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Discovery Through Writing: Relationships with Writing Processes and Text Quality

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ABSTRACT

This study compares a problem-solving account of discovery through writing, which attributes discovery to strategic rhetorical planning and assumes discovery is associated with better quality text, to a dual-process account, which attributes discovery to the combined effect of 2 conflicting processes with opposing relationships to text quality. Low and high self-monitors were asked to write under 2 planning conditions. Keystroke-logging was used to assess the relationship of writing processes with discovery and text quality. The results support the dual-process account: Discovery was related to spontaneous sentence production and global revision of text, which had opposing relationships with text quality.



KEYWORDS

writing processes; discovery; learning; knowledge-constituting; problem solving; text production; keystroke

Writing involves both expressing one's ideas in written form and communicating these ideas effectively to the reader. Within psychologically informed approaches to the teaching of writing, there has been an enduring tension between approaches that emphasize the development of students' capacity for self-expression (Britton, 1982; Britton, Burgess, Martin, McLeod, & Rosen, 1975; Elbow, 1973, 1981) and approaches that emphasize the requirements of effective communication and the development of the skills needed to satisfy them (Bereiter & Scardamalia, 1987; Hayes & Flower, 1986; Petrosky & Bartholomae, 1986). Underlying this tension are contrasting conceptions of the development of thought in writing. Thus, although there is general agreement that expert writing is a process of discovery or invention (Bereiter & Scardamalia, 1987; Flower & Hayes, 1980; Galbraith, 2009), theories differ over what this process involves, and hence about how best to go about the teaching of writing.

Problem-solving accounts of writing (Bereiter & Scardamalia, 1987; Flower & Hayes, 1980) attribute discovery to controlled problem-solving processes, and assume that in learning to write well, students will also be learning how to use writing to develop their understanding of a topic. Recently, an alternative dual-process account of discovery has been developed (Galbraith, 2009), which accepts problem-solving processes as one component involved in the development of understanding, but which in addition attributes discovery to spontaneous sentence production driven by the writer's implicit understanding of the topic. In consequence, it predicts a more complex, often conflicting, relationship between text quality and the development of understanding.

Despite the ubiquity of the assumption that writing is a process of discovery, the relationship between writing processes, text quality, and the development of understanding has typically been assumed, rather than being directly tested. In this article, we first outline the two alternative accounts of how writing leads to the development of understanding and describe how we use keystroke logging to capture writing processes. We then describe the results of a study using keystroke logging to assess the interrelationships between text quality, the development of the writer's understanding, and writing processes. We conclude

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by discussing the implications of the results for the two accounts of discovery through writing and for educational practice.

Problem-solving account of discovery

The original problem-solving model of Flower and Hayes (1980) describes the different cognitive processes involved in writing and distinguishes between three basic processes: (a) planning, which involves generating content, organizing, and goal setting; (b) translating, which involves converting ideas into text; and (c) revising, which involves reading and editing previously produced text. These processes operate on material retrieved from long-term memory in interaction with the text produced so far. An important feature of this account is the recursive nature of these processes. Planning, translating, and revision can, in principle, occur at any moment during writing. The way in which these processes are combined is controlled by a monitor and different configurations of these processes are assumed to reflect different writing strategies.

Subsequent research using this framework focused on expert-novice comparisons between writers, and typically used think-aloud protocols to capture differences in associated writing processes (Flower, Shriver, Carey, Haas, & Hayes, 1992; Kaufer, Hayes, & Flower, 1986; see also Hayes, 2009, 2012 for elaborations of the original model). This research showed that experts developed more elaborate representations of the rhetorical problem, planned and revised more extensively, and produced text in larger sentence parts than novices (Hayes & Flower, 1986). Flower and Hayes suggested that these differences in the extent to which writing is directed toward rhetorical goals were responsible for expert characterizations of writing as a process of discovery. Developing and then solving rhetorical problems led to moments of insight—“Eureka, now I see it” (Flower & Hayes, 1980, p. 21)—that led to a subjective change in the writer’s understanding of the topic.

Bereiter and Scardamalia (1987) characterized this difference between novice and expert writers as a contrast between a knowledge-telling model of writing and a knowledge-transforming model of writing, summing it up as a contrast between:

a simple think-say process of composition, reflected in such previously noted tendencies as that of making the order of presentation correspond to the order of idea generation and limiting revision to cosmetic improvements. ... The expert, on the other hand, carries on a two-way process of information transfer, which results in the joint evolution of the composition and the writer’s understanding of what he or she is trying to say (Scardamalia, Bereiter, & Steinbach, 1984, p. 178).

According to Bereiter and Scardamalia (1987), knowledge-telling is equivalent to the generation and translation components of Flower and Hayes’ (1980) model and characterizes the process by which content is retrieved from long-term memory and translated into words. Whereas novice writers immediately translate content retrieved from memory, experts’ translation is more deliberately controlled and involves the generation and evaluation of content with respect to rhetorical goals before translating it into words. Thus, Flower and Hayes, (1984) suggested that rhetorical problem-solving “goes all the way down” to text production:

Experienced writers often generate alternative instantiations all the way down the line—from their definition of the rhetorical problem to framing, focus and word choice—and they test and compare options. Children, on the other hand, have difficulty considering material as optional (if you can think it, it goes in the paper). (Flower & Hayes, 1984, p. 154).

The first assumption of the problem-solving account, then, is that discovery in writing is a consequence of adapting content to rhetorical goals, and that this applies to both the global planning involved in generating ideas and to the more local planning involved in formulating ideas in rhetorically appropriate text. Knowledge-telling involves the linear production of ideas in the order that they are retrieved from memory and the spontaneous translation of these ideas into words. Knowledge-transforming, by contrast, involves modifying the order in which ideas are produced, and deliberating over how to formulate these ideas to satisfy rhetorical goals. The result is that experts develop their understanding of the topic, whereas novices do not.

The second claim of the problem-solving account is that the processes involved in writing compete for limited cognitive resources (Hayes & Flower, 1980; McCutchen, 1996; Olive, 2014; Torrance & Galbraith, 2006). In particular, the processes involved in producing well-formed text conflict with the higher-level problem-solving processes involved in developing rhetorically appropriate content (Collins & Gentner, 1980; Kellogg, 1988, 1994, 2008). This conflict can be reduced by strategically separating the reflective processes from the processes involved in formulating these ideas in well-formed text. Thus, Kellogg (1987, 1988, 1994, 2008) has consistently found that outline planning is associated with higher-quality writing than when writers write without advance planning (see also Bereiter & Scardamalia, 1987; De La Paz & Graham, 2002; Flower et al., 1992; Galbraith, Ford, Walker, & Ford, 2005; Rau & Sebrechts, 1996). Furthermore, process analysis using directed retrospection (in which writers classify their current writing process in response to tones sounded at intervals during writing) indicated that this was because it enabled writers to allocate their attentional resources more effectively. In outline planning conditions, writers focus on generating and organizing ideas before writing, and then on translating these ideas into text during writing itself. By contrast, in single-draft conditions, writers combine idea generation and organization with translation during the writing of the text (Kellogg, 1987, 1994).

Overall, then, the problem-solving account claims that knowledge-transforming, combined with advanced planning, are responsible for both higher quality text and the development of the writer's understanding. So far as text quality is concerned, there is considerable evidence that the processes identified by the problem-solving account are, indeed, associated with improved quality (Alamargot & Chanquoy, 2001; Breetvelt, van den Bergh, & Rijlaarsdam, 1996; De La Paz & Graham, 2002; Deane et al., 2008; Englert, Raphael, & Anderson, 1991; Fidalgo, Torrance, & García, 2008; Graham & Perin, 2007; Torrance, Fidalgo, & García, 2007; Van den Bergh & Rijlaarsdam, 2001). Conspicuous by its absence, however, is research into relationships with the development of the writer's understanding. Instead, it is typically assumed that when writers show evidence of problem-solving processes, they will consequently change their understanding about the topic, and that producing high-quality text necessarily involves the development of understanding. This fundamental assumption of the problem-solving account remains to be tested.

Dual-process account

The dual-process account (Galbraith, 1999, 2009; Galbraith & Baaijen, 2015) accepts the problem-solving account of the contribution of explicit thinking to discovery and text quality, but provides an alternative account of the contribution of text production. This results in a different overall conception of how discovery occurs.

The first claim is about how content is accessed during text production. As we have shown, the problem-solving models characterize this as a knowledge-telling process in which ideas are retrieved from memory, and then translated into words. By contrast, the dual-process model characterizes this as a knowledge-constituting process in which semantic content is synthesized out of subconceptual units, and ideas are gradually constructed over a series of such syntheses (Galbraith, 1999, 2009). This derives from connectionist models of knowledge representation, in which information is represented as patterns of activation across a massive number of interconnected units analogous to neurons (Rumelhart, Smolensky, McClelland, & Hinton, 1986). In such networks (we have replaced the term *schemata* used in the original with the term *ideas*), “[ideas] are not ‘things’. There is no representational object which is an [idea]. Rather, [ideas] emerge at the moment they are needed from the interaction of large numbers of much simpler elements all working in concert with one another” (Rumelhart et al., 1986, p. 20).

Knowledge is not represented as a set of explicit interconnected ideas but, rather, is represented in the strength of the connections between units. It is the passing of activation through these connections that control the construction of knowledge in context. Galbraith (1999) characterized this fixed set of connections as the writer's *disposition* toward the topic. When a stimulus is presented to such a network, the full range of subconceptual units is initially activated, and then activation is passed between the units according to the strength of the connections between the units. When this process of parallel constraint satisfaction settles, the resulting pattern of activation across the units forms the semantic content of the

message to be translated into words. However, this initial output is only a partial best fit to the writer's knowledge. A further cycle of constraint satisfaction takes place leading to a further output, which modifies and further specifies the message (Galbraith, 1999, 2009). The result is that ideas, rather than being retrieved from memory, are synthesized over a series of bursts of text production (rapidly produced sentence parts) with each successive burst being produced as a dispositional response to the preceding burst. Hence, text production that is controlled by the disposition is intrinsically a process of discovery in which ideas are constituted as the text is produced.

The second claim of the dual-process model is that content is represented in two distinct ways in long-term memory. This is derived from the complementary learning systems (CLS) theory of learning and memory (McClelland, McNaughton, & O'Reilly, 1995; Norman, 2010; O'Reilly, Bhattacharyya, Howard & Ketz, 2014; Smith & De Coster, 2000). This postulates two memory systems: an episodic system, located in the hippocampus and characterized by O'Reilly et al. (2011, p. 1229) "as a sparse, pattern-separated system for rapidly learning episodic memories;" and a semantic system, characterized "as a distributed, overlapping system for gradually integrating across episodes to extract latent semantic structure." Similar dual-process theories, in which content is either directly retrieved or is synthesized from semantic material, account for a wide range of memory retrieval phenomena (Brainerd, Wright, Reyna, & Payne, 2002). According to the dual-process account (Galbraith, 1999, 2009; Galbraith & Baaijen, 2015), the effects of explicit problem-solving and text production on discovery vary depending on which of these systems predominates. Thus, explicit problem-solving is more effective when it operates on the stable representations of individual ideas in episodic memory and is less effective when it operates on emergent ideas as they are being constituted under the control of the semantic memory system. By contrast, text production is more effective when it is controlled by the implicit organization of semantic memory—the writer's disposition—and is less effective when the synthesis of content is reduced in scope and is directed towards the realization of pre-determined ideas retrieved from episodic memory.

These two claims result in an account of discovery as the product of two processes, with different relationships to text quality, rather than a single process with a unitary effect on text quality (Galbraith, 1999, 2009; Galbraith & Baaijen, 2015). The first process is dispositionally guided text production, in which content is synthesized as if for the first time in the way described in the knowledge-constituting model. This is associated with discovery when it produces ideas different to those currently stored in episodic memory. Because this is driven by the writer's disposition, rather than rhetorical goals, it is unrelated to text quality. This is the major difference with the problem-solving account, which attributes discovery through text production to controlled text production designed to satisfy rhetorical goals, and which, therefore, claims that it is positively related to text quality. The second process involves operations on ideas already stored in episodic memory or produced during text production. When ideas are simply output in the order that they occur the result is equivalent to knowledge-telling. When ideas are evaluated and reorganized in working memory to satisfy rhetorical goals the result is the creation of a more coherent knowledge object in episodic memory which is associated with increased understanding and higher quality text. This is equivalent to the knowledge-transforming process with the crucial qualification that, because it operates on pre-existing ideas, it does not by itself lead to the creation of new content. Discovery is at a maximum when the two processes—dispositionally guided text production and explicit rhetorical planning—are combined.

Previous research related to this model (see Galbraith, 2009, for a review) has involved assessing the effect of two variables—type of planning and individual differences in self-monitoring—on the generation of new ideas during writing and subjective changes in understanding. The type of planning manipulation has involved comparing outline planning with synthetic planning and is designed to manipulate the extent to which text production is guided by explicit content retrieved from episodic memory or the implicit structure of semantic memory. Outline planning involves generating ideas and then organizing these into a plan for the text (Kellogg, 1988, 1994, 2008); synthetic planning involves generating ideas and then identifying the overall goal for the text but not creating an explicit organization for the text.

The second variable—self-monitoring—is assumed to reflect the extent to which writers direct their writing toward rhetorical or dispositional goals. According to Snyder (1974), high self-monitors use cues

from the rhetorical context to guide their expressive behavior, whereas low self-monitors' expressive behavior is driven by their internal affective states, rather than tailored to the social situation. Self-monitoring is measured using a self-report questionnaire and has been extensively researched with strong support for its effects on communicative behavior (see Snyder, 1987; Snyder & Gangestad, 1986). In particular, Klein, Snyder, and Livingston (2004) showed that high self-monitors varied the ideas that they generated when they were confronted with different audiences whereas low self-monitors generated the same ideas regardless of the audience.

The consistent finding from this research is that although low and high self-monitors change their understanding of the topic to a similar extent as a function of writing, the change is associated with differences in the conditions under which new ideas are generated. Thus, high self-monitors generate more new ideas when they make notes in preparation for an essay than when they write full text (Galbraith, 1992) and when writing is outline planned, rather than synthetically planned (Galbraith, 1999; Galbraith, Torrance, & Hallam, 2006). By contrast, low self-monitors generate more new ideas when they write full text than when they make notes (Galbraith, 1992), and when writing is synthetically planned, rather than outline planned (Galbraith, 1999; Galbraith et al., 2006). Galbraith (2009) concluded that high self-monitors generate new ideas primarily through explicit planning designed to satisfy rhetorical goals, whereas low self-monitors generate new ideas primarily through dispositionally guided text production. Because they, nevertheless, experience similar changes in understanding, change in understanding is assumed to involve both processes; with low and high self-monitors prioritizing spontaneous text production and explicit problem-solving respectively. To date, however predictions about the processes involved in the development of understanding and their relationship to text quality have not been tested.

Measuring writing processes

Writing processes have typically been studied either by means of think-aloud protocols (e.g. Bereiter & Scardamalia, 1987; Braaksma, Rijlaarsdam, Van den Bergh, & van Hout-Wolters, 2004; Hayes & Flower, 1980) or by means of self-reports where participants categorize their own behavior when responding to concurrent probes during writing (e.g. Fidalgo et al., 2008; Kellogg, 1988). One consequence of this is that this research has focused on variations in the problem-solving processes involved—particularly goal setting, idea generation, and organization—and has classified text production as an undifferentiated process of *translation*. This means that it has not been able to capture a fundamental difference between the problem-solving and dual-process accounts. Moreover, concurrent verbal protocols inevitably intrude on the writing process with the possibility of either making it a more explicit process than it otherwise would be or of disrupting the normal process of writing.

We, therefore, decided to use keystroke logging to measure writing processes. An attraction of this method is that it provides an unobtrusive record of the moment-by-moment creation of the text. Furthermore, it should allow for more detailed measurement of variations in how text production processes are carried out. In practice, however, most previous research using keystroke logging has retained the focus on higher level thinking processes. Thus, the standard method for analyzing pauses during text production has been to use a threshold to distinguish *cognitive* pauses, assumed to reflect higher level thinking, from briefer pauses, assumed to be associated with lower level translation processes. Moreover, the general strategy has been to identify specific features (cognitive pauses, revisions, linearity) and then examine where these occur in the text. We have approached this from the opposite direction (Baaijen, Galbraith, & de Glopper, 2012). Thus, we identify the boundaries at different levels within the text—within words, between words, between sentences, and between paragraphs—and then estimate the average characteristics of the pause durations and revisions at these points (see Baaijen et al., 2012). This has the important consequence that it enables us to assess variations between writers in how they manage the transitions between units at different levels of text production. In addition, rather than examine each of these measures separately, as has typically been done in previous research, we have used principal component analysis to identify composite measures corresponding to general characteristics of the way

a text has been produced. Taken together, this enabled us to examine both explicit planning processes and, crucially, variation in the way text production is carried out.

In this article, we focus on two composite measures identified by principal component analysis. The first is a global linearity measure capturing the extent to which the global text structure is produced in a linear sequence or is revised during writing. This is similar to measures that have been used in previous research (Groenendijk, Janssen, Rijlaarsdam, & Van den Bergh, 2008; Severinson Eklundh, 1994; Van Waes & Schellens, 2003), and captures variations in processes above the sentence level. Consistent with the problem-solving account linear text production is assumed to reflect knowledge-telling; nonlinear text production reflects knowledge-transforming. The second is a sentence-production measure capturing the extent to which sentence production is controlled or spontaneous. Thus, at the more controlled extreme, sentence production is preceded by longer pauses followed by more extended bursts of words. This is consistent with the problem-solving account's characterization of the process responsible for discovery as involving the deliberate planning of content to satisfy rhetorical goals. At the more spontaneous extreme, sentence production is preceded by relatively brief pauses followed by shorter bursts of words which are revised during production. This is consistent with the dual-process account's claim that the process responsible for discovery involves rapid synthesis of content followed by revision.

Aim of the experiment and research questions

Empirical research inspired by problem-solving accounts has focused on the relationship between writing processes and text quality, but has not assessed how these relate to the development of understanding. In contrast, the dual-process account has typically focused on the conditions under which writers generate new ideas but has not directly examined which processes are involved or how these are related to text quality. Our aim in this study, therefore, was to measure both text quality and the development of understanding and to assess how these are related to writing processes.

To do this, we recreated conditions similar to those used in previous research (Galbraith, 1999; Galbraith et al., 2006). Thus, we asked two groups of low and high self-monitors to write either an outline planned or a synthetically planned text. These conditions are similar to those compared in previous research with the important difference that this study required writers in all conditions to produce a well-formed text. This was designed to make quality an important goal for the writers. In addition, we asked writers to rate their understanding before and after writing.

This was designed to address four sets of research questions. First, how are the two writing processes, represented by the global linearity and sentence production measures, related to the development of understanding? Both the problem-solving account and the dual-process account predict that increases in understanding will be associated with greater revision of global structure (i.e. will be negatively correlated with global linearity). The key difference is over the form of sentence production. The problem-solving account predicts that increased understanding will be associated with more controlled sentence production. The dual-process account predicts that it will be associated with more spontaneous sentence production and will be reduced when sentence production is guided by a pre-determined plan.

Second, how are the two writing processes related to text quality? The problem-solving account predicts that both controlled sentence production and revision of global structure will be associated with higher text quality. Following Kellogg's (1987, 1994) research showing that processes are redistributed when writing is outline-planned, the problem-solving account further predicts that this relationship will be moderated by the type of planning carried out in advance of writing. The relationship between writing processes and text quality will be stronger in the synthetic planning condition where these will be required during writing to ensure quality. In the outline condition, the relationship will be weaker because these operations can, instead, be carried out during advance planning and the writing process, itself, can be reduced to translating a predetermined plan. The dual-process account shares these predictions about the relationships between writing processes and text quality.

Third, how is text quality related to the development of understanding? This is the second key difference between the two accounts. The problem-solving account assumes that the same processes are responsible for the production of effective text and the development of understanding, and therefore

predicts that text quality and the development of understanding will be positively correlated. By contrast, the dual-process account predicts that there will be no direct relationship between text quality and the development of understanding.

Finally, how are these relationships moderated by self-monitoring? Because self-monitoring is assumed to reflect the extent to which writing is directed toward rhetorical goals, both accounts predict that high self-monitors should produce higher levels of global revision and more controlled sentence production than low self-monitors. The problem-solving account predicts that, in consequence, high self-monitors should develop their understanding more, and produce higher quality text than low self-monitors. By contrast, the dual-process account predicts that there will be no overall difference in the development of understanding.

Method

Participants

Eighty-four students from the University of Groningen in the Netherlands were recruited to participate in the experiment. They were all native Dutch speakers and received €10 for their participation. Their average age was 22.2 years ($SD = 3.8$). Participants were selected from an initial sample of 160 students using Snyder's revised 18-item self-monitoring scale (Snyder & Gangestad, 1986), and were classified as *high self-monitors* ($n = 42$) if they scored between 11 and 18 on the scale and as *low self-monitors* ($n = 42$) if they obtained a score between 0 and 8 on the scale. Participants obtaining a score of 9 or 10 were not invited to take part in the experiment. This procedure followed Snyder and Gangestad's (1986) recommendation that self-monitoring should be treated as a class variable, rather than a continuous variable. The questionnaire consists of 18 *statements*, which participants respond to by indicating whether they are true or false of their own behavior, and had satisfactory reliability (Cronbach's $\alpha = .70$). An example of a statement for high self-monitors is "*In different situations and with different people, I often act like very different persons;*" and an example of a statement for low self-monitors is "*I can only argue for ideas which I already believe.*"

In practice, six participants were not included in the final analysis. Four participants were excluded because they did not complete one or more of the tasks correctly, one participant was excluded because his process data were lost due to technical problems with the keystroke logging software and, finally, one participant was excluded due to insufficient knowledge about the topic. For the analysis, we therefore have a total sample of 78 participants.

Note that data were also collected about the participants' writing beliefs (White & Bruning, 2005). The relationship of these writing beliefs with the development of understanding and text quality have been reported in a separate paper (Baaijen, Galbraith, & de Glopper, 2014). Writing beliefs were not included in the present analysis of keystrokes because this would have increased the number of independent variables beyond the limits of the statistical models.

Design and procedure

The two groups of low and high self-monitors were randomly assigned to either an outline planning or synthetic planning condition. Of the excluded participants, two participants belonged to the high self-monitoring outline planning condition, two participants belonged to the high self-monitoring synthetic planning condition, and two participants belonged to the low self-monitoring outline planning condition.

All participants were tested individually and the time for the different tasks was held constant across all experimental conditions and all participants fully utilized the time available. In all four conditions, participants were asked to plan and write an article for the university newspaper discussing whether "our growing dependence on computers and the Internet is a good development or not." Before making a synthetic or outline plan for their articles, participants were asked to list—as they came to mind—all the ideas they could think of related to the topic for 10 min. The purpose of this task was to provide

Example outline plan	Example synthetic plan
<p>leedaren van zijn mening uitte via internet. Dit is een sterke voordeel van de media bij het verspreiden van informatie.</p> <p>- De huidige situatie (Inleiding)</p> <ul style="list-style-type: none">• Internet is "alle" handvaten• Een internet: mail/belien - informatie <p>- De verandering (hoofdstuk)</p> <ul style="list-style-type: none">• Gedrukte media• Persoonlijk• Spelling <p>- De gevolgen (hoofdstuk)</p> <ul style="list-style-type: none">• Internet: openbaar• Internet: beelden• Internet: andere• (Veranderende informatie: internet (leedaren: van mening publiceren)) <p>Conclusie</p> <ul style="list-style-type: none">• Gedrukte media: bekendheid• Internet: informatie• Internet: andere	<p>afstandelijkheid in internet en de computer in onze tijd. En persoonlijk, met de media de afstandelijkheid kunnen krijgen omgaan.</p>

Figure 1. Example of an outline plan and of a synthetic plan.

all participants with time to activate content about the topic. These lists were removed before the next phase, in which participants had to either create an outline for the text or identify an overall goal for their text.

In the synthetic planning condition, participants were given 5 min to write down a single sentence summing up their overall opinion of the topic. Participants in the outline planning conditions were given 5 min to construct a structured outline of the text. These two different types of advanced planning, therefore, both involved generating ideas before writing (during the preceding listing phase) but differed in the extent to which they involved organizing ideas. Synthetic planning required writers to sum up their overall goal for the text, but not to create an overall organization of the text to be written; outline planning required writers to make an explicit organization of the text before writing. Examples of the two types of plan are shown in Figure 1.

Following this initial planning phase, participants had 30 min to write a well-structured article for the university newspaper. It was stressed that they had to produce a reasoned argument reflecting their own opinion about the matter and that they should produce a completed article in the time available. Five minutes before the end of the session participants got a warning that there were only 5 min left to complete the article. During writing, all participants were allowed to consult their written plans and keystrokes were logged with the use of Inputlog (Leijten & van Waes, 2013). Because this runs in Word environment, this allowed participants to produce their articles in a familiar environment which gave them access to all word processing functions.

Writing process measures

We assessed writing processes using two independent scales—*sentence production* and *global linearity*—identified by principal component analysis of a set of keystroke measures. These scales were selected from a range of measures identified by Baaijen et al. (2012)) and were designed to assess the two main components identified in problem-solving and dual-process accounts of writing. See Baaijen et al. (2012) for a full description of the different type of measures that can be extracted from keystroke logs, and a discussion of the procedures involved in preparing keystroke logs for analysis. Here, we briefly describe the key distinction underlying our measures and then present the individual measures that we calculated for each scale. The results of the principal component analysis showing how the individual measures contribute to each scale, and the reliability of the scales, are shown in Table 1.

Table 1. Summary of Principal Component Analysis with Varimax Rotation for 2 Factor Solution.

Variables	Rotated Factor Loadings	
	Component 1 Global Linearity	Component 2 Sentence Production
1 Sentence linearity index	.849	.200
2 Percentage of I-bursts	– .830	.087
3 Percentage of time spent on events	– .824	– .009
4 Percentage of linear transitions between sentences	.773	.075
5 Number of production cycles	– .709	– .270
6 Percentage of linear transitions between words	.601	.363
7 Percentage of bursts terminated by revision at the leading edge	.113	– .901
8 Percentage words produced in P-bursts	.362	.809
9 Percentage of >2 second pauses between words	– .072	.741
10 Text modification index	– .399	– .675
11 Mean pause duration between sentences	.181	.636
Eigenvalues	4.7	2.4
% of variance	42.47	21.40
α	.80	.79

Note that factor loadings over .5 appear in bold

The key distinction underlying these measures is between linear transitions and event transitions between units of text (words and sentences in the present analysis). *Linear* transitions consist of uninterrupted transitions to the next unit of text. *Event* transitions include other operations before the production of the next unit and included scrolling, movements, and other operations. Events can either involve operations away from the sentence currently being produced (such as movements to review and/or revise words elsewhere in the text) or they can involve operations within the current sentence (such as deletion and/or revision of text immediately preceding the current location of the cursor). This distinction between linear transitions and event transitions at different levels was the primary distinction used to break the keystroke logs into units of analysis and formed the basis for the following measures.

Sentence production. This component was based on analysis of only those portions of the text produced as part of the forward progression of text production during the initial draft. It included the following measures.

Pauses. Because event transitions do not just reflect the amount of time spent preparing the next unit, pause times were only calculated for the linear transitions between units within sentences. Such linear transitions, aggregated across the text, are assumed to reflect the time required to plan the next unit of text (Baaijen et al., 2012; Chenoweth & Hayes, 2003; Hayes, 2009). We included two pause measures that captured independent variance in the extent to which participants paused between and within sentences:

- *Mean pause duration between sentences.* This measure consisted of the mean of log-transformed pause durations between linearly produced sentences. High scores indicated greater sentence preparation time.
- *Percentage of pauses > 2 sec between words.* This measure consisted of the number of extended pauses occurring between linearly produced words, calculated as a proportion of the total number of linear transitions between words. High scores indicated the extent to which participants spent extended time planning words during sentence production.

Bursts. Text production typically consists of rapidly produced sentence parts—defined as bursts—that are intended for inclusion in the text (Chenoweth & Hayes, 2003; Hayes, 2009). These bursts differ in the extent to which they are cleanly produced (*P-bursts*) or are revised during production (*R-bursts*). *P-bursts* are defined as bursts initiated after, and terminated by, a pause of at least 2 sec. They represent a clean burst of language production, in which content is translated into language without modification (Hayes, 2009). *R-bursts* are defined as bursts that are terminated in a revision at the leading edge and represent the breakdown of language production before the planned burst has terminated (Hayes, 2009). Two burst measures were included in the sentence production scale.

- *Percentage of R-bursts.* This measure consisted of the number of bursts revised at the leading edge of the text (current location of the cursor), expressed as a percentage of the total number of bursts. High scores indicate how frequently sentences were revised during production.
- *Percentage of words produced in P-bursts.* This measure consisted of the total number of words produced in P-bursts, expressed as a percentage of the total number of words in the keystroke log. High scores indicate how cleanly bursts were produced within sentences.

Text modification. The final measure included in this scale was also a measure of how much the text was revised during production, but in contrast to the other measures, was not exclusively measured at the sentence level. It consists of the ratio of the total number of characters produced in the keystroke log divided by the total number of characters in the final text. Text modification reflects the extent to which text was deleted during its production and, therefore, is a measure of how cleanly the text was produced, but calculated at the character level across the whole text.

When combined, using the loadings shown in Table 1, these measures form a reliable scale ($\alpha = .79$). High scores on this scale reflect longer pauses between sentences combined with less within-sentence revision, which we interpret as indicating that sentence production is relatively more controlled. Low scores reflect brief pauses between and within sentences combined with more within-sentence revision which we interpret as indicating that sentence production is relatively more spontaneous.

Global linearity. The key distinction for the measures loading on this component is between *linear* and *event* transitions. Measures derived from this distinction included:

- *Percentage of linear transitions between sentences.* This is the number of linear transitions at sentence boundaries as a proportion of the total number of sentence transitions. It reflects the extent to which sentence production is interrupted by other operations before the continuation of text production.
- *Percentage of linear transitions between words.* This is the number of linear transitions between words as a proportion of the total number of word transitions. Although this is a within-sentence measure, it was included here because interruptions to word production included movements across sentence boundaries to carry out operations earlier in the text.
- *Number of production cycles.* This measure was calculated with bursts as the unit of analysis and controlled for the number of words in the keystroke logs. A production cycle was defined as a sequence of language bursts produced without interruption, with each break away from the leading edge defined as the start of a new cycle. High scores indicated that the text was produced in a high number of cycles, and hence nonlinearly; low scores indicated that the text was produced in a few linearly produced cycles.
- *Percentage of time spent on events.* This was calculated as the percentage of the total time spent writing that was devoted to operations other than producing text or planning the next unit of text. Thus, writers who only briefly reread earlier sections of text, or who made minor modifications to earlier sections of the text would have low scores, whereas writers who spent longer reading earlier sections, or who made more substantial modifications or insertions earlier in the text, would have high scores.
- *Percentage of I-bursts.* This measure consisted of the number of bursts inserted within already written text, expressed as a percentage of the total number of bursts. It indicates the relative amount of text produced away from the leading edge compared to the amount produced during forward text production (P-bursts and R-bursts).

Finally, we also calculated a measure of the extent to which sentences were reordered during text production.

- *Sentence linearity index.* This measure was based on a comparison of the order of sentences in the final product with the order that they were produced during the process. It was calculated as the proportion of the sentences in the final product that were produced in the same order as in the keystroke log. High scores indicated that the sentences in the final text were produced linearly one after the other during writing; low scores indicated that sentences in the final text were nonlinearly produced during writing. It differs from the measure of linear transitions between sentences, in that it quantifies the extent to which sentences are created out of order, rather than just the extent to which forward sentence production is interrupted.

When combined, using the loadings shown in Table 1, these measures form a reliable scale ($\alpha = .80$). High scores on this component represent linearly produced texts; low scores represent non-linear text production and hence more revision of the global structure of the text.

Principal component analysis. This set of measures had a Kaiser-Meyer-Olkin sampling adequacy of .73 and Bartlett's test of sphericity was significant, ($\chi^2_{(55)} = 547.06, p < .001$), indicating that principal component analysis is appropriate for these data. Principal component analysis, using varimax rotation, confirmed that the measures formed two orthogonal components. Table 1 shows the loadings of each variable on each component after rotation, the amount of variance that each component accounts for, and Cronbach's alpha for the two components.

Development of understanding

Based on the procedure used in previous research (Galbraith, 2009), we assessed the development of understanding by asking participants to rate their understanding about the topic both immediately before and immediately after writing. This involved a simple subjective measure in which participants were asked to indicate how much they felt they knew about the topic on a 7-point scale, where 1 = *very little* and 7 = *a great deal*. The differences between their ratings before and after writing were taken as a measure of change in understanding as a consequence of writing. To control for variations in the degree of change as a function of initial understanding, initial ratings were entered as a covariate in statistical models.

Text quality

The quality of the texts was rated holistically by two independent judges on a 9-point scale based on a selection of criteria. Both raters were experienced writing tutors. The principal investigator—who was one of the raters—trained the second rater on 10 texts to familiarize them with the different criteria. These criteria consisted of: the coherence of the overall argument, the originality of the article, and the appropriateness of the tone of the article. The raters were instructed to focus on higher-order concerns, such as how fluently the text was expressed and whether the article showed evidence of thinking about the topic and discussing issues rather than just listing facts and features of the topic.

For the quality rating, we used the following procedure. Independently of each other, both raters read all essays to get a general impression about the range of features to look out for in the essays. Next, all essays were read again, but now they were sorted into three sets of *good*, *medium*, and *poor* text quality. Then, all sets were read again to subdivide them into three further subsets. This resulted in each essay receiving a score on a 9-point scale. Raters could move texts between any of the sets if they changed their minds. The two raters were encouraged to use the full 9-point scale and to use as much time as necessary to judge all essays as accurately and fairly as possible. Interrater reliability for this measure proved to be satisfactory ($r = .84, p < .001$). After computing the interrater reliability, the raters discussed all essays that were rated with a different score. The mean score was taken for essays that were less than two points away from each other. Essays with scores further apart than two points were thoroughly discussed until consensus was reached. This involved two texts of the total set of 84 texts.

Analysis

We used multiple regression to assess the effects of the independent variables on the dependent variables. To facilitate interpretation of interactions, all continuous variables were mean centered prior to analysis. For each analysis, we entered the variables in sets. Main effects were entered at step 1, two-way interactions at step 2, and three-way interactions at step 3. We then simplified the regression models by progressively removing nonsignificant terms, starting with the highest-level interactions. The final simplified models for each analysis are presented.

For the analyses where there were significant interactions, we carried out simple slopes analysis using the SPSS package PROCESS created by Hayes (2013). The interactions are plotted with high and low

Table 2. Means, Standard Deviations, Skew and Kurtosis and Correlations for all Variables.

	M	SD	Skew ^c	Kurtosis ^c	Correlations					
					1	2	3	4	5	6
1. Self-monitoring ^a										
2. Type of planning ^b					.03					
3. Initial subjective understanding	4.62	0.81	− 0.08	− 0.43	− .23*	.03				
4. Global linearity	0.00	1.00	− 0.46	0.09	.08	.06	.10			
5. Sentence production	0.00	1.00	− 0.09	− 0.10	.09	.07	− .06	.00		
6. Change in understanding(Arctan)	0.15	0.47	− 0.11	0.45	− .17	− .19	− .35**	− .24*	.01	
7. Text quality	5.17	1.94	− 0.05	− 0.76	.11	.14	.03	.19	.21	− .10

Note. $N = 78$, * $p < .05$, ** $p < .01$, (2 tailed).

^aDummy coded, low self-monitoring = 0, high self-monitoring = 1.

^bDummy coded, synthetic planning = 0, outline planning = 1.

^cStandard error for skew = 0.27; standard error for kurtosis = 0.54.

levels of continuous variables, defined as 1 standard deviation above or below the mean (Aiken & West, 1991). The significance of simple slopes was also estimated at these points.

We checked all models for compliance with assumptions of normally distributed and homoscedastic residuals. In addition, we checked for influential cases using centered leverage, Cook's distance, standardized DfBeta, and covariance ratios. Distributions were satisfactory, and the proportion of relatively extreme cases was within the bounds to be expected for the sample size. However, we did identify one highly influential case in the model for change in understanding. The results for the initial analysis included a significant three-way interaction ($b = -0.56$, $se = 0.23$, $p = .02$). However, influence analysis showed that this was entirely a consequence of a single multivariate outlier (Mahalanobis distance, $\chi^2_{(12)} = 40.02$, $p < .001$), a high self-monitor in the synthetic planning condition who produced a relatively low global linearity score and who rated their understanding as having decreased after writing. When this case was removed from the analysis, the three-way interaction was no longer significant ($b = -0.19$, $se = 0.30$, $p = .54$). Because the three-way interaction was entirely a consequence of the outlier, and the models were otherwise equivalent, we deleted this case from these analyses.

Results

The results are presented in three sections. First, we present the descriptive statistics, showing the bivariate correlations between the variables, and assessing how these correspond with our initial predictions. In the second section, we assess the relationships between the predictor variables and the development of understanding. Finally, we assess the combined effects of the predictor variables on text quality, and how adding text quality as a predictor affects the relationships between writing processes and the development of understanding.

Bivariate relationships between writing processes and outcome measures

Table 2 shows the descriptive statistics for, and correlations between, all variables. As indicated by the skew and kurtosis statistics shown in the table, all the continuous variables satisfied the assumptions of normality.¹

Inspection of the correlations indicated that the bivariate relationships between the variables were generally weak and nonsignificant. Of these, three features are worth noting.

¹ The one initial exception to this was the change in understanding variable. Scrutiny of the distribution of scores for this variable indicated that, although it was relatively symmetrical (skew = -0.26 , $se = 0.27$), it had significant positive kurtosis ($kurtosis = 2.23$, $se = 0.54$, $z = 4.14$, $p < .001$). Application of an arctan transformation reduced kurtosis to a satisfactory level (see Table 3), and the transformed variable was subsequently used in all analyses.

First, there were no significant relationships between either self-monitoring or type of planning and the two process measures. This indicates that neither of these variables had a direct effect on the extent to which the two writing processes were carried out.

Second, there was a significant negative correlation between global linearity and the development of understanding ($r = -.24, p = .04$), indicating that revision of global structure was associated with increased understanding. This is consistent with the predictions of both the problem-solving and dual-process accounts.

Third, there was a general contrast in how the independent variables were related to the development of understanding and text quality. Tests of these differences, however, varied in whether they were significant. Thus, high self-monitors showed lower levels of development of understanding but higher levels of text quality than low self-monitors (n.s., $z = 1.73, p = .08$). Outline planning was associated with less development of understanding but with higher text quality ($z = 2.04, p = .04$). Global linearity was associated with less development of understanding but with higher text quality ($z = 2.68, p = .01$). Controlled sentence production had similar, nonsignificant relationships with both development of understanding and text quality (n.s., $z = 1.24, p = .21$). This pattern of differences indicates that outline planning and revision of global structure had different effects on the development of understanding and text quality.

Finally, note also that participants' initial ratings of their understanding were negatively correlated with self-monitoring and with change in understanding. These relationships were, therefore, controlled as covariates in all the regression models reported below.

Relationships between writing processes and changes in subjective understanding

This analysis addressed the question of how the two processes were related to changes in understanding. It tested whether revision of global structure was associated with increased understanding, and the key question of whether increases in understanding were associated with controlled sentence production, as predicted by the problem-solving account, or synthetically planned, spontaneous sentence production, as predicted by the dual-process account. To do this, we regressed change in understanding on self-monitoring, type of planning, sentence production, and global linearity, controlling for initial ratings of understanding and including the interactions between these variables. The final model for this analysis is shown as model 1 in Table 3.

This analysis showed that two predictors made significant, independent contributions to the development of understanding. First, there was a significant negative relationship between global linearity and change in understanding.

Table 3. Predicting Development of Subjective Understanding from Type of Planning, Sentence Production, Global Linearity (Model 1) and Text Quality (Model 2)

	Model 1			Model 2		
	B	SE	β	B	SE	β
Constant	0.27	0.07		0.27	0.06	
Initial Subjective Understanding (ISU)	− 0.16	0.06	− .28**	− 0.20	0.06	− .36**
Type of planning (Condition)	− 0.20	0.09	− .22*	− 0.22	0.09	− .24*
Global linearity (GL)	− 0.10	0.05	− .22*	− 0.06	0.07	− .12
Sentence production (SP)	− 0.12	0.07	− .27	− 0.20	0.07	− .41**
Condition * SP	0.24	0.09	.37*	0.33	0.09	.52**
Text Quality				0.06	0.04	.26
ISU * Text Quality				0.08	0.03	.27**
Condition * GL				− 0.07	0.09	− .11
GL * Text Quality				− 0.06	0.03	− .26
Condition * Text Quality				− 0.12	0.05	− .37*
Condition * Text Quality * GL				0.10	0.04	.35*

Model 1: $R^2 = 0.29$, Adjusted $R^2 = 0.24$, $F(5, 71) = 5.90, p < .001$, * $p < .05$ ** $p < .01$.

Model 2: $R^2 = 0.45$, Adjusted $R^2 = 0.36$, $F(11, 65) = 4.80, p < .001$, * $p < .05$ ** $p < .01$.

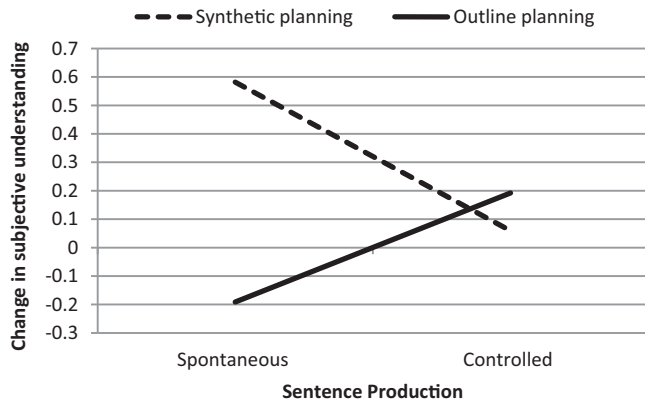


Figure 2. Relationship between sentence production and change in understanding as a function of type of planning.

Second, there was also a significant two-way interaction between type of planning and sentence production, indicating that the relationship between sentence production and change in understanding varied depending on type of planning. This interaction is plotted in Figure 2.

As can be seen in Figure 2, the interaction reflects the fact that, within the synthetic planning condition, increases in understanding were associated with spontaneous, rather than controlled, sentence production ($b = -0.19$, $se = 0.07$, $t(65) = 2.80$, $p = .007$). By contrast, in the outline planning condition, increases in understanding were generally low, and the relationship was in the opposite direction, with spontaneous sentence production now associated with decreases in understanding ($b = 0.14$, $se = 0.06$, $t(65) = 2.28$, $p = .03$). Thus, controlled sentence production was generally unrelated with changes in understanding, and was unaffected by whether writing was synthetically or outline planned ($b = 0.11$, $se = 0.13$, $t(65) = 0.90$, $p = .37$). By contrast, the effect of spontaneous sentence production depended crucially on whether writing was synthetically or outline planned ($b = -0.55$, $se = 0.13$, $t(65) = 4.29$, $p < .001$).

Relationship between writing processes and text quality. This analysis was designed to answer two questions about the relationships between writing processes and text quality. First, are controlled sentence production and revision of global structure associated with the production of higher-quality text, as predicted by both the dual-process and problem-solving accounts? Second, are these relationships moderated by the type of planning carried out before writing and individual differences in self-monitoring? To test these hypotheses, we regressed text quality on self-monitoring, type of planning, sentence production and global linearity, along with the associated interactions. The final model is shown in Table 4.

Table 4 shows two significant effects: (a) a three-way interaction between type of planning, global linearity, and sentence production, indicating that the relationship between writing processes and text

Table 4. Text Quality Predicted by Self-monitoring, Sentence Production and Global Linearity

	B	SE	β
Constant	4.79	0.35	
Self-monitoring (SM)	0.31	0.41	.08
Type of planning	0.48	0.41	.13
Global linearity (GL)	− 0.21	0.33	− .11
Sentence production (SP)	0.46	0.30	.24
Global linearity * SP	− 1.19	0.36	− .48**
Self-monitoring * GL	0.95	0.45	.29*
Type of planning * GL	0.26	0.44	.10
Type of planning * SP	− 0.14	0.41	− .05
Type of planning * GL * SP	1.06	0.53	.28*

$R^2 = .27$, Adjusted $R^2 = .17$, $F(9, 68) = 2.75$, $p = .008$. * $p < .05$, ** $p < .01$.

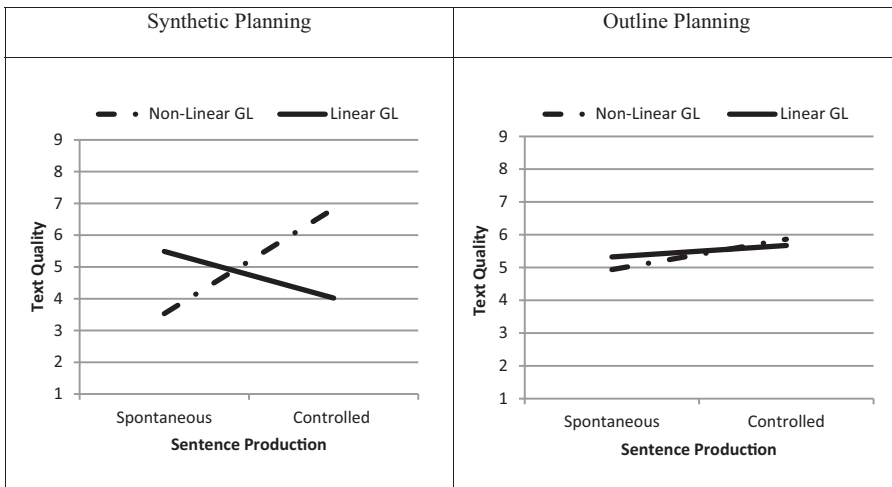


Figure 3. Relationship between sentence production and text quality as a function of global linearity and type of planning.

quality was moderated by the type of planning carried out in advance of writing; and (b) a two-way interaction between self-monitoring and global linearity, indicating that the effect of global linearity was moderated by individual differences in self-monitoring. All other significant terms in the model contributed to these two effects. The nature of these interactions is explored in the following. Figure 3 shows the relationships between writing processes and text quality separately for the two planning conditions.

Consider the outline planning condition first. Here, although the relationships with text quality were positive for both controlled sentence production ($b = 0.32$, $se = 0.28$, $t(68) = 1.14$, $p = .26$) and global linearity ($b = 0.05$, $se = 0.35$, $t(68) = 0.14$, $p = .89$), neither of these relationships was statistically significant. By contrast, in the synthetic planning condition, there was clear evidence of a positive relationship between controlled sentence production and text quality. However, this was moderated by global linearity (a significant interaction between sentence production and global linearity, $b = -1.19$, $se = 0.36$, $t(68) = -3.26$, $p = .002$). Thus, when writing was nonlinearly produced, text quality was strongly related to controlled sentence production ($b = 1.65$, $se = 0.47$, $t(68) = 3.48$, $p = .009$). By contrast, when writing was linearly produced, there was no relationship between sentence production and text quality ($b = -0.73$, $se = 0.46$, $t(68) = 1.59$, $p = .12$). This pattern of results indicates that, when writing is not organized in advance, the production of high quality text requires that the writer both revises the global structure of the text during writing, and carefully controls the production of individual sentences.

The two-way interaction between self-monitoring and global linearity is plotted in Figure 4. As can be seen in Figure 4, this interaction reflects the fact that high self-monitors produced better texts than low self-monitors when they wrote linearly ($b = 1.26$, $se = 0.59$, $t(68) = 2.14$, $p = .03$), but not when texts were nonlinearly produced ($b = -0.65$, $se = 0.64$, $t(68) = 1.01$, $p = .32$). This suggests that high self-monitors were better able to manage mental planning of text than the low self-monitors.

Relationship between text quality and the development of understanding

The final analysis was designed to address the question of how text quality relates to the development of understanding. The problem solving-account's prediction that text quality should be correlated with increased understanding has already been disconfirmed by the nonsignificant, negative correlation between text quality and the development of understanding (see Table 3), and the contrasting results for text quality and the development of understanding (see preceding two sections). This analysis was, therefore, designed to address the more specific question of whether the relationship between text quality and the development of understanding varied as a function of the two writing processes and type of planning and self-monitoring. To do this, we added text quality and associated interactions into the regression model for change in understanding (see model 2 in Table 3).

Comparing Model 2 with Model 1 in Table 3 shows that adding text quality to the model increases the amount of variance accounted for in the development of understanding by 16%, indicating that text quality does account for some of the variation in the development of understanding. Three factors account for this increase in variance.

First, the interaction between type of planning and sentence production, which represents the effect of synthetically planned, spontaneous sentence production, remains significant, and makes a larger contribution to increased understanding ($\beta = .52$ in model 2 compared to $\beta = .37$ in model 1; a 6% increase in variance) when text quality is included. This is a consequence of the negative relationship between synthetically planned, spontaneous sentence production and text quality (see Table 4) and indicates that this form of sentence production makes a larger contribution to the development of understanding precisely to the extent that it is associated with a decrease in text quality.

Second, the negative relationship between global linearity and the development of understanding is reduced, and no longer significant in Model 2. Instead, there is a significant three-way interaction between type of planning, global linearity, and text quality indicating that the relationship between text quality and the development of understanding varied depending on the global linearity and type of planning. This interaction is plotted in Figure 5, with the relationships plotted separately for synthetic and outline planning conditions.

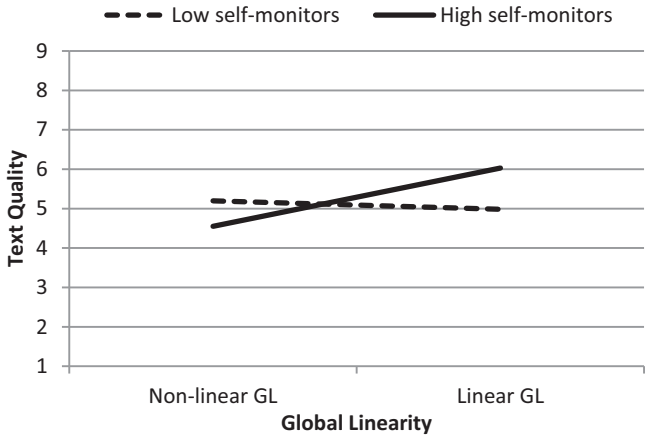


Figure 4. Relationship between global linearity and text quality as a function of self-monitoring.

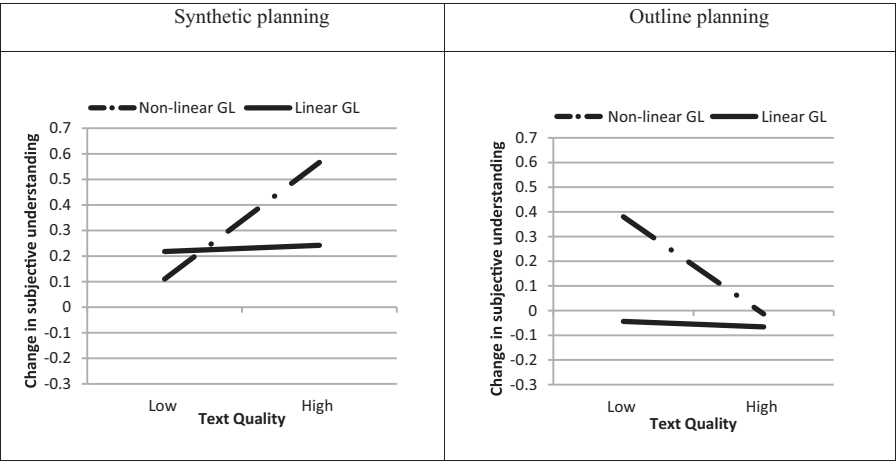


Figure 5. Relationship between text quality and change in subjective understanding as a function of global linearity and type of planning.

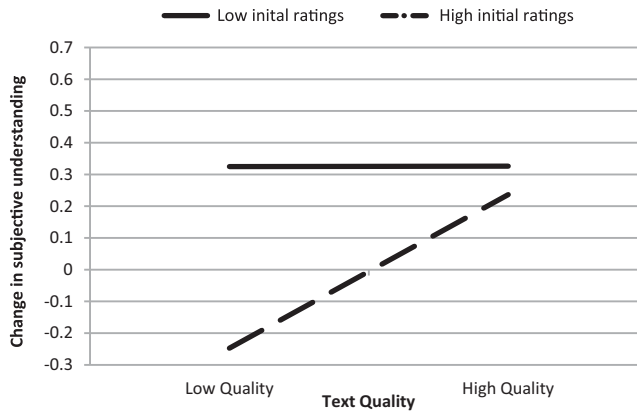


Figure 6. Relationship between text quality and change in subjective understanding as a function of initial ratings of subjective understanding.

As can be seen in Figure 5, the three-way interaction reflects the fact that the relationships between text quality and change in understanding varied depending on the type of planning that had been carried out, and on the extent to which the global structure of the texts was revised during writing (low global linearity). Thus, although increases in understanding were greater when the global structure of text was revised (the dashed lines in Figure 5) than for linearly produced texts (the solid lines) for both types of planning, the relationship with text quality was in opposite directions (a significant interaction between text quality and type of planning for the nonlinear texts ($b = -0.22$, $se = 0.06$, $t(65) = 3.37$, $p = .001$). For the synthetic planning condition, globally revised texts showed a positive relationship between text quality and the development of understanding ($b = 0.12$, $se = 0.05$, $t(65) = 2.58$, $p = .01$); for the outline planned condition, these texts showed a negative relationship ($b = -0.10$, $se = 0.05$, $t(65) = 2.19$, $p = .03$).

Finally, the third contribution to the model was a significant two-way interaction between initial rating of understanding and text quality. As can be seen in Figure 6, this interaction reflects the fact that text quality was positively related to increased understanding for writers with higher levels of initial understanding ($b = -0.12$, $se = 0.05$, $t(65) = 2.51$, $p = .02$), but unrelated to increased understanding for writers with lower levels of initial understanding ($b = 0.00$, $se = 0.04$, $t(65) = 0.01$, $p = .99$). It is important to note here that the writers with higher initial understanding generally increased their understanding less than those with lower initial understanding, and that the relationship for writers with high initial understanding is a symmetrical one, with lower-quality text being associated with decreased understanding and higher-quality text associated with increased understanding. This result partially supports the problem-solving account but suggests that the positive relationship between text quality and increased understanding is restricted to writers with relatively high initial understanding.

Discussion

This study was designed to evaluate two contrasting accounts of discovery through writing. The essential claim of the problem-solving account (Bereiter & Scardamalia, 1987; Hayes & Flower, 1980) is epitomized in its characterization of expert writing as a knowledge-transforming process and claims that discovery is a consequence of the writer adapting their ideas to produce a more rhetorically effective text. By contrast, the dual-process account (Galbraith, 2009) claims that discovery is the joint product of two different processes—synthetically planned, spontaneous text production, and revision of global structure—which have different effects on text quality. This study is the first, to our knowledge, to directly investigate the processes associated with the development of writers' subjective understanding and to explicitly assess how these are associated with the quality of the text.

The results support the dual-process model. First, the fact that increased understanding was associated both with greater revision of global structure and with synthetically planned, spontaneous sentence production supports its claim that the development of understanding involves two independent components: (a) the development of new content in the course of sentence production, and (b) the reorganization of the writer's mental model of the global structure of ideas (Galbraith, 2009). Second, contrary to the problem-solving account's predictions, neither of these components had direct relationships with text quality. The sentence production component was associated with poorer-quality text and the relationship for the global revision component varied depending on the type of planning carried out before writing. In particular, global revision was negatively associated with high quality text in the outline planning condition. Taken together, these findings support the main predictions of the dual-process model. They also call into question the predictions of the problem-solving account about the processes responsible for discovery through writing and about the relationship between text quality and discovery.

In what follows, we first discuss these two main findings. We then discuss the validity of our interpretations of the measures of writing processes and the development of understanding, suggesting how they could be tested in future research. We conclude by discussing some of the educational implications of the research.

Relationships between writing processes and the development of understanding

Previous research has not explicitly tested how writing processes are related to the development of understanding. Rather, it has typically simply assumed that revision of text or changes of mind apparent in think-aloud protocols are equivalent to the development of understanding (see, for example, Scardamalia et al., 1984). Furthermore, because the methods used have typically involved a relatively high-level classification of events during concurrent or retrospective protocols (e.g. Braaksma et al., 2004; Kellogg, 1988), different forms of sentence production have been uniformly classified as *translation*. The first novel feature of our findings, therefore, is to establish reliable relationships between different components of the writing process and writer's subjective ratings of their understanding.

The first relationship was with the reorganization of global structure. This is consistent with Bereiter and Scardamalia's (1987) distinction between knowledge-telling and knowledge-transforming. It also provides empirical support for Scardamalia et al. (1984, p. 178) claim that revision "results in the joint evolution of the composition and the writer's understanding of what he or she is trying to say." Thus, relatively linear writing can be equated with the unproblematic translation of ideas into text (knowledge-telling) and nonlinear writing with modification of ideas to resolve rhetorical problems as they occur during text production (knowledge-transforming). It is important to note here, however, that when text quality was included in the regression model the strength of the relationship between global revision and development of understanding varied depending on text quality. We discuss possible explanations for this complex interaction in the next section when we consider how this form of change in understanding is related to text quality.

This relationship with global revision is consistent with both the dual-process and the problem-solving accounts. The key difference between the two accounts, however, lies in the form of text production that is associated with the development of understanding. These results suggest that the development of understanding is associated with synthetically planned spontaneous sentence production as predicted by the dual-process model, rather than the controlled sentence production predicted by the problem-solving account. An important feature of this finding was that spontaneous sentence production was associated with diametrically opposite effects, depending on whether writing was outline planned or not. This suggests that the effect depends not just on how sentences are produced, but also on the form in which the content that serves as the input to sentence production is represented. We argue that this reflects a contrast between knowledge-telling and knowledge-constituting. In the outline planning condition, text production is a matter of translating predetermined ideas into text, and is essentially a process of knowledge-telling, without any developments in the writer's understanding. By contrast, in the synthetic planning condition, where only the overall goal for the text is specified in advance, and not the sequence of ideas to be produced, sentence production is guided by the implicit organization of

content in semantic memory and hence becomes a knowledge-constituting process (Galbraith, 2009). These findings indicate that this specific form of text production is, indeed, strongly associated with the development of understanding, in contrast with other forms of text production.

Overall, this component of the analysis provides empirical support for the general assumption of previous research that global revision is associated with the development of the writer's understanding, but also suggests that a specific form of sentence production with the characteristics predicted by the dual-process model also makes a major contribution. The fact that these two components made independent contributions to the development of understanding indicates that they can take place separately. However, development of understanding is maximized when the writer both formulates their ideas in synthetically planned text and revises the global structure of their ideas into a coherent mental model. Although these findings are consistent with the predictions of the dual-process model, further research is needed to establish what underlying processes are involved in the two components of the development of understanding that we have identified and to test whether they have the characteristics specified by the dual-process model.

Text quality and its relationship with the development of understanding

Our next two research questions were about how the two processes are associated with text quality, and about how text quality and the development of understanding are related.

When we ignored the extent to which writers developed their understanding and simply assessed the direct relationships between writing processes and text quality, the results were as would be expected by the problem-solving account and are consistent with previous research investigating effects on text quality. Thus, in line with Kellogg's research (1994), the relationships between writing processes and text quality varied depending on the type of planning carried out in advance of writing. This is consistent with Kellogg's finding that outline planning leads to a redistribution of processes, in which the selection and organization of content is carried out in advance of, rather than during, the writing of the text itself. Hence, the fact that there were no significant relationships between writing processes and text quality within the outline condition is presumably because the relevant processes have been carried out in advance of writing, and text production itself is reduced to the translation of a predetermined plan into text. By contrast, in the synthetic planning condition, where writers have to carry out the relevant processes during, rather than in advance of, writing, higher text quality was, indeed, associated with greater revision of global structure and more controlled sentence production, just as the problem-solving account would predict.

Previous research has not explicitly assessed the extent to which writers experience a development of understanding through writing. It has simply been assumed that discovery is a consequence of adapting content to rhetorical goals, and hence that there will be a positive relationship between text quality and the development of understanding. Our inclusion of an explicit measure of the development of understanding revealed that there is no such straightforward relationship. Instead, there was a complex interaction involving different relationships for sentence production and global linearity, which were in turn moderated by the type of planning carried out in advance of writing. The results indicate that this complex relationship involves three factors.

First, the process primarily responsible for the development of understanding—synthetically planned, spontaneous sentence production—was associated with poorer quality text. This directly contradicts the problem-solving account's claim for a positive relationship between discovery and text quality. According to the dual-process account, this is because this is driven by the writer's implicit understanding and is directed toward constituting the writer's understanding burst by burst as it emerges in the text, rather than to satisfy rhetorical goals. This is an intrinsic conflict: to clarify their understanding the writer has to follow the path of their thought in the text as it unfolds; but in so doing they are unable to control text production to ensure that the idea is communicated clearly to the reader. Any relationship with text quality is incidental.

Second, although there was a positive relationship between text quality and the development of understanding for revision of global structure, this was restricted to the synthetic planning condition

and was, in fact, in the opposite direction in the outline planning condition. The positive relationship within the synthetic planning condition is consistent with the claim, common to the dual-process and problem-solving accounts, that in modifying the global structure of ideas to make the text more rhetorically effective the writer also develops their understanding. The fact, however, that the relationship was negative for the outline planned condition directly contradicts the problem-solving account: Writers produce high quality text precisely to the extent that they do not develop their understanding, and, conversely, when they do increase their understanding it is at the expense of producing high quality text.

One possible explanation for this is that when structure is established in advance of writing, then revision is more reactive in form (Galbraith & Torrance, 2004) and is designed to revise the text to ensure that it corresponds with the original plan. When this is carried out successfully, it is associated with an improvement in the quality of the text, but, as we found here, does not lead to change in the writer's understanding. However, when the writer is unable to maintain their original plan and has to revise the global structure of the text their understanding changes at the expense of maintaining coherent organization. By contrast, in the synthetic planning condition where structure is not imposed in advance, then revision is more proactive in form (Galbraith & Torrance, 2004) and involves constructing a structure compatible with the writer's understanding as it emerges during sentence production. When this is successful the quality of the text is improved, and the writer's understanding is further enhanced. When it is unsuccessful, the writer's understanding is not enhanced and text is of poorer quality. Further research is needed, perhaps using think-aloud protocols, to identify the processes involved here and to test whether goals are, indeed, coordinated in different ways in the synthetic and outline planning conditions.

The final contribution to this relationship was the relatively small positive relationship between text quality and the development of understanding for writers whose initial understanding was already high. Because this was independent of both the different writing processes and of type of planning, the relationship provides support for the problem-solving account's claim for a general relationship between text quality and the development of understanding. It suggests that when the writer already has well-developed understanding of the topic, operations designed to increase the rhetorical effectiveness of the text also clarify the writer's understanding.

Individual differences

Our final research question was about whether individual differences in self-monitoring affected the extent to which writers engaged in the two writing processes or their effects on outcomes. There was little evidence of this. At first sight, this contradicts the research reviewed by Galbraith (2009), which has showed consistent effects of self-monitoring on the generation of ideas during writing. There is, however, an important difference between this experiment and previous studies. These have typically examined idea generation within more extended episodes of less structured planning (Galbraith, 1992). In the experiment most similar in design to this study (Galbraith et al., 2006), the study design imposed weaker rhetorical constraints on text production. The more controlled design of our experiment may have reduced the opportunity for low and high self-monitors to choose how they combined processes and hence have reduced the effects of self-monitoring.

The one exception to this lack of effect of self-monitoring was the finding that high self-monitors produced higher quality text than the low self-monitors when they wrote linearly. This implies that high self-monitors produced better texts when they worked out the global structure of the text before writing out the text itself and were less effective when they revised the global structure of the text in the course of writing. Although this is consistent with a difference in how low and high self-monitors combine the component processes of writing, the lack of other significant effects makes it difficult to draw firm conclusions. There is a need for further research, across a wider range of writing conditions and using larger samples, to establish whether self-monitoring affects how the writing processes are carried out and combined, and how this is related to effects on idea generation.

Limitations

We have argued that the principal advantage of using keystroke analysis over think-aloud protocols is that it enables one to analyze variations in how sentence production is carried out, and as we have seen this has been productive in identifying contrasts in the effects of writing on the development of understanding and text quality. However, by themselves, keystroke measures do not provide direct information about the processes involved (see Baaijen et al., 2012; Galbraith & Baaijen, *in press*). This study provides indications about where relevant processes are likely to occur and a set of hypotheses about what these involve, but does not provide direct evidence about the underlying cognitive processes. To test these hypotheses, future research, using a similar design, needs to combine keystroke logging with other methods. For example, verbal protocols could be used to elucidate differences between outline and synthetic planning, to examine the nature of the revisions made during sentence production, and to examine the goals guiding revision of global structure under different planning conditions. Such think-aloud measures would be less useful for testing hypotheses about the nature of the processes taking place during the pauses preceding sentence production. However, these are also empirically testable. The dual-process model claims that these reflect a contrast between the synthesis of ideas controlled by semantic memory and the retrieval of pre-existing ideas from episodic memory. This hypothesis could be tested by asking participants to produce sentences following either synthetic or outline planning and examining whether semantic memory (located in the neocortex) and episodic memory (located in the hippocampus) are differentially activated in the two conditions.

A second limitation is that the measure of the writer's subjective understanding of the topic is based on a single rating before and after writing. It is important to note, first, that this is necessarily a subjective rating insofar as the claims of the two models are about the changing state of the writer's experience and it is this which is assumed to influence the writer's decisions during writing. Furthermore, the measure behaved systematically and in theoretically meaningful ways in response to the experimental manipulations. That said, there is clearly an important question about what cognitive properties this measure represents. According to the dual-process model, subjective ratings of understanding reflect a combination of the availability of ideas in the writer's long-term memory and the coherence of their organization. The validity of this assumption is supported by previous research showing that increased ratings of understanding correlate strongly ($r \sim .70$), under specific conditions, with the number of new ideas that writers generate after writing (Galbraith, 1992, 1996, 1999). Galbraith et al. (2006) also found, using ratings of the similarity between ideas, systematic effects of different types of writing on the coherence of ideas. In particular, in outline planning conditions, the production of new ideas was negatively correlated with the coherence of ideas, suggesting a similar conflict to that found in the outline planning condition of this study. This suggests that an important next step for research is to combine the process measures used in this study with the idea generation and coherence measures used in previous research to establish how changes in ideas produced by different processes are related to changes in the writer's subjective understanding. Furthermore, given that our results have suggested that there is a dynamic interaction between processes during writing, it would be interesting to investigate how these relationships vary over the course of text production rather than relying on aggregated measures as we have done in this study.

A third limitation is that these results are based on writing about a single topic under specific rhetorical constraints. Clearly, the generality of the findings across topics and contexts needs to be established. A particularly important question here is whether the findings generalize to handwritten, rather than keyboarded, texts. There are a number of differences between keyboarding and handwriting (Van Waes & Schellens, 2003)—principally a tendency for more preplanning and postdraft revision in handwriting than keyboarding—which would be expected to affect how process measures relate to the development of understanding and text quality. Our expectation is that although these relationships may vary, they will be interpretable in terms of the interactions between the controlled problems-solving processes and the spontaneous sentence production processes that we have observed here.

Educational Implications

Current strategy-based approaches to the teaching of writing are directly based on problem-solving models of writing and there is good evidence that they are effective so far as quality is concerned (e.g., Graham & Perin, 2007). Our results for the text quality measure are consistent with these findings. However, our findings also suggest that outline planning reduces the development of understanding during text production and is associated with a conflict during revision that disrupts text quality. The problem is that, because of the assumption that effective writing is intrinsically a knowledge-transforming process, effects on the writer's understanding have not been assessed in past research. Given that development of understanding may be related to motivation to write and that it may lead to conflicts in writing, particularly during revision, it is important that assessment of the effectiveness of such strategies should include an assessment of effects on the development of understanding.

The results also indicate a potential solution to the conflict between discovery and text quality that occurs when writing is outline planned. This would involve an alternative drafting strategy similar to the kind of revision strategy advocated by Elbow (1973, 1981) and others. In such a strategy, planning would still involve generating ideas and establishing one's overall goal for the text, but would not involve creating a global structure for the text. Text production during the initial draft would be relatively spontaneous and designed to capture the writer's implicit understanding of their ideas, rather than focusing on reader comprehension. Revision would focus initially on identifying the global structure of the ideas constituted in the initial draft and then on revising the text into a rhetorically effective form.

If spontaneous sentence production is an important component of the development of understanding, then it is important to develop student's ability to express themselves fluently in writing. Meta-analyses have suggested that sentence-combining may be an effective way of developing this (Andrews et al., 2006; Graham & Perin, 2007) and recent research has provided good evidence that embedded grammar teaching has positive effects on student writing (Jones, Myhill, & Bailey, 2013; Myhill, Jones, Lines, & Watson, 2012). A key question here is whether this form of instruction also has a positive effect on the development of students' understanding during writing.

Finally, the assumption by problem-solving models that the development of understanding is driven by rhetorical goals implies that in learning to write well, students will also develop their understanding. Our results suggest, however, that learning to write is not necessarily the same thing as writing to learn. It is noticeable, therefore, that a productive line of research on learning journals (Glogger, Schwonke, Holzäpfel, Nückles, & Renkl, 2012; Wäschle, Gebhardt, Oberbusch, & Nückles, 2015) focusses on learning goals, rather than the production of communicative text. Thus, students are encouraged to articulate their understanding in response to metacognitive prompts about their learning. This is consistent with these findings in that it includes elements that could be equated with both the components of discovery identified in this study, but crucially does not require students to produce genre-appropriate communicative text.

Conclusion

We began this article by referring to the perennial conflict between expressive and communicative goals in the teaching of writing. In this article, we have operationalized this as a conflict between the development of the writer's understanding and text quality. We have argued that problem-solving models assume that these involve the same kinds of processes and, therefore, that there is no conflict between them. By contrast, the dual-process model assumes that the development of understanding has two components: (a) the global organizing process which is compatible with communicative goals and (b) the spontaneous articulation of thought which is incompatible with them. The results suggest that there is, indeed, a conflict between these goals, and in particular, that outlining and controlled sentence production, which enhance quality, suppress the development of understanding. This study has provided indications of the factors that affect this conflict and suggested some ways in which it can be reconciled. Future research, particularly on revision drafting strategies, and on the factors affecting the two components of discovery, may ultimately lead to the development of instructional strategies which resolve the conflict.

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