrieve relevant knowledge from long-term memory at just the right moment. Ericsson and Kintsch (1995) called this form of knowledge accessibility long-term working memory and distinguished it from laboriously maintaining information in an active state in short-term working memory. This indirectly helps with the overload on the central executive component of working memory by reducing the occasions on which it is needed. The ability to rely on long-term working memory ought to help writers to manage the composition process (McCutchen, 2000). Indeed, a high degree of domain-specific knowledge about the topic significantly reduces the momentary demands made on executive attention (Kellogg, 2001).

Writing about topics that students know well provides a scaffold to support the writer and avoid overloading the limited resources of working memory. This permits more executive attention to be allocated to the juggling of planning, generating, and reviewing than would be the case when writing about a topic less well-known to the students. For example, seniors in college should know the most about their major field and so should be provided with extensive opportunities to write within the discipline for purely cognitive reasons. Although the writing across the curriculum movement has rightly stressed the value of situating writing assignments within the discourse community of a discipline on the grounds that writing is inherently a social act, the practice can also be recommended as means to reduce the demands on working memory. Writing within the discipline of one's major field thus provides an opportunity to practice the complex coordination of writing processes because it frees short-term working memory for the task.

6.2 Attentional Funneling

The second approach trains the writer to better manage the coordination of planning, sentence generating, motor programming, and reviewing as reading or editing. This can be accomplished through the use of strategies that funnel effort to a single process at a given moment in time. With sufficient expertise as a writer, the ability to juggle planning, sentence generation, and reviewing concurrently is a tremendously powerful means of composing fluently and effectively. But attempting to do so without sufficient domain knowledge and general writing capability is a recipe for overloading working memory. Thus, as an educational intervention, it helps to teach students how to use prewriting and drafting strategies effectively. In a meta-analysis of the literature on writing interventions effective with adolescent and high school students, Graham and Perrin (2007) observed that the explicit teaching of strategies for planning, revising, and editing their compositions produced a large effect size (d = .82). Such strategies often benefit the quality and fluency of writing by reducing the degree to which one must simultaneously juggle multiple processes. The strategies funnel limited attention and storage to only one or two processes momentarily (Kellogg, 1986).

To illustrate the concept of attentional funneling, consider the use of outlining as a prewriting strategy (Kellogg, 1988). In creating a topic outline during the conceptualization phase of prewriting, before a first draft is attempted, the writer funnels working memory resources to planning and to a lesser extent reviewing. By definition, the writer is not yet attempting to compose complete sentences for inclusion in the first draft of the text. Conceivably, fragments of sentences or even complete sentences could be mentally composed during prewriting, but by outlining the writer funnels attention to the macrostructure of the text-to-be rather than its microstructure. By accomplishing this advanced organization of ideas during the prewriting phase of composition, writers can focus attention on sentence generation in producing a first draft. The data show that outlining first does not shut down the interaction of planning, generation, and reviewing entirely during drafting. Rather, it allows relatively more time to be devoted to generating sentences and cohesive links among them when the macrostructure of the text has been sketched out in the form of a hierarchical structure.

Both the outline and no outline groups studied by Kellogg (1988) reported planning, sentence generation, and reviewing during their composition of the document, but the outlining in advance during prewriting funneled more time and effort to sentence generation.

Galbraith and Torrance (2004) replicated the advantage of organizational planning during prewriting and further showed that organized notes aid writing regardless of whether or not these notes are available in preparing a final draft of the text. However, their findings also suggested that just generating text without any planning in advance can also benefit a writer, as long as these initial unorganized notes or sentences are not available to the writer in preparing the final draft. In this case writers engage in a proactive form of revision during the drafting of the text so as to produce the organizational structure without advanced planning. It is possible to focus on constituting the ideas to be included in a text during prewriting without regard for their organization. Of interest, this strategy works only as long as these unorganized ideas are not made available to the writer during the drafting of the text. Having the notes available for reading could make it difficult to funnel attention to planning, sentence generation, and reviewing during the drafting of the text.

6.3 Deliberate Practice

The third approach attempts to lessen the burden of each writing process on working memory through extensive and deliberate practice (Kellogg & Whiteford, 2009). The aim is to train writers so that planning, sentence generation, and reviewing each become relatively automatic. McCutchen (1988) made the important point that these processes are too complex to become automatic in the strict sense of becoming effortless, unintentional, and unavailable to conscious awareness. Still, it is certainly possible to reduce the *relative effort* required to plan ideas and their organizational structure, fluently generate sentences and cohesive links among them, and review the plans and text from the perspective of both the author and the imagined reader (Kellogg, 1994).

In fact, the development of effective writing skill is impossible without reducing these relative demands based on the assumptions of the 1996 model. Overload of the central executive with negative consequences for writing skill is to be expected unless the demands of individual processes are reduced through domain-specific knowledge, strategy use, or achieving relatively automatic processing. The only known way to make a process less effortful and more automatic is through repetitive practice. Concerted training undertaken with the aim of attaining expertise in either physical or cognitive tasks is known as deliberate practice (Ericsson, et al., 1993). Deliberate practice requires (1) effortful exertion to improve performance, (2) intrinsic motivation to engage in the task, (3) practice tasks that are within reach of the individual's current level of ability, (4) feedback that provides knowledge of results, and (5) high levels of repetition.

The best-documented case of how extensive practice reduces the effortful demands of writing processes is concerned with lower level mechanical skills. With a sufficient degree of experience, children can reduce the effort demands of transcription as they learn to master handwriting and spelling (McCutchen, 1996; Bourdin & Fayol, 1994). In fact, until this mastery of lower-level writing skills is achieved, the higher order processes of planning, sentence generation, and reviewing are chronically under funded and writers stay at the basic level of knowledge-telling in composition skill (Bereiter & Scardamalia, 1987; Kellogg, 2008).

Another example concerns the development of editing skills. In written French agreement in number of the subject and verb is relatively complex given its silent orthography. Although speakers may be fluent in French, they may still be prone at times to number agreement errors in written composition. Such errors must be detected and edited during the reviewing process. For young, relatively inexperienced writers the editing process entails a slow, effortful algorithm of comparing the suffix of the noun with the verb ending (Largy, Dédévan, & Hupet, 2004). However, as the writer gains experience this effortful process is gradually replaced with a rapid and relatively automatic check done with little attention. It is thus through extended practice with editing for a specific kind of error that a relatively automatic procedure emerges.

A final example of an effective instructional intervention based on the principle of deliberate practice concerns the exercise of sentence combining. Students are taught how to combine sentences; they repeatedly practice combining two or more basic sentences into a single complex sentence. The exercise thus explicitly trains writers how to generate complex and sophisticated sentences. Graham and Perrin (2007) reported that sentence combining produces a moderate, but statistically reliable, benefit to students in their ability to generate complex sentences (d = .50). Zimmerman and Kitsantas (2002) extended this work further and found that college students learned to combine sentences best when they practiced after observation of a model performing a procedure for combining two sentences and when external feedback was provided. From the perspective of the 1996 model, sentence-combining exercises help by reducing the attention and storage demands of generating syntactically complex sentences through repetition. It is precisely such sophisticated sentences that place the greatest demands on working memory and would most benefit from deliberate practice.

7. Conclusion

In sum, the 1996 model of how working memory supports writing processes has been successful first and foremost in spawning a sizeable literature on how writing works. The evidence from this literature has sustained several of the core predictions of the model, while casting serious doubt on some of its assumptions. It has further raised questions for future research, particularly with regard to the role of spatial WM in written composition. Although testing of the model is by no means complete, there are a number of implications for educational practice in the preparation and training of student writers that warrant notice. All of them concern ways of reducing the likelihood that the novice writer will be overwhelmed by the demands of written composition on limited working memory. To the extent that developing writers struggle because part of their available knowledge lies inaccessible during composition, interventions focused on working memory should be of considerable benefit.

Notes

1. This paper is based on the John R. Hayes Lecture given by the first author at the European Writing Conference (EARLI SigWriting 2012) held in Porto.
2. Michael Cahill is now at the Center for Integrative Research on Cognition, Learning, and Education at Washington University in St. Louis.

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