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A State-of-the-Art Review of the Real-Time Computer-Aided Study of the Writing Process

MUHAMMAD M. ABDEL LATIF*
University of Essex

ABSTRACT

Writing researchers have developed various methods for investigating the writing process since the 1970s. The early 1980s saw the occurrence of the real-time computer-aided study of the writing process that relies on the protocols generated by recording the computer screen activities as writers compose using the word processor. This article reviews literature on that approach to studying the writing process. The article begins with defining the real-time computer-aided study of the writing process, tracing its historical development, and explaining the advantages it offers, then it gives a brief description of the software that has been used in the computer-aided writing process research and discusses the ways of analyzing the logged data, and it ends with overviewing the computer-aided writing process research.[1.]

KEYWORDS: Writing process, keystroke logging, computer-generated protocols, computer-based writing, writing strategies, computer-based revision, real-time writing, writing research

* ***Address for correspondence***: Muhammad M. Abdel Latif. Department of Language & Linguistics, University of Essex, Wivenhoe Park, Colchester, CO4 3SQ, UK. Tel: +44 7791315741, Fax: +44 1206 872198, email: mmmabd@essex.ac.uk.

I. INTRODUCTION

Writing is a cognitively demanding process in which a lot of strategies are used. The 1970s and 1980s witnessed a shift in teaching writing from emphasis on the product of writing activities to emphasis on the process of developing that written product. The emergence of the process movement in both first language (L1) and second language/foreign language (L2/FL) writing was influenced by some early research on L1 composing, specifically Emig's (1971) seminal study and Flower and Hayes's (1981) cognitive model of writing. These early studies have indicated that writing is best understood as 'a set of hierarchical and recursive thinking processes' guided by the growing network of goals generated or adapted by writers (Flower & Hayes, 1981: 366). The assumptions underlying writing process research are that examining students' written products tells us very little about their instructional needs and that effective teaching of writing needs to be based on knowing how writers compose their texts. By investigating the writing process, researchers try to find out how writers develop their texts and what kind of strategies, i.e. planning, retrieving, reviewing, monitoring and revising, they employ while composing. Writing process research can inform us about the strategies used by good and poor writers and the different thinking patterns involved in composing the text, and about the difficulties students may encounter while composing; thus we can adapt our teaching methods to meet students' writing needs. Pedagogically speaking, assessing the writing process, which is a main component in writing process instruction, is of utmost importance as it can be used for raising their consciousness about good writing strategies and for training students in using them.

Since Emig's (1971) seminal work on the writing processes of her twelfth grader subjects, increasing attention has been given to investigating the way writers compose their texts. The early writing process studies that occurred in an infrequent and rare way in the 1970s paved the way for a growing number of studies on the area since the early 1980s and until the present time. This growing number of studies on students' writing processes has informed researchers (i.e. Bereiter & Scardamalia, 1987; Chenoweth & Hayes, 2001; Flower & Hayes, 1981; Grabe & Kaplan, 1996; Kellogg, 1996) in building their own theories or models of the cognitive process of writing. The massive shift from focusing on the product approach to the process approach in writing research was also accompanied by incorporating new research methods in the writing area. Writing researchers have developed different methods and techniques for collecting and analyzing the writing process data, including the think-aloud method, writers' retrospective accounts stimulated by their texts or the video or audio recording of the writing session, questionnaires, process logs, text analysis, naturalistic observation, video-based observation, and the real-time computer-aided study of the writing process which is an observation-based method. This last method, the real-time computer-aided study of the writing process, will be discussed in detail in this article. The article traces the historical development of the real-time computer-aided study of the writing process and briefly describes some of the software used for observing and analyzing the logged data, then it reviews the ways of analyzing the logged data and the research employing the method to investigate the target area.

II. REAL-TIME COMPUTER-AIDED STUDY OF THE WRITING PROCESS: DEFINITION, HISTORICAL DEVELOPMENT, AND RATIONALE

The computer has increasingly been incorporated in writing research and teaching since its large-scale introduction into education in the late 1970s. The advent of computer-based writing has created new areas for investigating the writing process and has led researchers to develop new methods for observing the real-time writing process (Spelman Miller, 2000: 127). The real-time computer-aided approach to studying the writing process can be defined as observing and analyzing the online writing process through recording computer screen activities, i.e. the keyboard presses and cursor movements, scrolling, the timing of each movement and pauses between these movements. In light of this definition, there are two dimensions of that approach to studying the writing process: observing or recording the writing process and analyzing the recorded data. The real-time computer-aided writing process can be observed via two methods: a) using a camera to record the computer screen activities; and b) using a computerized programme to record keystroke logging. At present, the latter method is more commonly used by writing researchers than the former. That is why some terms such as 'logged data' and 'keystroke logging' will be used in this chapter to refer to both methods. Some of the keystroke logging programmes work independently of word processors while others function within the word processor used. Most keystroke recording programmes have a replay feature by which the text can be played back in real time. The data generated by either method, which may be called the real-time writing protocol, the computer-generated protocol or the logged data, is often saved as log-files for later processing. As for the computer-aided analysis of the writing process, this means analyzing the logged data using some software developed for that purpose.

The real-time computer-aided approach to studying the writing process occurred in the early 1980s. It can be argued that this approach was influenced by Matsuhashi's two early reported studies (Matsuhashi, 1981; Matsuhashi & Cooper, 1978) which derived their observational method from research on the temporal aspects of speech production. In these two studies, the video time-monitored observation was employed to investigate pausing in writing. The subjects transcribed their texts on a specially-sized pad placed on a desk. A video camera was used to focus on the pad and it sent signals to a special effects generator allowing these signals to be recorded concurrently and be replayed on a split screen, and to a data time generator that recorded the real-time of the writing session in minutes, seconds, and tenths of seconds. The data in the two studies were analyzed in terms of pause time, transcribing time, pause length, pause location and words per minute. Though the real-time computer-aid method was introduced to the writing process area in the early 1980s, a few studies employed this method were conducted during that decade. Collier's (1983) study might be the earliest one to video-record the computer screen activities. Another early study that employed the computer screen video-recording was reported by Benesch (1987). As for using computerized programmes to record the computer screen activities, an early attempt was made by Bridwell-Bowles, Sirc and Brooke (1985) who examined students' writing using Playback programme for creating keystroke data. Other early studies using keystroke

logging include those ones reported by Balkema (1985), Bridwell-Bowles, Johnson and Brehe (1987), Flinn (1987a; 1987b), Lutz (1987) and Sirc (1988). It could be noted that all of these previous studies that employed the keystroke logging method were conducted in the L1 writing context. L2 or FL writing studies using keystroke logging seem to have occurred only in the1990s, a decade that saw an increasing use of real-time methods in writing process research as desktop computers and keystroke tracking software became ubiquitous (Levy & Olive, 2001: 4). Since the early 1990s, new keystroke logging software has been introduced and some computer-aided analysis programmes have been developed as well.

The real-time computer-aided observation of the writing process offers researchers a lot of advantages. This data storage process is unobtrusive, i.e. it does not interfere with using the word processor (Leijten & Van Waes, 2005). Being an unobtrusive data collection method, computer-aided observation overcomes the potential problems involved in using other instruments, e.g. think-aloud method, retrospective interviews and questionnaires, for collecting data about the writing process such as reactivity, difficulty of retrieval and social desirability. Replaying the keystroke-recorded writing sessions allows us to know not only the problems writers encounter in their writing but also their problems in using the computer (Lansman, Smith & Weber, 1993: 89). It provides us with a clear understanding of the dynamics of text production (Spelman Miller & Sullivan, 2006: 4) and with a distribution of time and effort allocated to writing subprocesses (Levy & Ransdell, 1994: 219). One main advantage offered by the real-time computer-aided observation of the writing session is that the data recorded can be archived and studied by other researchers (Levy & Ransdell, 1996: 160). The logged data is a rich source for studying writing process, particularly those aspects related to writing fluency and temporal aspects of writing such as pausing and the timing of the writing activities. When using this kind of observational data to complement other data sources, this enriches our understanding of the complex processing involved in writing (Ransdell, 1995: 97). It also fits well within the case study and ethnographic approaches to studying the writing process (Flinn, 1987a: 42). Protocols generated by logging software bridge the gap between the case study approach and the quantitative approach to investigating the writing process as they allow researchers to examine writers' strategies in detail and to quantify them (Lansman *et al*., 1993: 89). Finally, real-time computer-aided observation can be used with writers of different ages and different language developmental levels.

However, keystroke logged data is not without its criticisms. The main criticism of this type of data is the difficulty of interpreting it due to lack of information about writers' internal cognitive processes. The other difficulties involved in assessing the writing process using the logged data and the ways of addressing these difficulties are highlighted in sections IV and VI, respectively**.** The next section briefly describes some of the software writing researchers have used to observe the writing process and to analyze it.

III. SOFTWARE USED FOR OBSERVING AND ANALYZING THE WRITING PROCESS

Software employed in studying the writing process can be classified into two categories: software used for recording the computer screen activities (digital cameras or keystroke logging software) and software used for analyzing the computer-generated protocols. In the following paragraphs, some of the computerized programmes of both categories used in the writing process research are briefly described.

III.1. Programmes Used For Recording the Computer Screen Activities

Early software developed for recording keystroke movements include: a) COMPTRACE: a modified version of the MILLIKEN Word Processor for the Apple IIe that records keystrokes and replays the composing session (Flinn, 1987a, 1987b); b) Writing Environment (WE): software that is implemented on UNIX workstations and has four system modes (Network Mode, Tree Mode, Edit Mode and Text Mode) appearing in four windows on the computer screen, with each of which writers can view their texts differently and perform different operations as well; c) Keytrap: a resident programme that records all keystrokes and the pauses between them and analyzes some aspects of the writing process (Janssen, Van Waes & Van den Bergh, 1996); and d) ScreenRecorder: a camera and macro that functions within MediaTracks, a presentation graphics programme, by capturing the computer screen activities invisibly (Radziemski, 1995). WinWhatWhere Investigator and Camtasia Studio Software are two recent programmes that have been used in some studies (e.g. Figueredo, 2006; Youngquist, 2003), though not described in detail by the authors who reported using them.

ScriptLog and Inputlog are two recently developed logging programmes. ScriptLog has three main modules: a design module in which the task requirements are identified, a recording module providing a binfile comprising the writing session activities and their timing, and an analysis module allowing researchers to extract selected patterns from the binifile (Stromqvist, Holmqvist, Johansson, Karlsson & Wengelin, 2006). As for Inputlog, it is developed for Windows environments. In developing Inputlog, Leijten and Van Waes (2005) derived some of the characteristics of two earlier programmes (JEdit and Trace-it), on the one hand, and ScriptLog on the other hand. The aim of designing Inputlog is to analyze several aspects of the writing process quickly and accurately. The programme can perform the following functions: recording the writing session data in Microsoft Word, generating data files for analyses, playing the recorded session in different rates of speeds, and capturing the dictated input using speech recognition software. What distinguishes Inputlog from Trace-it and ScriptLog is it records keystroke and mouse movements independently of the word processor used and it can also record other actions such as using online or programming reference features. In addition, Inputlog can analyze the writing process aspects in different ways. Leijten and Van Waes (2005: 16) point out that some new

components are planned to be integrated in the next version of Inputlog; these are: a revision analysis component, a progression analysis component, and a speech recognition or dictated text component which will allow researchers to explore its effect on the writing process and may also offer them the possibility of simultaneously transcribing thinking-aloud verbalizations and retrospective interviews.

Writing researchers have reported using a few computerized programmes for recording the non-English word processors data. Ta Kupu and Système-D are two of these programmes. Ta Kupu is word processing software for the Maori language and it also includes a data logging, and an evaluation and analysis tool, Tirohia, which can be used for replaying a record of the student's interaction in real time and examining interaction logfiles at a fine-grained level (Barbour, Cunningham & Ford, 1993). Système-D, on the other hand, is a French word processing programme developed by Noblitt, Sola and Pet (1987). Using this programme, writers of French access some referencing features, including a bilingual dictionary (French-English), a verb conjugator, a reference grammar, a vocabulary index and a phrase index. Système-D has a query tracking device that generates a log of the information accessed by writers while composing on the computer and gives a record of the following data: a) the time of beginning and ending the writing task; (b) the order of information accessed in real time; (c) dictionary searches in both French and English; and d) other grammar and vocabulary inquiries (Scott & New, 1994; New, 1999).

Another category of the logging software is used for examining specific aspects of the writing process or the writing process in a specific mode. Two types of this category can be identified in the literature: reaction time software, and translation process software. Some writing researchers have used reaction time tasks or triple tasks to measure the amount time and efforts allocated to the writing subprocesses. The triple task, a procedure proposed by Kellogg (1986), incorporates three tasks: a writing task, a reaction time task (auditory signal detection) and a directed retrospection task. Using this technique, participants are asked to compose on the computer as a primary task and to respond as quickly as possible to an auditory probe (e.g. a beep or a tone) by pressing a labeled button on a response category box or key in the keyboard to identify the writing subprocesses (planning, translating, reviewing, and other) in which they engage (Olive, Kellogg & Piolat, 2001). Participants are instructed to use the planning category when they create or organize ideas and set global or local goals, the translating category when they put ideas into words, the reviewing category when they read the text written, evaluate the text or plans and detect errors, and the other category when they engage in any other thoughts that do not fit within the three previous categories (Kellogg, 2001). Thus, the triple task technique makes use of immediate testing with verbal protocol and directed retrospection while composing and provides an estimate of the processing time devoted to each of the writing subcomponents (Olive *et al*., 2001). Some other computerized programmes have been developed to employ that technique such as PASCAL (Kellogg, 1987, 1988) and SCRIPTKELL that runs on a Macintosh machine and automatically records and analyzes the aspects constituting the dependent variables of Kellogg's procedure such as number of reactions, frequency of category choices, mean reaction times and mean difference scores (Piolat, Olive, Roussey, Thunin & Ziegler, 1999).

Translog is a programme developed for collecting real-time data about the cognitive aspects of the translation process, i.e. translating from one language to another, that could supplement other data gathered by introspective and/or retrospective instruments. The main assumption behind developing Translog is that by examining the temporal patterns of typing and pausing during the translation process, we could reach a better understanding of the dynamic interaction of the processes involved in it. Translog can also be used for recording most writing tasks, including the post-editing of a machine translated text. The programme has two main components: a Supervisor component that creates files, and a User component that runs these files and creates logfiles. The two components have five functions: three performed by the Supervisor component (preparing project, displaying the logfile content and analyzing it) and two performed by the User component (displaying source text and receiving textual input, and logging keystroke real-time data) (Jakobsen, 2006).

III.2. Logged Data Analysis Programmes

Another type of the software used for studying the writing process is the computerized programmes that can analyze the logfiles generated. S-notation, Progression Analysis and LS Graph are three examples of these programmes.

III.2.1. S-notation

This software is derived from the manual notation of the videotaped handwritten revision developed by Matsuhashi (1987) in which she transcribed the successive changes made by her subject to her texts and the place and order of these changes. It simplifies the analysis of online-revision by automatically identifying connected episodes of revision in readable notation, displaying the successive changes within a text. The resulting representation helps researchers to overcome problems encountered when analyzing raw keystroke logfiles and to analyze the changes made by writers both qualitatively and quantitatively (Kollberg & Severinson-Eklundh, 2001; Severinson-Eklundh & Kollberg: 2003). In order to create an S-notation file, the logfile is transformed to a Move-Insert-Delete (MID) file, independent of the word processor used, which includes a list of elementary keystroke operations (moves, insertions and deletions) in the order writers make them. Trace-it, general-purpose software developed for investigating writing strategies, presents the MID file generated by the S-notation in two windows: one for the revision record generated by the S-notation and the other for the final text produced. Trace-it has a replay feature which helps researchers to manually code the revisions and it can identify three types of revisions: repetitive revisions at one cursor location, embedded revisions and sequence of revisions in a previously written text (Severinson-Eklundh & Kollberg, 2003). S-notation can also identify the revisions generated by JEdit which functions as a logging word processor and runs on a Macintosh machine.

III.2.2. Progression Analysis

Perrin (2001, 2003) has presented Progression Analysis which is derived from S-notation and provides the progression of the writing session in several episodes. It incorporates keystroke logging analysis with retrospective accounts to interpret the writing process. Progression Analysis is a multilevel method for investigating the writing process as it examines three levels of the writing process, i.e. its context (macro level), the development of the text or its progression (meso level) and the use of writing strategies (micro level).

III.2.3. LS Graph

This programme represents the logged data graphically. One main feature of the graphical representation provided by LS Graph is the mult-layered information it presents, e.g. revision analysis, manual analysis of logged data and verbal data analysis. LS Graph can be used in both reseacrching and teaching writing to identify the different patterns of writing strategies used (Lindgren & Sullivan, 2002). Lindgren, Sullivan, Lindgren and Spelman Miller (2007) have presented an expanded version of LS Graph, Geographical Information Systems (GIS), which is used for visualizing spatial and temporal information about cognitive activities and for creating information layers from large quantities of data. GIS helps in identifying the time, the location and the way various writing cognitive activities occur and in understanding the intra- and inter-individual differences in writing processes.

The following section discusses the different ways of analyzing the data generated by the logging software.

IV. ANALYZING THE WRITING PROCESS LOGGED DATA

The keystroke logged data are saved as logfiles which have records of pauses, deletions, insertions and cursor movements, etc. The analysis and the interpretation of the logged data is not as easy process as it might seem due to lack of information about internal cognitive processes (Lindgren, 2005). The different word processors used in the previous studies increase the difficulties of comparing the taxonomies proposed by writing researchers. In addition, addressing the typographical corrections and the processor functions is another thorny issue in analyzing the logged data of the writing process. However, there are specific trends for analyzing the logged data of the writing process that can be identified in the previous studies. Generally speaking, taxonomies used in the previous computer-aided writing studies have focused on analyzing the logged data in three different ways: analyzing the whole writing process, analyzing the revision component and analyzing the temporal analysis of the writing process. Examples of the taxonomies belonging to these three categories of analyzing the logged data are given below.

IV.1. Analyzing the Whole Writing Process

Some studies employing the keystroke logging method used taxonomies to analyze the writing process as whole. An example of these taxonomies is Bridwell-Bowles *et al*.'s (1987) which includes the following types of writing behaviours: pausing, text production, editing, revision, cursor movement, scrolling and combinations of more than one operation. A different taxonomy that has been used for analyzing the ScreenRecorder data was developed by Owston, Murphy and Wideman (1992). Their taxonomy has four main categories which are based on keyboard actions; these categories are: a) text scanning and cursor movements (backward cursor, forward cursor, page up, page down, beginning point, endpoint and block highlight); b) menu-bar icon use (Apple, File, Edit, Windows, Search, Format, Spelling and Macros); c) text deletion (Backspace and Block); and d) text addition (Insert and Text Entry). Another taxonomy integrating a component for using computer referencing features was developed by Scott and New (1994). This taxonomy includes two categories: a) strategies considered to be effective for foreign language writing (adherence to guidelines, example inquiry, conjugation inquiry, French dictionary inquiry, circumlocution, browsing, error avoidance, a recursive approach and final revising); and b) other FL writing aspects evaluated (English dictionary dependence, quality of lexis and the time spent on the task in relation to the number of lines produced). The first category of strategies were given a frequency score of 1 = Never to 5 = Very often.

Combining the keystroke recorded data with verbal protocols, Levy and Ransdell (1994) developed a coding scheme of the writing process which has two main categories, one for the written protocols and the other for the verbal protocols. The written protocol category includes typing, deleting, superficial errors, meaningful changes, pausing at various levels of the text produced, any movement in text, and new paragraph. The verbal protocol category encompases pausing in speech, writing content, speaking and writing the same content, planning future topic content and rereading text written. In a later study, Levy and Ransdell (1995) developed their combinational response patterns for determining the writing subprocesses. These patterns include responses from writing protocol scored from visual track, pausing or starting new paragraph, typing, deleting, making meaningful or non-meaningful changes and any cursor movement.

Recently, Leijten and Van Waes (2005) developed categorization and transcription models for analyzing the composing process of their subjects. The categorization model is used for describing the different aspects of the writing process, i.e. writing modes, technical problems, revisions and pauses. The S-notation-based transcription model, on the other hand, provides a multi-layered linear representation of the writing process.

IV.2. Analyzing Online Revision

A main focus of the real-time computer-aided studies is analyzing the revisions made by writers while composing using the computer. Some real-time computer revision studies (e.g.

Lindgren & Sullivan, 2003) have used those taxonomies developed for handwritten revision. However, the majority of these studies have analyzed the logged data of revision in terms of computer-related categories. The following three taxonomies are examples of how real-time revisions were analyzed.

New (1999) has developed a Système-D-based taxonomy of revision which includes four categories, three of which are related to the type and level of changes made to the text (formal changes, meaning changes and length of changes) and one is related to the use of Système-D functions or inquiries. The formal changes category includes: spelling, tense, number, modality and word form, abbreviation, contraction, punctuation, capitalization, paragraph format, other format such as spacing and indent, typographical corrections, grammar and no change. The meaning changes category encompasses: addition, deletion, substitution, permutation, distribution and consolidation. The length of changes category has the following types: graphical change, lexical change, phrasal change, clausal change, sentence change and multi-sentence change. The last category, Système-D functions, includes: both English and French dictionary inquiries (example and conjugate, note and scroll), index (vocabulary, phrase and phrase) and save. Van Waes and Schellens (2003) have analyzed online revisions in terms of seven categories. These are: a) number of revisions; b) type of revision (addition, deletion, substitution and reordering); c) level of revision (letter, word, phrase, sentence, paragraph, layout and punctuation); d) purpose of revision (correction of typing errors, revision of form and revision of content); e) location of revision (title, first paragraph, first sentence of paragraph and elsewhere); f) remoteness of revision as measured in terms of the number of lines above or below the point of inscription; and g) temporal location of revision (stage, segment and unit). A recent keystroke data-based revision taxonomy was used by Stevenson, Schoonen and de Glopper (2006). The four dimensions of their multi-dimensional revision taxonomy are: a) orientation (content, language and typing); b) domain (clause and above, below-clause and below-word); c) location (pre-text, point of inscription and previous text); and d) action (addition, deletion, substitution and other).

IV.3. Analyzing the Temporal Aspects of the Writing Process

Real-time computer-aided writing is a rich area for examining and analyzing the temporal aspects of the writing process because the logged data provide an accurate account of the timing of each key press, cursor movement and pause. A main focus of temporal analysis of the logged data is the location of pauses. Levy and Ransdell (1994) analyzed pause location in terms of pausing within a word, pausing within a clause or a sentence, pausing within a paragraph and general pausing between paragraphs. Similarly, Van Waes and Schellens (2003) identified pauses within the sentence, at sentence boundaries, and at paragraph boundaries. On the other hand, Spelman Miller (2000) defined pause location based on potential completion points at a number of levels: character, word, intermediate constituent, clause and sentence.

Van Waes and Schellens's (2003) more comprehensive taxonomy of the writing process temporal aspects includes the following categories: a) ratio of time spent pausing to time spent actively writing; b) number of words in the final text; c) duration of pauses; d) number of pauses; e) type of pause (formulation pauses and revision pauses); f) linguistic location of pauses (character, word, clause and sentence); and g) temporal location of pauses. The two authors constructed their subjects writers' profiles based on analyzing the variables related to three aspects of the writing process: time spent on writing the final product, total duration of the writing process, and duration of each stage of the process (stage 1 from starting to completing the first draft and stage 2 from completing the first draft to completing the final version). Combining pause with edits, Epting's (2004) taxonomy has these categories: a) question reviews (number of reviews and total review time); b) pause measures (pre-response time, post-response time, average pause length, total number of pauses and total number of non-stop pauses); c) pause associated edits (PAEs) (deletions, substitutions, insertions, backspace and total PAEs); d) edits without pause (EWPs) (deletions, substitutions, insertions, backspace and total PAEs); and e) total edit indices (total PAEs and EWPs, and keystroke/released characters). Hayes and Chenoweth (2006) analyzed some other temporal and logged data aspects; these include: a) transcription rate (words typed per minute); b) error rate (uncorrected errors per 100 words); c) correction rate (corrected errors per 100 words); d) wasted keystrokes (percentage of total keystrokes devoted to deleting errors and to typing the errors that were corrected); and e) number of bursts in each trial (a burst is a period of continuous typing followed by a spontaneous pause of 2 or more seconds in which no typing occurred).

In the following section, the author briefly reviews the previous studies employing keystroke logging in investigating the writing process.

V. COMPUTER-AIDED WRITING PROCESS RESEARCH: AN OVERVIEW

The previous studies using keystroke logging in investigating the writing process can be classified into five categories: a) studies on revision; b) studies on the temporal aspects of the writing process; c) studies on using the logged data to stimulate writers' retrospection; d) studies on the writing process as a whole; and e) studies on the other aspects of the writing process.

V.1. Studies on Revision

A large number of studies have used keystroke logging to investigate revision. Some of these studies were conducted in the L1 context, including Bonk and Reynolds's (1990) intervention study on the revisions made by students in five tasks, Epting's (2004) investigation of the revising strategies of college students, and Severinson-Eklundh and Kollberg's (2003) study of revisions made by Swedish university students in their L1. The

three studies revealed that expert modeling of writing prompts lowered the number of changes students made during the writing process (Bonk & Reynolds, 1990), that the computer-based writing task had a major influence on revisions resulting from problem-solving processes (Severinson-Eklundh & Kollberg, 2003), and that writing and editing behaviors varied depending on pre-response time, i.e. the amount of time spent before beginning writing (Epting, 2004). The two studies conducted by New (1999) and Kim (2002) have used keystroke logging to examine revision in the FL and L2 contexts, respectively. Using Système-D, New (1999) found that advanced intermediate level learners of French (FL) were mainly concerned with making changes for form rather than for content in computer-aided writing and that their linguistic concerns and lack of explicit instruction of revision and computer strategies hindered the reviewing and reworking of their texts. Kim (2002) made use of Track Changes functions in Microsoft Word to identify the textual changes made by her English-as-a-second-language (ESL) subjects and found that intermediate writers made more mechanics changes than advanced writers and that both groups made the largest number of changes in grammar.

Other researchers have used keystroke logging to examine revising in both L1 and L2/FL. Using Trace-it to compare the online revisions made by undergraduate writers in L1 (English) and FL (German), Thorson (2000) found that writers made more immediate and distant revisions in German than in English. The two studies of Lindgren (2005) and Lindgren and Sullivan (2006) used keystroke logging to examine revising in L1 (Swedish) and English-as-a-foreign-language (EFL) writing. Both studies found that writers undertook more pre-contextual revision of both form and concepts in their English texts than in their Swedish texts. The latter study also indicated that writers revised more at the point of inscription in FL than in L1. Stevenson *et al*. (2006) used Trace-it to compare online revisions made by 22 Dutch junior high school writers composing four argumentative essays, two in Dutch and two in English (FL). Their results indicated that writers made revisions at the linguistic level more frequently in FL than in L1 and that little relationship was found between revision frequencies and text quality.

Some researchers used keystroke logging to compare how students revise in the computer-based mode and in the handwriting mode. Collier (1983), and Collier and Werier (1995) video-recorded the computer screen activities of 3 professional writers to compare their computer revisions with their pen and paper ones. While the results of the first study showed that revision using a word processor is more complex than pen and paper revision, data obtained from the second study suggest that both writing modes are 'equally effective in creating texts'. Similar to Collier's (1983) results, Lutz (1987) found that her subjects, professional writers and experienced PhD student writers, spent more time writing, produced less text and made more changes on the computer task than on the pen and paper task. Lam (1992) used computer stroke records and text analysis to analyze ESL student writers' revision in relation to task mode (computer-based vs. pen and paper mode) and task type (expressive, persuasive and transactional). Her study showed that writers made more changes and revised more recursively in their computer drafts than in pen and paper ones, but did not revise differently in the three task types. Using ScreenRecorder, Owston *et al*.

(1992) compared the effect of computer-based writing and a paper and pen writing on text quality and revision strategies. Contrarily to the findings of many studies reviewed here, their study found that writing on a computer neither led to making more revisions nor producing a text with a better quality than writing using pen and paper.

V.2. Studies on the Temporal Aspects of the Writing Process

Many studies have made use of the logged data in exploring the temporal aspects of the writing process such as writers' pausing and production rate. Using Keytrap, Van Waes (1991) compared the effect of writing in three different modes (pen and paper, computer with a 25-line screen, and computer with a 66-line screen) on the time spent writing, text length, pause behaviour and revisions made. Van Weas's study revealed that compared to pen and paper writers, computer writers spent more time writing the first draft, produced longer text, paused more in the beginning of the sentences and spent less time on pauses between sentences and paragraphs, revised more at the letter level and less at the word level. But the total number of revisions, total writing and pausing time were comparable in computer and pen and paper writing modes. Replicating the same study, Van Waes and Schellens (2003) reached similar results.

The effort and time allocated to writing subprocesses were examined by Levy and Ransdell (1994, 1995, 1996) through videotaping of the computer screen and EventLog for analyzing the data, and by Piolat, Kellogg and Farioli (2001) using SCRIPTKELL. Levy and Ransdell's three studies indicated that writers devoted more time to generating text and planning ideas than to reviewing and revising and that the time devoted to each of these four subprocesses varied at the different phases of the composing task. Similar results were reached by Piolat *et al*. whose study revealed that 'planning and translating decreased across the first, second, and third phases of writing, whereas evaluation, revision, and execution increased slightly'. Examining the temporal differences between computer writing and pen and paper writing using reaction time tasks, Kellogg and Mueller's (1993) two experiments revealed that the use of word processor restructured the writing process in that writers allocated more working memory efforts to planning and reviewing when using the computer than when writing longhand. In a naturalistic case study employing the videotaping of the computer monitor, Ballard (1994) looked at the pausing behaviour of a professional ESL writer while composing different tasks using a word processor. Ballard's study indicated that puase length was longer prior to T-units than within T-units and that fluent writing, measured in terms pause length, had few pauses greater than 10 seconds. Janssen *et al*. (1996) used Keytrap to examine writers' pausing while they think-aloud. The logged data provided them with evidence that the think-aloud method does influence writers' pausing due to its reactivity.

Spelman Miller (2000, 2006) looked at the pause related phenomena (pause duration, pause frequency, pause rate and pause location) and rate of production (within text span) of 10 L1 (English) and 11 ESL university student writers of English through the micro analysis

of the keystroke logging data. Results showed that ESL writers tended to pause longer than native-English writers at all locations, particularly at clause and sentence completion points and that they had a lower rate of production. Rate of production has also been addressed in a recent study by Hayes and Chenoweth (2006) who used articulatory suppression, a technique that reduces working memory, to test the hypothesis that verbal working memory is not involved in typing and editing the text. The logged data they collected did not confirm the tested hypothesis as writers in the articulatory suppression condition typed their texts significantly more slowly and made significantly more errors than they did in the control condition. In their attempt to develop a new index for measuring writing fluency, Matsuno, Sakaue, Morita and Sugiura (2007) used keystroke logging to observe L1 and EFL writers' production rate. Based on their findings that the Japanese writers of English had heavier production processing efforts or loads and were less fluent than native writers of Engilsh, they conclude that the reduction value of the processing loads can be an effective index for measuring writing fluency.

V.3. Studies on Using the Logged Data to Stimulate Writers' Retrospection

Another area of the computer-aided writing process research is using the logged data to stimulate writers' retrospective accounts of their composing strategies and to raise their awareness of them. Two early attempts of that kind were made by Flinn (1987a) who used the data logged by COMPTRACE to stimulate 2 sixth graders' retrospective thoughts about their revising strategies, and Sirc (1988) who used the real-time playbacks of the computer keystroke-recorded writing sessions to stimulate his subjects' retrospective accounts of their composing process. These two studies revealed that replaying the logged data was very a helpful tool in stimulating subjects' retrospective thoughts about their composing decisions. Likewise, Ransdell (1995) found that using the real-time replay of the keystrokes, generated by special memory-resident software during word processing, to stimulate her subjects' retrospective accounts while watching their letters display is less intrusive than having them think aloud while composing. Replaying the data logged by Trace-it in stimulated recall sessions, Sullivan and Lindgren (2002) found that these sessions helped the subjects become aware of their writing behaviours and approach the writing tasks differently. Similarly, Lindgren and Sullivan's (2003) study indicated that stimulated recall, when used together with keystroke logging, raised students' awareness about revising and increased their non-surface revisions.

V.4. Studies on the Writing Process as a Whole

Some few studies employed the computer-aided methods to investigate the writing process as a whole without focusing on a specific component or aspect of it. These include the studies conducted by Bridwell-Bowles *et al*. (1985, 1987), Balkema (1985) and Bisaillon

(1997) who used a video-recorded computer-based task to examine the composing process of four advanced university learners of French as an L2. These four studies revealed that writing expertise played an important role employing the handwritten-task composing behaviours on the compute-based tasks (Bridwell-Bowles *et al*., 1985), and that computer writers made more superficial changes than meaningful changes to the text (Balkema, 1985), and spent more time on pausing than on other subprocesses (planning, text production and revising) (Bridwell-Bowles *et al*., 1987*)* and on correcting the written text, at the word level in particular, than on generating ideas (Bisaillon, 1997).

V.5. Studies on the Other Aspects of the Writing Process

The logged data has been used to explore other different aspects of the writing process. Webb (1992) investigated undergraduates' reading during composing by recording their transcription and cursor movements through which he inferred their reading behaviours based on the implied vision of the text. His study revealed that writers who reread their texts more did not necessarily rewrite more and that some writers' decisions about content and structure occurred prior to transcribing the text while others organized their texts while transcribing it. Using JEDIT and S-notation to investigate the non-linearity of the computer-based text, Severinson-Eklundh (1994) confirmed the hypothesis that writers composing on the computer developed their texts in a non-linear way, i.e. in a different order from that of the final presentation of the text.

Other aspects examined in the keystroke logging research of the writing process include students' use of integrated graphic media while composing (Johnson, 1992) and their use of spelling checker (Figueredo, 2006). Johnson's study showed that the writers who used graphic production tools to incorporate pictures or drawings into their reports made broader and more extended use of other program components than writers who did not make use of these tools. Figueredo's study, on the other hand, revealed that children participants whose typing skill accounted for differences in the length of their stories used the spell checker most often to correct misspellings and that they were mostly successful at choosing the correct words on the spell checker's list, regardless of its position on the list.

The logged data has also been used to examine the influence of some explanatory variables on the writing process such as word-processing–based teaching vs. non-word-processing teaching of writing (Benesch, 1987; Radziemski, 1995) and electronic writing proficiency (Youngquist, 2003). Benesch found that her 3 ESL college students made extensive revisions with pen and paper but they did not use computer time to revise, rather they used it for generating ideas, editing, and gaining familiarity with the technology. Radziemski's study showed a positive effect for word processing instruction on improving text quality. Youngquist's (2003) study indicated that neither word processing skills nor perceptions determined the quality of essays, but instruction that integrated technology to support the pedagogy of the writing classroom resulted in enhancing the quality of students' work.

Some other published works on the computer-aided study of the writing process (e.g. Flinn, 1987b; Jakobsen, 2006; Scott & New, 1994; Smith, Lansman & Weber, 1990) were mainly concerned with presenting some software and explaining the advantages it offers.

VI. CONCLUSION

This article has reviewed the software used for recording and analyzing the real-time data of the writing process, and the different trends of writing process research employing the keystroke logging method. Compared to other related methods, keystroke logging is an unobtrusive, effective and simple way of collecting data about the composing process. In addition, the data offered by this method about writers' revision and the temporal aspects of their processes in particular are unobtainable by other methods. The logged data have deepened our understanding of these two important dimensions of the writing process and enabled writing researchers to have a clearer and more accurate picture about them. Results on using the logged data to stimulate students' retrospective accounts of their writing process are also promising in that they have shown the effectiveness of this type of data as a secondary research method and as a teaching tool that can inform teachers about their students' writing process and computer writing proficiency and help students become aware of their own writing strategies. Given that computers are increasingly used for performing different writing tasks, we might expect that keystroke logging will be the most commonly used data source in writing process research in the years to come.

As the review has shown, however, analyzing and interpreting the logged data is not an easy process. The area of analyzing the logged data is still lacking truly valid taxonomies for analyzing this kind of data; these analysis categorizations need to be consistent with those developed for analyzing writing process introspective and retrospective data. An optimal way of making the most use of keystroke logging data is to combine it with other data sources, such as verbal reports, that can help us identify writers' internal processes. More research is needed on how combining keystroke logging with different data sources can enhance our understanding of the writing process. This approach has been adopted by some of the above reviewed studies, e.g. Lindgren (2005) and Stevenson *et al*. (2006). Recently, keystroke logging data has been combined with eye-tracking, a technique that can provide important information about what writers do while composing particularly in their monitoring and revision operations and about the interaction between perception and production while composing (Stromqvist *et al*., 2006: 62, 70).

As the above review of the previous writing process studies employing keystroke logging shows, the majority of these studies have investigated either writers' revisions or the temporal aspects of their composing. More research is needed on the writing process aspects that have received little attention in the previous studies such as reviewing strategies and using the referencing features of word processors. In addition, the findings reached by the previous studies reviewed about writers' revisions or the temporal aspects of their composing process need to be documented by further research employing keystroke logging.

It can be noted also that only thirteen out of the forty-six studies reviewed in the above section have used keystroke logging in exploring L2/FL composing, and that none of the studies reviewed has used this method in investigating the writing process in some languages such as Chinese, Spanish or Arabic. Accordingly, more writing process research making use of the logged data is needed in the L2/FL contexts and in these unexplored cultural backgrounds. Finally, more research is needed to further document the pedagogical implications of the keystroke logging method.

NOTES

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