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Eye and Pen: A new device for studying reading during writing

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We present a new method for studying reading during writing and the relationships between these two activities. The Eye and Pen device makes a synchronous recording of handwriting and eye movements during written composition. It complements existing online methods by providing a fine-grained description of the visual information fixated during pauses as well as during the actual writing act. This device can contribute to the exploration of several research issues, since it can be used to investigate the role of the text produced so far and the documentary sources displayed in the task environment. The study of the engagement of reading during writing should provide important information about the dynamics of writing processes based on visual information.

Written language is a universal form of expression that is increasingly present in our lives, thanks to new information technology. Writing is a particularly complex human activity. The writer has to construct a coherent idea and formulate it in accordance with orthographic rules (e.g., rules of grammar and spelling), all the while ensuring that it is clear to the reader. The ability to carry out and coordinate these various mental processes within a limited time frame is often the sign of expertise in text composition.

For the cognitive science researcher, identifying the rules governing the implementation and coordination of these processes is the key to understanding the act and dynamics of writing. Various complementary online methods have been developed in order to achieve this aim. The Eye and Pen device described here supplements these methods by yoking the signal from a digitizing tablet on which the subject writes (marking the location and state of the pen) with the signal from an eye tracker (marking the location of gaze in the task environment). By combining these two signals, the researcher can study the nature of the visual information fixated during pausing and writing. It then becomes possible to explore relatively unknown aspects of writing, such as the reading of the text produced so far and documentary sources, during writing.

In this article, a brief overview of the cognitive conception of text composition and the online methods currently used to study it is followed by a description of the Eye and Pen device. Its methodological relevance is discussed, and empirical issues that can be addressed are presented. To conclude, prospects for future research are suggested.

A Cognitive Approach to Writing and Unresolved Issues

From the point of view of cognitive psychology, text production is a complex mental activity that requires the management of four main processes in working memory (see Alamargot & Chanquoy, 2001, 2002, for reviews). (1) The planning process involves preparing the content of the text or a sentence by selecting, organizing, and developing items of domain knowledge according to rhetorical, pragmatic, and linguistic goals (Hayes & Nash, 1996; Torrance, Thomas, & Robinson, 1996). (2) The formulation process consists in translating the product of planning (preverbal message) into correct sentences, obeying spelling and grammatical rules (Berninger, 1999; Fayol,

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Hupet, & Largy, 1999) and using cohesive markers such as anaphora and other connectives (Costermans & Fayol, 1997). (3) The execution process allows the subject to write the verbal message on a sheet of paper or a computer screen, controlling his or her graphomotor movements on the basis of visual and kinesthetic feedback (Graham & Weintraub, 1996; Smyth & Silvers, 1987). (4) Because the resulting text is rarely a perfect first draft, the revision process involves reading the text produced so far in order to assess it and, if necessary, reengage the writing processes in order to modify its form and/or content (Butterfield, Hacker, & Albertson, 1996; Hayes, Flower, Schriver, Stratman, & Carey, 1987).

Text composition is a dynamic activity, and the engagement of planning, formulation, execution, and revision processes can be described with reference to two different axes. (1) Along the syntagmatic axis, writing processes are implemented sequentially and recursively throughout the activity (e.g., the subject writes for a certain amount of time, then embarks on a revision process). (2) Along the paradigmatic axis, a variable number of processes can be engaged in simultaneously (i.e., in parallel) at any given time (e.g., the subject formulates and transcribes the current sentence while planning the content of the forthcoming sentence). Although the writer can exercise a degree of metacognitive control over the sequencing of the writing processes (Hacker, 1994), working memory capacity also plays a decisive role in determining this dynamic. Writing processes can be undertaken in parallel as long as working memory capacity is not exceeded by the cumulative demands of these processes (Flower & Hayes, 1980; Kellogg, 1996). Accordingly, if low-level processes are not sufficiently automatic and/or the demands placed on controlled processes are too high, the writer will be constrained to modify his or her writing strategy by sequencing and postponing some of the processes (e.g., if considerable cognitive resources have to be allocated to the formulation of a sentence, the planning of the following sentence must be postponed). Thus, a writer who is not able to think about text continuation while writing will frequently have to alternate phases of pausing (to prepare the text) and writing (to formulate and execute the planned text; Chanquoy, Foulin, & Fayol, 1990).

Studies based on Hayes and Flower's (1980) model have sought to identify the nature and development of planning (Burtis, Bereiter, Scardamalia, & Tetroe, 1983), revision (Scardamalia & Bereiter, 1983), and formulation (Kaufer, Hayes, & Flower, 1986) as well as the role of long-term memory in these processes (Caccamise, 1987; Kellogg, 1987; Voss, Vesonder, & Spilich, 1980). Computer-assisted writing environments have been developed and tested experimentally (Duin & Graves, 1987; Kellogg, 1988).

With the development of a capacity theory of writing (McCutchen, 1996) and the appearance of Kellogg's (1996) model, the emphasis has shifted to the role of working memory in the management of writing processes (Chanquoy & Alamargot, 2002; Ransdell & Levy, 1996). This approach has made it possible to produce more accurate descriptions of graphomotor processing (Bourdin & Fayol, 2002), orthographic processing (Fayol, Largy, & Lemaire, 1994), and strategies for writing in a second language (Ransdell, Arecco, & Levy, 2001; van Gelderen & Oostdam, 2002).

These various areas of research are still wide open and the subject of many studies. However, despite the diversity of the themes tackled, little is known about the impact of the task environment, especially on how the text produced so far and documentary sources are processed during writing (Hayes, 1996). Referring to documentary sources in order to produce a text (e.g., in order to summarize or simplify the information) is a frequent activity in the classroom, at university, and in the workplace. Similarly, during text production referring back to the text produced so far is vital when the subject needs to reactivate in working memory that which has already been written in order to resume the text or revise it.

In order to analyze how the subject uses the task environment while writing, one must understand how the reading process functions during writing. Investigations of this topic have focused above all on revision (reading in order to assess the text produced so far—Butterfield et al., 1996; Hayes et al., 1987) and the summarizing of documents (reading and analyzing sources in order to develop text content—M. L. Kennedy, 1985; McGinley, 1992; Nash, Schumacher, & Carlson, 1993). A variety of methods have been used, including comparing the writing performance of poor and proficient readers (McCutchen, Francis, & Kerr, 1997); analyzing the strategies adopted by writers in order to draw on either the text produced so far or the sources, by filming the writers' activity (O'Hara, Taylor, Newman, & Sellen, 2002) or by recording concomitant verbalization (Breetvelt, van den Bergh, & Rijlaarsdam, 1996); eliminating or altering visual feedback using invisible ink or masks in order to record the effects on the quality of the text (Dansac & Passerault, 1996; Hull & Smith, 1983; Olive & Piolat, 2002); and controlling access to sources so that the writer has to stop writing in order to view sources on a computer screen (Dansac & Alamargot, 1999).

These various methods are interesting because they help to demonstrate the importance of visual information during writing and the major role played by reading. However, they fail to provide any direct and accurate indication of the information read at a given point in the writing act (e.g., the words fixated in the text produced so far and/or in documentary sources) or of how this information is read (e.g., the duration and number of eye fixations on the words). Eye and Pen was developed to remedy these shortfalls. This device makes it possible to investigate the influence of the task environment by providing a fine-grained analysis of the temporal characteristics of reading in coordination with writing.

A presentation of the device's characteristics and its place alongside other methods for the real-time study of writing will be followed by a description of the main issues it can help to resolve in the field of text production.

EYE AND PEN: PRESENTATION AND DISCUSSION

Overview of Eye and Pen: A Digitizing Tablet and an Eye Tracker

The Eye and Pen device (see Figure 1) was designed to allow the synchronous recording of handwriting (by means of a digitizing tablet) and eye movements (via an optical eye-tracking system).

It can be connected to various types of tablet. A screen tablet allows the subject to write directly on a screen, which then displays the written text alongside other types of information (instructions, images, documents, etc.). Eye and Pen is also compatible with different types of eye trackers, which allow researchers to control the degree of restraint involved according to whether the eye tracker immobilizes the head with a bite bar or chinrest, or instead, being head mounted, allows free movement of the head (see below for a discussion, as well as Richardson & Spivey, 2004a, 2004b, for a presentation of the main eye-tracking systems and the areas of study that have been covered thus far).

The Eye and Pen software carries out three tasks: data recording, data processing, and control of the experimental sessions.

Data recording. During the data recording phase, Eye and Pen synchronizes the data produced by the digitizing tablet and the eye tracker (see the Appendix). The digitizing tablet transmits information about the state of the pen point (degree of pressure on the surface) as well as spatial and temporal data about the pen as it moves across the surface (subsequently enabling the software to analyze and reconstruct the written text as well as the pauses when the pen is either raised or pressed down). The eye tracker transmits spatial and temporal data about the point of regard on the surface of the tablet. The point of regard is extrapolated from the position of the corneal reflection in relation to the center of the pupil. The synchronization of the signals from the tablet and the eye tracker reveals the direction of the gaze during pauses as well as during actual writing.

Data processing. The software has various functions for displaying and analyzing the data it records (see Figure 2). A semi-automated analyzing system allows the researcher to select, encode, and export data about Eye and Pen movements.

Control of the experimental sessions. The Eye and Pen software makes it possible to automate an experiment by means of a simple scripting language. Programmed by the experimenter, the script controls (1) the display of information on the computer or tablet screen (e.g., writing assignments, words to copy, pictures to describe) in accordance with a set procedure or as a function of the writer's own activity (e.g., when he or she moves the pen to a particular area of the tablet to indicate that he or she has finished), and (2) the operation of the eye tracker (e.g., start and end of data flow recording, calibration of the eye tracker between items).

Conducting an Experiment Using Eye and Pen

A typical experiment using the Eye and Pen device comprises four steps: setting up the materials, calibrating the eye tracker, recording writer activity, and processing the data.

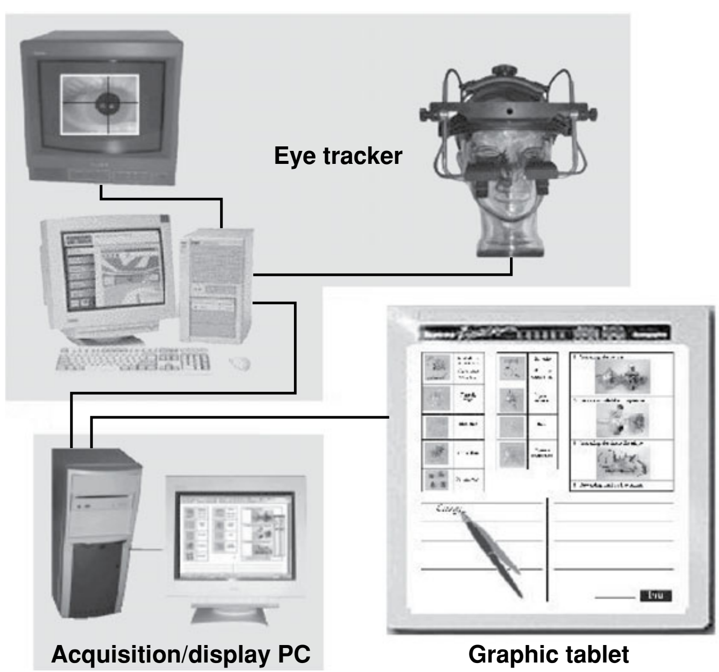

Figure 1. Eye and Pen recording apparatus.

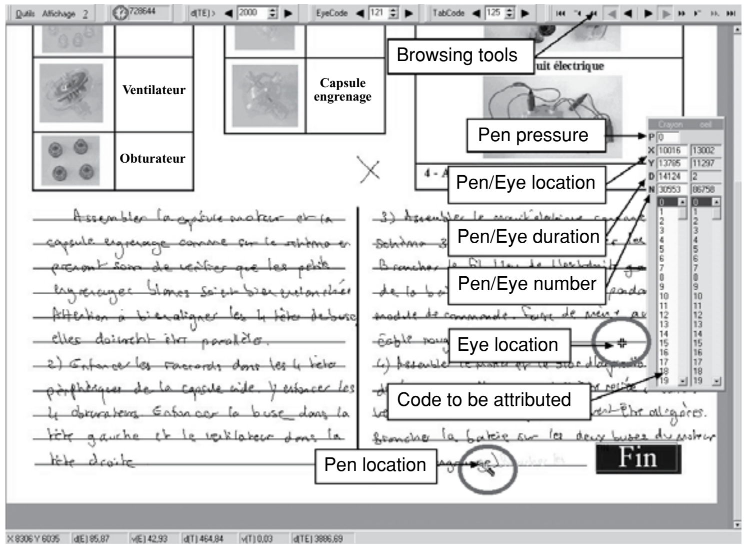

Figure 2. Processing interface and text to be analyzed.

Setting up the materials. When a head-mounted eye tracker is used, the first stage consists in mounting the headset on the subject's head, then positioning and properly adjusting the cameras (either CMOS or CCD, depending on the eye tracker) as well as the lighting directed toward the eyes (using infrared diodes) in order to record a clear image of the pupil and the corneal reflection. This phase generally does not last more than 5 min, although it depends on the skill of the experimenter and the morphological and physical characteristics of the subject (eye size, shape of face, thickness of eyelashes, makeup, etc.). When a head restraint system is used, it may be necessary to make a dental impression beforehand. Using silicone-based substances, a sufficiently rigid and accurate impression can be made in approximately 15 min. This impression is then placed on a fixed holder on which the cameras are also positioned. The subject continues to bite on this impression throughout the session (there are other means of immobilizing the head, such as chinrests and forehead rests, but these are less reliable than the bite bar).

Calibrating the eye tracker. Every eye tracker must be calibrated before the recording session (and even between trials within a session) if it is to supply accurate data. The calibration procedure varies according to the nature of the eye tracker, but the general principle is that the subject fixates a set of points displayed on the screen or digitizing tablet (usually representing a mesh of 9–25 points) so that the system can record the position of the eye in relation to these reference points. To check the quality of the calibration, a second trial is conducted, and the data recording is triggered only if the difference between the two trials is below a certain threshold. This phase generally lasts 1–2 min.

Recording writer activity. After the calibration is complete and the task assignments have been given, recording of the eye and graphomotor data can begin. A procedure for checking the validity of the calibration can be carried out at any time, thereby allowing the experimenter to recalibrate the device if the eye data is not sufficiently accurate (with a head movement compensation system, the headset may move slightly and cause a spatial drift of the eye data). Should the experimental task comprise several items (e.g., writing a series of sentences), it is advisable to carry out regular calibrations (e.g., every two or four items).

Processing the data. The writing data analysis module of Eye and Pen was inspired by the G-Studio software (Chesnet, Guillabert, & Espéret, 1994). The written text, digitized by the tablet, is displayed on the PC screen together with two cursors representing the "Eye" and "Pen" positions. The information fixated by the writer can be displayed on the screen as a background picture of the task environment (see Figure 2).

Hence, all of the writing activity can be displayed as if it had been videotaped. It is possible to "reconstruct" the synchronized movements of the pen and eye on the screen, rewinding or fast-forwarding at will. Every event (movement or halting of the pen, position of the gaze during a saccade or a fixation) is identified by its chronological number. Each event can be given a category code to help in further inspection and data exportation. The experimenter may define areas of interest within the task environment by using the mouse or entering spatial coordinates. Each area has its own code, which is automatically given to any eye data recorded within its boundaries. This helps to categorize eye movements and extract several dependent variables.

The experimenter can also define sequences within the text in order to isolate specific sections. Sequences are episodes located in time, manually defined by entering start and finish times (e.g., by using the mouse). Sequences may be of any duration, making it possible to isolate instances in which the subject writes an entire paragraph or perhaps just a single letter. Sequences are numbered by their order of definition, but they can be given keywords to categorize the writing phenomenon involved and/or its linguistic and semantic context. When it comes to encoding the data, Eye and Pen offers many options for exporting them to ASCII files, which can then be imported into most types of statistical software, spreadsheets, or word processors.

Methodological Basis of Eye and Pen

Verbal protocols, double and triple tasks, and the recording of pauses and output during writing currently represent the three main methods of real-time analysis of writing. By recording eye movements during periods of pausing and writing, Eye and Pen supplements these existing online methods, especially the recording of pauses and flows, and holds out several interesting prospects for future research.

Existing online methods for studying written production. The method involving the use of *think-aloud protocols* consists in recording and interpreting the writer's description of his or her own thoughts. This information may be gathered either during the activity (concomitant protocols—Hayes & Flower, 1983) or some time thereafter (retrospective protocols or interviews—Schumacher, Klare, Cronin, & Moses, 1984). Associated with a posteriori categorization criteria for think-aloud protocols, this method (and all its variants) is eminently suitable for identifying controlled writing processes (i.e., those accessible to the subject's consciousness) and describing their chronological sequence. Indeed, it enabled the development of the first text production model (Hayes & Flower, 1980) and has since been widely used in research (Gufoni, Fayol, & Gombert, 1994; Torrance et al., 1996; van den Bergh & Rijlaarsdam, 1999).

The *double-task method* makes it possible to compare attentional resources allocated to controlled processes during writing. Based on the paradigm of the added task and the premise of the additivity of demands for cognitive resources, the analysis of variations in performance on the secondary task (often defined in terms of reaction time to a signal—e.g., the subject has to press a button as quickly as possible after hearing a sound) makes it possible to deduce variations in the cognitive resources allocated to the main task (the written composition). In order to identify the processes involved, the double-task method has been supplemented by an additional verbalization task. Two versions of the so-called "triple task" have been developed: (1) The version developed by Kellogg (1987) uses directed retrospective protocols. Immediately after responding to a bleep, the writer indicates whether the interrupted process concerned content planning, text formulation, or revision. She or he then resumes text production until the next secondary task takes place, the average interval between these interruptions being on the order of 40 sec. (2) The version of the triple task developed by Levy and Ransdell (1994) relies on concomitant verbal protocols. The writer continuously verbalizes her or his thoughts while carrying out the main and secondary tasks. The analysis consists of the subsequent description of the verbal productions made while carrying out the double task. The usefulness of both versions of the triple task method lies in its ability to identify the nature and cognitive demands of the process under way at a given point in production. Depending on whether the secondary task is carried out during writing or during a pause, it is possible to assess the cost of any processes that may be taking place alongside the graphomotor execution (Olive & Kellogg, 2002).

The *pauses-and-rates method* consists in recording variations in writing speed throughout production and deducing the nature of the processes engaged in according to the length and location of pauses in the text. The recording paradigm differs according to whether the text is typed or handwritten.

The method for studying pauses and typing rates consists in logging the precise times when keys are pressed or released. Various types of software have been used until now, including Recording Word-Star (Sirc & Bridwell-Bowles, 1988), real-time replay (Ransdell, 1990), S-notation (Severinson & Kollberg, 1994), and ScriptLog (Ahlsén & Strömqvist, 1999).

The most widespread technique used today for studying pauses during handwriting involves a digitizing tablet. Connected to a computer, the tablet records the spatial and temporal coordinates of the pen point (whether or not it is moving across the surface of the tablet) as well as the pressure exerted on it (see G-Studio software, Chesnet et al., 1994).

These three online methods have provided invaluable information and have contributed greatly to advances in writing research. They complement each other in that they gauge different aspects of text production. The method that uses think-aloud protocols identifies controlled processes, whereas the method using double or triple tasks measures the cost of these processes, and the pauses-and-rates method analyzes the way they unfold over time.

Obviously, each of these methods has its limitations (see Piolat & Pélissier, 1998, for a review). Verbal protocols cannot reveal processes that are too automatic or too quick for the subject to be aware of them. The double and triple task methods may cause cognitive overload and trigger a trade-off between the main and secondary tasks. Moreover, depending on the nature of the secondary task, it may regularly interrupt the processing of the main task (e.g., to respond to a bleep by pressing a button, the subject has to stop writing). Even if the quality of the finished text does not appear to have been adversely affected (Piolat & Olive, 2000), the writer probably had to implement the writing processes more frequently throughout the activity. The pauses-and-rates method does not place the writer in a double-task situation or interrupt the processes, yet it fails to provide any direct indication of the nature and/or demands of the ongoing processes. This makes it vital to analyze the length of pauses in relation to their location in the text (e.g., before the text, a paragraph, a sentence, a proposition, a word; see Foulin, 1995, for a review) and/or to compare pause duration in different contexts of production (Chanquoy et al., 1990).

One way to improve the interpretation of pauses is to link them to an additional item of information. Because writers work in a physical environment, analyzing their eye movements during pausing and writing opens up interesting prospects. According to Richardson and Spivey (2004a), since eye movements can be tracked by modern technology with great speed and accuracy, they now constitute a valuable source of information. If graphomotor execution is regarded as the output of text production, the analysis of eye movements during writing makes it possible to establish a link between the visual input of writing and its graphomotor output. It can constitute a powerful paradigm for exploring how people use the visual information contained in the task environment to compose a text during writing processes.

Advantages and disadvantages of Eye and Pen. The originality of Eye and Pen lies in the way it complements the pauses-and-rates method by recording eye movements. Generally used to study reading processes (Rayner, 1998) or problem-solving strategies (Salvucci & Anderson, 2001), the eye-tracking system has only rarely been used to record eye movements during writing. Inhoff and his collaborators seem to have been the first to make a combined recording of graphomotor and eye activities (see Inhoff & Gordon, 1998, for a summary). Their device is dedicated to typewriting. The information that the expert typist has to copy is displayed on a computer screen, in a mobile window controlled by the eye. The system records the keypresses synchronized with eye fixations on the letters to be copied. This technique is very useful for studying variations in the eye–hand span (a copy span) due to the linguistic characteristics of the words to be copied and/or the motor complexity of the act of copying. The Eye and Pen device can be regarded as an extension of the system developed by Inhoff, although the two devices differ on at least two counts.

To start with, Eye and Pen is dedicated to the study of handwriting. Handwriting remains the most widespread mode of production in the social context and the most heavily used in the classroom. Moreover, although the use of today's computers involves keyboards, the increasing use of styluses and screen tablets (e.g., personal data assistants [PDAs], tablet PCs) means that handwriting is once more becoming central to the entry of computer data. Because Eye and Pen does not rely on the use of a computer keyboard, studies can entail a wider range of writing tasks (e.g., copying, free composition, note-taking, annotating, editing, solving mathematical problems) and can be conducted with populations that have no experience of typing (e.g., children or older subjects). Used with a screen tablet, Eye and Pen makes it possible to study in real time how these populations read and use a variety of electronic documents and resources (e.g., dictionaries, encyclopedias) in a variety of writing activities (e.g., note-taking, summarizing, abstracting, revising) and a variety of contexts (e.g., in the workplace, at school).

Second, Eye and Pen does not involve a word processor. Its use is not restricted to the analysis of writing and text composition; any graphomotor activity, including drawing, can be investigated. With the screen tablet, it can be used to simulate and study the navigation of graphic operating systems or stylus-controlled software (e.g., the PDA operating system).

Like any other recording method or device, Eye and Pen also has several drawbacks, mainly linked to the recording of eye movements.

First, some types of eye trackers require that the subject's head be kept still. As Richardson and Spivey (2004a) commented, a balance has to be struck between obtaining a high-precision record of an observer's point of regard and allowing natural head and body movements. It is therefore up to researchers to make these choices according to the nature of the eye trackers available to them, their hypotheses, and the degree of accuracy required. The greatest degree of accuracy is obtained when the head is restrained with a bite bar, notably with Purkinje eye trackers. Most reading studies have been carried out in these conditions (see Rayner, 1998, for a review). Restraining the head has an impact on eye and head coordination and the programming of saccades (Herst, Epelboim, & Steinman, 2001). According to Collewijn, Steinman, Erkelens, Pizlo, and van der Steen (1992), saccadic speed is reduced because of the partial inhibition of the natural commands to shift the gaze (see also Kowler et al., 1992, and Lee, 1999, who studied the influence of free-headed reading on ocular parameters).

From a technical point of view, Eye and Pen can be used with various makes of digitizing tablets and eye trackers (see the Appendix). In order to preserve the natural writing situation, it is possible to use an eye tracker that produces very accurate recordings while allowing free head movements. The EyeLink2 system (SR Research) is a good compromise.

The second drawback is that even when the eye tracker does not require the head to be kept still, there is the major problem (linked to any measurement of eye movements using a system of corneal reflection) of how to stabilize the spatial characteristics of the task environment. In the case of reading a text displayed on a screen, the advice is that the distance between eye and screen should be twice the diagonal of the screen (in general, approximately 72 cm). The screen's surface should be vertical, and the subject's gaze at rest should be directed perpendicularly to the center of this screen (according to the EyeLink2 user manual). This positioning minimizes angular deformations and maximizes data recording accuracy. As for writing, the optimum position for recording ocular parameters, depending on the writer's natural posture and the system's recording constraints, is with the tablet set at an angle of 30º–50º. To ensure optimum writing comfort (depending on the length of the writer's forearm), the writer's eyes should be 34 cm away from the center of the tablet. This position is very similar to that required for writing on a pad or a handheld PDA (see Figure 3).

In addition to the angle at which it has to be placed, the tablet must remain in a fixed position throughout the session. This means that the writer has to position his or her chair in relation to the tablet and not vice versa. Although typewriting also requires the writer to adopt a particular posture (according to the position of the screen and keyboard), in the case of Eye and Pen it is important to analyze how the specific angle and fixed position of the tablet might modify writing speed. It is possible that an unaccustomed writing position would result in greater control of graphomotor execution, thereby resulting in a reduction in the resources available for higher level processes (Bourdin & Fayol, 2002). This indirect effect of posture on high-level processing needs to be investigated. That said, the potential effect would appear to be less than that introduced by the think-aloud method, for instance, since concomitant verbalization places the writer in such a constant double-task situation that his or her performance on the main task (writing) is likely to be impaired (Janssen, van Waes, & van den Bergh, 1996). Although Eye and Pen introduces constraints regarding writing posture, it has the advantage of recording graphomotor and ocular parameters continuously—that is, without interrupting the processes engaged in by the writer during this period (unlike the double- and triple-task method).

Figure 3. EyeLink2 eye tracker with Wacom 18sx screen tablet. The head is free, and the tablet is set at an angle of 50º.

Examples of Issues Addressed by Eye and Pen

A pilot study was conducted using Eye and Pen to test the system's possibilities. Several examples of the findings are presented here in order to demonstrate how Eye and Pen allows researchers to study reading during writing and how the analysis of reading–writing coordination can provide information about the dynamics of writing processes.

In this pilot study, the graphomotor and eye activity of 25 adult writers was recorded while they were composing a procedural text. The participants were first familiarized with the assembly of a model turbine. They were then asked to write a text that would enable readers to assemble the model correctly. At any time during the production phase, the writers could refer to five categories of information always available within the task environment: (1) photographs of each of the nine parts of the turbine, (2) the labels of each of these parts, (3) photographs of the three assembly steps, (4) the labels of each of the assembly steps, and (5) the text produced so far. Prior to the composition task, the subjects were tested on four measures (writing memory span, lexical fluency, graphomotor fluency, and referential domain expertise) for assessment of their writing abilities (see Alamargot, Dansac, & Chesnet, in press).

The Study of Reading During Writing: Documentary Sources and Text Produced So Far

In order to study reading during writing, two questions first need to be answered. (1) What are the intrinsic characteristics of reading (in terms of fixations and saccades) when it is placed at the service of writing? (2) What is the relationship between reading and the other writing processes?

Characteristics of reading during writing. This issue has seldom been investigated until now. The characteristics of the ocular parameters involved in writing are largely unknown except in the case of typewritten copying (see above, Inhoff & Gordon, 1998). Although fixations, gazes, and saccades have been studied for years in scene perception or in reading (A. Kennedy, Radach, Heller, & Pynte, 2000), their usefulness within the framework of text composition, particularly handwritten composition, is unknown. There is no doubt that most of their characteristics can be generalized from reading research, but researchers have yet to examine exactly how the handwriting situation may generate specific eye activity. According to Chesnet and Alamargot (2005), alternating between periods of writing and periods of pausing results in a succession of different eye behaviors, which correspond to the linear reading of the text or sources, information searches, the control of graphomotor activity, and the supervision of handwriting quality. Caporossi, Alamargot, and Chesnet (2004) sought to highlight these different types of eye behavior by applying data-mining processes to data acquired using Eye and Pen for 1 of the subjects in our pilot study. The results of a clusterwise regression analysis confirmed the presence and recursiveness of these four different oculo-graphomotor patterns throughout the text production process. These could be identified by the length of the fixations, the speed of the saccades, and the distance between the pen point and the point of regard. These encouraging results need to be studied in greater depth and confirmed in order to identify the characteristics of these various eye behaviors and the conditions in which they occur most accurately.

Relationship between reading and other writing processes. Regarding the relationship between reading and other writing processes, it can be assumed that the reading process (1) encodes the information contained in the documentary sources and/or the text produced so far and (2) develops the representations that will subsequently be handled by the other writing processes (planning, formulation, and revision). The way visual information is read and processed during text composition can provide relevant indicators of the presence and course of other writing processes that rely on this information.

The principle behind the pilot study was to control the content of the sources by presenting the conceptual photographs and linguistic information (related lexicon) concerning the various parts and assembly stages. Studying how these different pieces of information are fixated while text production is in progress can reveal more about the relations between source sampling and the planning and formulation processes.

In order to define the course of planning, the total text production time was divided into three equal periods and the nature of the information fixated during pauses was analyzed for each of these periods (see Kellogg, 1987). In the first period, the longest pauses were dedicated mainly to studying the different parts making up the turbine. In the second, these pauses were concerned with consulting the assembly steps. In the third, the writers' eye movements during these pauses differed according to working memory capacity: High-span writers (as assessed via a verbal production span test; Daneman & Green, 1986) switched back and forth between the assembly steps and the text more often than low-span writers did. This result indicates that only writers with a high working memory capacity can implement complex monitoring processes during pauses (see also Alamargot, Dansac, Ros, & Chuy, 2005).

Hence, Eye and Pen provides a means of investigating progress in elaborating text content by identifying changes in the nature of the visual information fixated in order to do so. The first experimental results, based on the production of a procedural text, reveal several different planning phases. Local planning (appropriating concepts and the relevant lexicon) gives way to overall planning and then, provided that there is sufficient working memory capacity, to verification of the extent to which the text matches the sources. The principle behind this analysis of planning can be extended to different types of sources (e.g., images, propositions) and different types of texts (e.g., descriptive, argumentative, synoptic).

Similarly, in the case of the formulation process, Eye and Pen makes it possible to analyze the correspondence between an item of information that is consulted and the production of the matching word(s). One frequent and typical form of behavior observed during the pilot study is exemplified by Subject 6, who began her text with the words *Prendre tout d'abord la capsule moteur* ("First of all, take the motor capsule"). During the production of the first five words (*Prendre tout d'abord la capsule*), the point of regard did not stray from the pen. After the word *capsule*, the writer began a 665-msec pause. Within this pause, the point of regard rested on the space after the word *capsule* for 531 msec before a saccade drew it directly to the area of the lexicon associated with *capsule moteur*. A fairly long fixation (684 msec) then began. During this fixation, after 96 msec the subject resumed the writing of the first letter of the next word (*moteur*) without moving her point of regard. At the end of the fixation, a saccade drew the point of regard directly back to the line of handwriting and the subject finished the word *moteur*.

Matching what is looked at with what is produced is an interesting exercise, since it provides a means of identifying the course of the formulation process and, especially here, lexicon choice. This principle has recently been adopted in investigating the course of oral formulation. Meyer, Sleiderink, and Levelt (1998) recorded speakers' eye movements as they named pictures, and Griffin and Bock (2000) did so as speakers described pictures. The analysis of the interval between the perception of the conceptual information and its evocation sheds light on the unfolding of conceptual and linguistic processes. As the example described earlier suggests, Eye and Pen is ideal for applying the same research methods to writing.

All the studies that have been referred to focused on the reading of sources. However, bridging the gap between what is read and what is written can also be applied to the text produced so far. This involves analyzing the functioning and course of the formulation and revision processes. It may be necessary to read the text produced so far in order to ensure linguistic cohesion. To connect two parts of a sentence, the writer may have to (re)read the antecedent before producing the anaphor. The same phenomenon may also occur when a verb agreement is being worked out, if the distance between the subject and the verb is too great. Indeed, by exploring his or her text, the writer should be able to discover which formulation processes have been implemented. This understanding can be reached with the help of Eye and Pen by analyzing, as in reading studies (see Baccino & Pynte, 1998), the relationships between the linguistic units being processed (e.g., the writer pauses just before writing an anaphor) and the linguistic units that are under visual focus (e.g., the writer fixates the referent of the anaphor during a pause, then writes the appropriate anaphor).

When it comes to revision, a similar analysis of the linguistic and semantic units fixated immediately prior to a revision episode should make it possible to identify what triggers the process and how an anomaly is detected (see below).

Studying the Coordination of Reading and Writing: A Means of Assessing the Dynamics of Processing

One of the more complex issues in text production is that of the dynamics of the different processes involved, since it is difficult to highlight their sequential and parallel engagement (along syntagmatic and paradigmatic axes). Eye and Pen can help to shed light on this issue by revealing when reading is conducted in parallel with execution. When this occurs, the gaze is directed away from the moving pen and fixates an item of information, either in the text or in the sources, that is different from the subject being formulated (the mind is also far from the pen). This type of parallel processing manifests itself in a phenomenon of desynchronization between eye and moving hand, which has already been observed in painting (Miall & Tchalenko, 2001; Tchalenko, 2001) but never before in writing. And yet, as the pilot Eye and Pen study suggests, this is a frequent and sizable phenomenon in the case of source-based text production (see Alamargot et al., in press).

In the pilot study, writers were assumed to be engaged in a parallel reading process if they kept writing when they directed their gaze away from the pen position, so that the latter was outside the parafoveal field of vision, at a visual angle of about 6º from the point of fixation (see Alamargot et al., in press, for a more detailed presentation and discussion of criteria). Under these conditions, the eye encodes information about the writing environment that does not concern graphomotor execution. Results show that these parallel events make up quite an extensive phenomenon: Their mean duration is 540 msec, and they represent about 10% of actual execution time (see Figure 4).

Another sequence observed in the text of Subject 6 provides a perfect illustration of how Eye and Pen can help to identify the subtle mechanisms involved in parallel processing, especially in the case of spelling revision. This example concerns a parallel event that occurred as the following sentence was being written: *Les différentes bornes de la capsule doivent être situé vers l'extérieur pour permettre* . . . ("The various pins of the capsule must be pointing outward, in order to allow . . ."). The beginning of this sentence was written with the eye following the pen movement. A spelling error was made in the word *situé* (in this context, "pointing"), which should agree with the gender and number of the related noun *bornes* ("pins"). As the subject began writing the second "e" in the word *permettre* ("to allow"), her gaze left the pen (for 405 msec) and fixated the misspelled word. When the "e" was complete, her gaze returned to the pen. The writer then completed the word *permettre*. At the end of the word, the writer made a pause of 826 msec, during which she briefly fixated the letter "é" of the word *situé*, before spending the rest of the pause resolving the error by adding "es" (*situées*).

Prendre tout d'abord la capsule **m**oteu**r** et y joindre
la capsule d'engrena**g**e en faisant bien attenti**on à ce**
que les deux branches de cette dernière soit vers la
première**.** Les différents cables de la capsule
doivent être
situées vers l'extérieur pour per**me**ttre le
branchement
définitif**.**
Prendre ensuite **la** **cap**sule vide **et p**lacer **c**inq
raccords et la buse sur les **s**ix branches de cette
dernière.
Placer ensuite les 4 o**b**tura**te**u**r**s en étoile autour de
la
capsule et **jo**in**dre** en face de la b**use** le ventilateur**.**
Une fois ces opérations terminées, il est temps
d'assembler **les** **d**eux **co**n**str**uctions en faisant
attention que les
différents **eng**renages permettant la mise en
fonctionnement
de l'appareil soit bien reliés.
Prendre la ba**tt**erie et y fixer le **mo**dule **d**e
commande
Les **d**eux branchements batteries**/**module **de**
commande
doivent être réalisé après assemblage de **la** batteri**e,**
sur **la** **c**onstruction **ca**psule mo**teur** **et c**ouple
engrenage
au moyen des deux raccords restants. Les placer
sur le dessus et y **en**clench**er** la batter**ie** cable bleu à
gauche et cable roug**e** **à** droite.

Figure 4. Parallel events (underlined and boldfaced) in the text composed by Subject 6.

This description of eye and graphomotor activities during this episode using Eye and Pen is very fruitful, since it suggests that the detection of a spelling error and its subsequent correction can be done in two separate stages. Detection can occur in parallel with graphomotor execution, whereas correction can be postponed until after the current word has been written. Hence, the location and nature of the detected error are probably maintained in working memory until the pause and the start of the correction process. This means that during sentence production, writers have access to a memory trace, at least of the orthographic features of the text just written. This interesting finding raises further questions. Does the writer also have access during writing to a semantic trace of this text? Similarly, does he or she have access to a spatial representation of this text that can be used as a basis for calculating a regression saccade that takes the point of regard directly to the location of the error? Whatever the nature and number of these representations, how rapidly do these memory traces decay? Until now, these questions, which are central to understanding the course of text production, have received very little attention (see Fayol et al., 1994; Largy & Dedeyan, 2002). The example related here, of error detection's paralleling writing, provides a good demonstration of the possibilities offered by Eye and Pen to study the nature and dynamics of subtle linguistic and spelling mechanisms.

CONCLUSION

Since the advent in 1980 of Hayes and Flower's groundbreaking model, research into text production has progressed in terms of both the issues tackled and the methods used. The purpose of experimental studies is no longer simply to describe the general working of the chief components of processing (planning, formulation, and revision), but also to conduct a fine-grained analysis of the processes involved as well as of the ways in which they are implemented. This shift in research perspectives has been made easier by improvements in investigative tools and techniques, in particular real-time methods.

Designed to study the complexity of text production, existing online methods have provided extremely useful results concerning the course and demands of planning, formulation, and revision processes. However, these methods seem to have considered only the output of these processes (e.g., variations in graphomotor activity for pauses, content of working memory for think-aloud protocols) or their consequences (e.g., variations in cognitive demands for secondary tasks). One possible way of extending this investigation would therefore be to consider the visual input of writing activity as well.

By combining analyses of writing activity (pauses and rates) and eye movements, the Eye and Pen device provides a unique body of information. It can be regarded as a new method for investigating the role of the task environment and the relatively unknown process of reading during writing. The reading of sources and the text produced so far generates representations in working memory that are then handled by the other writing processes. Hence, describing the different items of visual information successively fixated in the task environment should make it possible to identify some of the writing processes involved. Moreover, when researchers analyze the course of reading in relation to the course of graphomotor execution and vice versa, they can highlight the processes that parallel writing. It is in this sense that Eye and Pen can be regarded as a new and interesting method for identifying some of the writing processes and their dynamics, by correlating the activity's visual input and graphomotor output. Indeed, it may well open doors to many largely unexplored areas and help us tackle three particularly important issues.

First, it is surely vital to devote further research to investigating the significance of ocular parameters in written production, and especially to determine to what extent fixated visual information is the information that is processed in working memory. In reading studies, it is generally assumed that information perceived in the foveal and parafoveal fields of vision is that which remains in the attentional focus (Reichle, Rayner, & Pollatsek, 2003). However, this assumption can be applied to writing only in part. The temporal management of writing is different from that of reading. When composing a text, the writer may have to make long pauses to find something to write about or find the best way of expressing it. When this happens, attention may not necessarily remain focused on the writing environment. Phenomena referred to as "averting the gaze" may occur (see Ehrlichman & Weinberger, 1978, for a review). In the case of writing, the gaze may be directed toward a particular point on the sheet of paper, but "the eye does not see." These periods, familiar to every writer, seem to be more frequent when the processing under way is complex and demanding (Glenberg, Schroeder, & Robertson, 1998). During these periods, it is not the fixated external information that is processed but internal information—that is, representations elaborated in working memory on the basis of reflexive representations or content retrieved from long-term memory. Future studies will therefore be needed to differentiate between fixations corresponding to the acquisition of visual information and those linked to the withdrawal of attention from the task environment—that is, the neutralization of the visual input. This distinction could be partly achieved by analyzing the correspondence (or lack thereof) between the fixated information and the words written immediately following the fixation (see the section on the relationship between reading and other writing processes, above). However, in absolute terms, it is difficult to state with certainty that every item of fixated visual information is an item of processed information. This limitation does not arise solely from Eye and Pen but is intrinsic to all real-time variables. Also for this reason, what counts is not so much the absolute value of the temporal parameter but the way it varies according to experimental conditions.

A second important issue concerns the need to change our conception of the processing temporality of writing. Studies based on the analysis of pauses generally take into account only pauses lasting more than a certain amount of time, which may be as long as 2 sec (Schilperoord, 1996; for a review, see Foulin, 1995). Studying the longest pauses provides a means of describing the unfolding of the most obvious controlled processes. However, the data gathered in the pilot study show that a determining item of information (e.g., a spelling mistake) can be processed within very short periods of time, lasting only a few hundred milliseconds, like fixations in reading. The sort of very fine-grained description made possible by measuring eye movements means that the temporal unit that has been used until now in order to analyze text production processes must be changed. One likely result of such a change is that psychological significance will be given to hitherto neglected temporal events. Anderson (2002) has already drafted a new temporal scale of the various processes involved in different mental activities, which will probably lead to in-depth modifications in our conception of handwriting and text composition processes.

Third, the writer's eye and graphomotor movements can be regarded as a continuous flow of events that can now be recorded nonstop, thanks to Eye and Pen. The high sampling level potentially makes it possible to investigate not just discrete data (pauses, fixations) but continuous data (acceleration and deceleration of pen and eye movements) as well. It thus becomes possible to regard eye and graphomotor data and their relations as a complex signal that can be studied only with the use of multivariate and data-mining methods to extract previously unknown behaviors and eye/pen patterns. It is for this reason that the early data collected by Caporossi et al. (2004) is interesting, since it leads us to adopt a more dynamic and continuous vision of written production. It is doubtless also in this area that Eye and Pen can serve as an adjunct to existing online methods, helping to model writing processes and their dynamics.

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APPENDIX
Technical Data

The Eye and Pen system involves two PC microcomputers. The first runs software provided by the eye tracker manufacturer, which calculates and sends the gaze coordinates to the second PC through a serial COM port or a network link, depending on the eye tracker model.

The second PC runs the Eye and Pen software that records the coordinates supplied by the eye tracker in parallel with the information provided by the digitizing tablet (spatial coordinates of the pen on the tablet surface and pen pressure). All these data are stamped with common base millisecond timing.

Eye and Pen was developed and tested using Wacom digitizing tablets (UD 1212R, Intuos and Intuos2, size A4+) and screen tablets (Cintiq 15X and 18sx) with a maximum sampling rate of 100 or 200 Hz. They operate with a cordless pen that indicates pressure on a 512- or 1,024-level scale. With basic digitizing tablets, an ink pen can be used. It is then possible to write (or draw) on ordinary sheets of paper, with the restriction that the sheet must not be moved during the recording session.

At the present time, Eye and Pen can support three makes of eye tracker: Eyeputer (Alphabio), EyeLink2 (SR Research), and ASL Model 504 (ASL). However, other devices on the market are currently being integrated. This integration does not pose any technical problems provided that a DLL library is supplied with the eye tracker.

Pen movement data and eye movement data are stored in separate files. Recording time is limited only by the physical size of the computer hard disk and depends on the sampling rates used.

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