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Sirine Bouriga, Thierry Olive

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**Is typewriting more resources-demanding than handwriting
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Correspondence: Thierry Olive, Thierry.olive@univ-poitiers.fr

Abstract

The present study investigated cognitive effort of handwriting and typing of undergraduate students. In Experiment 1, we used a secondary reaction time task to assess the cognitive effort required by undergraduates when carrying out handwriting and typing copying tasks. Students had longer reaction times, indicating greater cognitive effort, when typing than when handwriting. In experiments 2a and 2b, we investigated whether the additional cost of typing affected an ongoing activity.

Participants performed a short-term memory task that required them to type or write by hand words to recall. As Experiment 1 suggested that typewriting was more effortful than handwriting, so it should leave fewer resources to devote to memorizing words, which would result in a better handwritten than typed recall results. Overall, handwriting led to better recall than typing, particularly with the longest lists of words. This implies that, even in undergraduates, typing is still more effortful than handwriting and therefore has a negative impact on performance of an ongoing activity. The educational implications of the findings are discussed.

1. Introduction: writing with computers

Computers are ubiquitous in daily life, particularly for students, who use computers for both personal and academic purposes. In addition, the use of writing has strongly grown in the last decades, mainly as a consequence of the emergence of social networks and digital communication (Brandt, 2015). As a result, students compose texts and take notes more frequently with computers than with pen and paper. It is therefore important to study how the characteristics of the computer (keyboard, screen size, presence or absence of a mouse etc.) and of the word processor application (presentation modes, spellcheckers, etc.) may affect how students compose texts or take notes. Furthermore, writing being a transversal skill used for several other learning, difficulties with writing, and in the present case with typing, might deprecate learning. In the study we present in this article, we therefore compared the cognitive effort of typing and of handwriting of undergraduate students and, second, we investigated whether typing, by contrast with handwriting, may be detrimental to on-going learning activities.

The impact of using a computer for composing a text has long been an issue of debate with regard to whether composing with a computer is beneficial or not to writers. Empirical studies have indeed provided mixed results showing positive and negative effects of computers when composing texts (e.g., Yamamoto, 2007). Two metareviews (Bangert-Drowns, 1993; Goldberg et al., 2003) concluded that texts composed with a computer are generally longer and of higher compositional quality than handwritten texts, with students with learning disabilities benefitting most (Morphy & Graham, 2012). Nevertheless, writing with a computer might also create difficulties for writers. For example, revising errors in a text presented in scrolling mode requires more reading than when it is presented in a mode with visible page borders (Piolat et al., 1997). The presence of marks that signal spelling or grammatical errors draws writers' attention

away from their on-going thoughts and reflections, leading them to devote more effort to revising the surface aspects of their text than its content (Daiute, 1986; Van Waes & Schellens, 2003).

Writing with a computer also increases the cognitive effort required for the writing processes (Kellogg & Mueller, 1993) as well as increasing the number of pauses and total pause time (Van Waes & Schellens, 2003), and it reduces frequency of planning and reviewing (Kellogg, 2001).

Similarly, whether using a computer for taking notes is beneficial or detrimental is still in debates, especially regarding learning outcomes. Some studies indeed found negative effects of taking notes computers, others found benefits, while in some cases longhand and computer note takers did not differ. For instance, Bui et al. (2013) observed that laptop note takers recalled more information than longhand note takers on an immediate performance test. Fiorella and Mayer (2017) examined student's retention and transfer of information and observed that the students who took notes with a computer outperformed those who used pen and paper. Mueller and Oppenheimer (2014) showed that computer note taking negatively affected students' responses to conceptual questions (Experiments 1 and 2) but did not affect memory of factual information which was recalled at the same extent by longhand and computer note takers, excepted when the students were asked to study their notes after the note-taking session (Exp. 3). In this case, responses to factual questions were better when notes were taken with pen and paper. However, in Experiment 3, all students were asked to review their notes before responding to questions, which was not the case in experiments 1 and 2. Morehead et al. (2019) observed opposite findings: longhand note takers performed better at factual questions but not at conceptual questions. According to Luo et al. (2018) taking notes with a computer generally lead students to change their learning strategy by adopting more linear and verbatim strategies (see also Piolat et al., 2005). For example, Fiorella and Mayer (2017) showed that students used less

spatial learning strategy when taking notes with a computer than with pen and paper. These changes in learning strategy may result in different processing and encoding of information. With more verbatim strategies, students would, on one hand, tend to encode information verbally and, on another hand, would process it at less deep levels (Aragón-Mendizábal et al., 2016; Luo et al., 2018). The effects on achievement of using a computer for taking notes therefore appear to depend on students' strategies for taking and reviewing notes, as well as on the format of the information presented to students.

This discrepancy in findings may result from different characteristics of the writing environments with which students may be more or less skilled. For example, composing with pen and paper or with a computer requires different input devices (a pen or a physical keyboard), common motor and visual spaces in handwriting but different ones when typing (the pen on the sheet vs. the keyboard below the computer monitor; Wollscheid et al., 2016), with visual spaces of various sizes which can result in different global senses of the text (Hansen & Haas, 1988). Of interest, differences in typing skills lead to attentional division: low skilled typists need to divide their attention between the motor and visual spaces while high skilled typist can focus their attention onto the visual space (the text displayed on the screen). In addition, word processor applications may provide beneficial and effective support to the writer with tools that are not available when writing with pen and paper. For instance, spellcheckers and grammatical analyzers can help writers to avoid orthographical errors; plan modes can help the writer to organize a text and to review its structure; the legibility of the typed text facilitates rereading and reviewing, etc. The same holds with note taking applications which can provide different options to students that may be more or less beneficial (Boyle, 2012). Accordingly, comparing writing or note taking with pen and paper or with a computer requires considering the differences between

analog and digital writing environments. In the present study, we precisely focused on input modality (and their related consequences) by looking at possible difference between handwriting (with a pen and paper) and typing (on a physical keyboard) skills.

When using computers for writing or for taking notes, students' typing skills may indeed be a source of difficulty for students, and particularly for those who experience learning difficulties (Weigelt-Marion & Weintraub, 2018) or dystypia (Sharma et al., 2019). Although a majority of students now have several years of typing experience and may be considered skilled typists (Logan & Crump, 2011), learning to type is less formalized than learning to handwrite, which requires long and intensive training from kindergarten to primary school (Berninger et al., 2015; Connelly et al., 2007; Cutler & Graham, 2008; Graham & Weintraub, 1996; Morin et al., 2009; Troia et al., 2009; Vander-Hart et al., 2010). Generally, students teach themselves to type and acquire suboptimal, idiosyncratic finger-key associations (Yamagoshi & Logan, 2014).

From this perspective, a first question is whether typing is as automated as handwriting in undergraduate students? A second, is whether less automated typing may affect an on-going activity that involves typing? Low skills in transcription may indeed be detrimental because resources that otherwise would have been allotted to the central processes involved in taking notes or composing a text have to be devoted to the mechanical process of transcription (for handwriting see Bourdin & Fayol, 1994, 2000; McCutchen, 2000). It follows that students' poor typing skills may affect their writing performance or academic success. This study aimed to provide answers to these two questions. In Experiment 1, we evaluated students' cognitive effort related to typing. In Experiments 2a and 2b, we compared writers' word memorization when required to type or write responses by hand.

2. Handwriting and typewriting skills

Writing down a segment of text requires several cognitive processes: conceptualizing and structuring the content, formulating a text segment by selecting syntactic frames, accessing the mental lexicon, finding the correct spelling of words and revising what one has written. Prepared segments of language can be transcribed in handwriting or by typing; both processes involve motor activity that creates a representation of the appropriate graphical symbols in the writing space. Handwriting, however, is a very fine and complex motor activity, and typing requires bimanual coordination

2.1. Learning to handwrite and to type

Learning to write by hand requires children to acquire knowledge on how to trace the letters of the alphabet and to practice handwriting to gain proficiency in movement execution and manual dexterity. Practicing handwriting allows children to learn the motoric parameters of each letter and to develop procedural knowledge that specifies letter shape, stroke order and direction (van Sommers, 1984). They use retroactive control based on visual and motor feedback to monitor their production, which is made stroke by stroke. With practice, children build motor programs at the letter level, each motor program consisting of chunks of strokes, and they switch to proactive control of their handwriting. At this stage movement variability decreases and movement fluency and speed increase. At the beginning of learning, handwriting is highly effortful but with practice, it is only towards the age of 11-12 years that children begin to master handwriting and their personal handwriting style emerges. Handwriting is considered automatic around 14 years old (Tucha et al., 2006).

Learning to type is a different process. Novice typists serially encode the letters of the words, find the correct key and then move a finger to that key (Yamaguchi & Logan, 2014).

Translating letters to keystrokes is very effortful at this stage. In contrast, skilled typists use all fingers from both hands and press the appropriate keys without looking at the keyboard (Johansson et al., 2010) by encoding a word and activating in parallel multiple keystrokes (Crump & Logan, 2010). Acquisition of typing results from three types of associations: (a) associations between words and letters, (b) associations between letters and keys and (c) associations between keys and fingers. Skilled typing is hierarchically controlled with an outer loop that operates on the word-level, whilst an inner loop operates on the letter- or keystroke-level (Logan & Crump, 2011). While practicing and acquiring knowledge of words, typists chunk letters according to their probability of co-occurrence or contingency (Yamaguchi & Logan, 2014).

2.2. The effect of low transcription skills on writing performance

Transcription skills play an important role in writing performance. They are the main contributor to fluency and quality of composition in primary grade children (Berninger et al., 1992) and their contribution decreases during intermediate and junior high grades giving place to constraints related to linguistic skills (see also Limpo & Alves, 2013). Transcription skills continue to contribute to writing performance in undergraduates composing for an examination (Connelly et al., 2005). Associations between undergraduate students' handwriting fluency and the quality of their note taking have also been observed (Peverly & Sumowski, 2012).

Poor handwriting affects central processes by competing for common working memory resources. Indeed, whereas adult recall a similar number of words when speaking or when writing, children recall more words when speaking than when writing (Bourdin & Fayol, 1994; Janczyk et al., 2018). Because handwriting is slower than speaking it is possible that the time it took children to handwrite the words made them forget words. After controlling for recall rate,

Bourdin & Fayol (1994) observed a modality effect in children but not adults and observed that adults who used an effortful unfamiliar cursive upper-case calligraphy also recalled fewer words than when they used their familiar, automatized handwriting style. Grabowski (2010) extended these findings to typing by asking adult participants to recall words with scrambled keyboard. As expected, participants recalled fewer words with such a keyboard than with a familiar standard one.

3. Rationale

Although today's students have some typing skills as they frequently use keyboards, few of them receive formal training in typing (at least in France where the study has been conducted), so we first tested the hypothesis that typing is more resources-demanding than handwriting in undergraduate students. In Experiment 1 we assessed students' cognitive effort during the copying of a text in handwriting and by typing. Because Experiment 1 showed that typing was more resources-demanding than handwriting, we next tested whether these additional demands hampered usual execution of central processes. In Experiments 2a and 2b, students memorized words they subsequently had to recall by typing or in handwriting. Since typing was more resources-demanding than writing by hand, one would expect fewer resources to be available for maintaining words in short-term memory. Hence, we predicted that students would recall more words when writing them by hand than when typing them.

4. Experiment 1: Cognitive effort of typing during copying

In this experiment we assessed students' cognitive effort - defined as the amount of working memory capacity or resources needed for copying - when copying a text by handwriting

and by typing. This task was performed with a pen and paper as well as a keyboard and a computer. The copying task was chosen because it mainly involves transcription processes and limits the involvement of other higher-level processes, as students do not need to plan, formulate or revise a text. Despite the virtual absence of higher-level processes, text copying involves resources to temporarily store the text segments to be copied in short-term memory. Therefore, the formatting of copy sheets has been designed to minimize the short-term demands associated with memorizing these text segments. To this end, the original text had to be copied onto blank lines inserted between the lines of the original text so that it would remain in the same physical space as the copied text. In this way, students were able to consult the original text when they needed to read it.

Students copied the text whilst simultaneously responding to randomly distributed auditory probes. Reaction times (RT) to secondary auditory signals can indeed be considered as a measure of the effort associated with the primary activity that is interrupted by the signal (Kahneman, 1973; Kerr, 1973; Power, 1986). When simultaneously performed, the primary and secondary tasks have to share limited cognitive resources. No longer having the amount of resources that they usually require, the primary or secondary tasks are affected and their performance is presumed to decrease. As a consequence, secondary RTs are interpreted as revealing cognitive effort related to the primary task. The secondary reaction time task has been used in several studies on text composing (for a review, see Olive, 2004) and note taking (e.g., Olive & Barbier, 2017), and it does not interfere with the primary task (Piolat et al., 1999). We therefore expected that typing would require more cognitive resources, which should result in longer RTs. In addition, as previous research has shown that typing is faster than handwriting,

we also expected that participants would take more time to copy the text by handwriting than by typing.

4.1. Method

4.1.1. Participants

Thirty French undergraduate students (27 women), aged between 18 and 22 years ($M = 20$ years and 1 month), participated in the experiment in return for course credits. Each student completed the copying task twice, once by hand with a pen and paper and once by typing on the keyboard on a computer. Since the study was designed to assess the cognitive effort of typical undergraduate students, no selection of participants was made based on level of typing skill.

Therefore, all students who did not present psychological or medical difficulties were considered typical and were included in the study whatever their mastery of typing¹. All students reported having used physical and virtual keyboards on a daily basis for several years and the majority of them (over 90%) used a keyboard to take notes during class. Students who used a pen and paper to take notes reported using a keyboard to work and revise their notes. All the students also reported having more than ten years of experience with keyboards. None had received formal typing instructions.

1. All students also performed the Alphabet Task initially designed to assess handwriting automaticity in children (Berninger & Rutberg, 1992). The students carried out this task both by handwriting and by typing. Mean typing scores ($M = 31$, $SD = 6.2$) were significantly higher than handwriting scores ($M = 22$; $SD = 4.2$, $t(29) = -9.12$, $p < .001$). In addition, the typing scores at the alphabet task did not correlate significantly with cognitive effort of copying ($r = -.18$, $p = .35$). Because, to our knowledge, no other published data informs on the typed alphabet task in adults, it is therefore difficult to claim, based on the scores at the typed alphabet task, that typing is more automated than handwriting in undergraduate students. We rather suggest that these higher scores presumably do not capture typing automatization in adults, but rather the well-known higher speed of typing.

All students were treated in accordance with ethical guidelines: they gave free and informed consent before beginning the experiment, they were informed of their right to withdraw from the study, and the study guaranteed confidentiality. At the end of the study, the participants were debriefed about the goal of the study. All collected data were processed in accordance with the European Union's General Data Protection Regulation.

4.1.2 Copying and reaction time tasks

Copying task. The participants copied two texts, one by handwriting and the other by typing (the order of the two tasks was counterbalanced across participants). Two 26-line texts were used, each containing 239 words. In both the typing and handwriting conditions, the two texts were presented with an empty line below each line of text. In the handwriting condition, the text to be copied was presented on a A4 sheet of paper. Students were asked to use their normal handwriting style. In the typing condition, the text was presented on a 23-inch monitor of a desktop computer so that an A4-like zone was visible. We used Microsoft Word for presenting the text to copy and for recording the copied texts. The text to copy was displayed as a watermark and the line spacing of the Microsoft Word document was set to match the watermark lines. The pairing of text with condition was counterbalanced across conditions and participants (see Appendix A).

Reaction time task. Whilst they were copying the texts, students were asked to respond as quickly as possible to auditory probes that were presented at random intervals by pressing a pedal with their dominant foot. All students first performed the reaction time task on its own (see Procedure below), which allowed us to calculate their mean baseline RT and thus control for individual differences in RTs. Cognitive effort was indexed by subtracting mean baseline RT from each RTs collected during the copying task: the greater the difference, the higher the

cognitive effort. As in previous studies that used this method (see Olive et al., 2002), a series of 25 auditory probes were played at intervals of between 5 and 15 seconds in the baseline RT task, and at intervals of between 15 and 25 seconds during the secondary RT task, until the participant had finished copying. The ScriptKell program (Piolat et al., 1999) was used to randomly distribute the auditory probes, record the participants' RTs, and to record copying duration. Copying duration corresponded to the time elapsed between launch of Scriptkell and press on the end task key.

4.1.3. Procedure

Students were tested individually over two sessions. In one session, they copied the text in one mode (handwriting or typing) and in the second in the other mode; the order was counterbalanced. The same procedure was used in both these sessions. First, the students performed the RT task. After this, they performed the copying task. The experimenter explained to them that whilst they were copying, they would have to respond as quickly to the auditory probes, just as they had before.

4.2. Results

We analyzed modal (handwriting or typing) differences in RTs for assessing cognitive effort and in copying duration. Descriptive data are presented in Table 1. All collected RTs were first screened for outliers. RTs that deviated from the mean by more than 2.5 *SDs* were removed (4.5% of all RTs, which corresponded to 91 RTs). Because the Shapiro-Wilk test indicated that RTs were not normally distributed ($w = 0.82, p < .001$), we conducted a non-parametric analysis of RTs with the Wilcoxon test. This test confirmed that RTs when typing were significantly higher than when handwriting, $z = 27, p < .001, r_{rb} = 0.77$. Copying duration being normally

distributed, we ran a one-sided paired t -test which indicated that copying the text was shorter by typing than by handwriting, $t(28) = 4.47, p < .001$, Cohen's $d = 0.83$.

Table 1

Means and standard deviations of copying duration and cognitive effort in Experiment 1

	Handwriting		Typing	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Cognitive effort (in ms)	96	69	171	104 ***
Copying duration (in seconds)	636	90	511	128 ***

Note. *** $p < .0001$.

The fact that typing is faster than handwriting might explain the difference in cognitive effort. To test this possible relation between output rate and cognitive effort, we correlated copying durations to length of RTs in both the handwriting and typing conditions. Significant correlations would suggest that cognitive effort would reflect difference in output rate but not in level of automatization. A low positive but non-significant correlation was observed in handwriting ($r = .22, p = .23$) and no relation was observed in typing, $r = .04, p = .85$ (see Figure 1). This suggests that cognitive effort and copying duration may be minimally related in handwriting (the positive correlation indicates that the longer is copying duration, the higher the cognitive effort could be) and are not related in typing. We complemented this analysis by correlating copying duration when typing to the increase in RTs when typing (the difference in RTs between the typing and handwriting conditions). Again, these two variables were minimally and non-significantly correlated, $r = .10, p = .61$. None of these correlations being significant, cognitive effort may be little, if any, determined by copying duration.

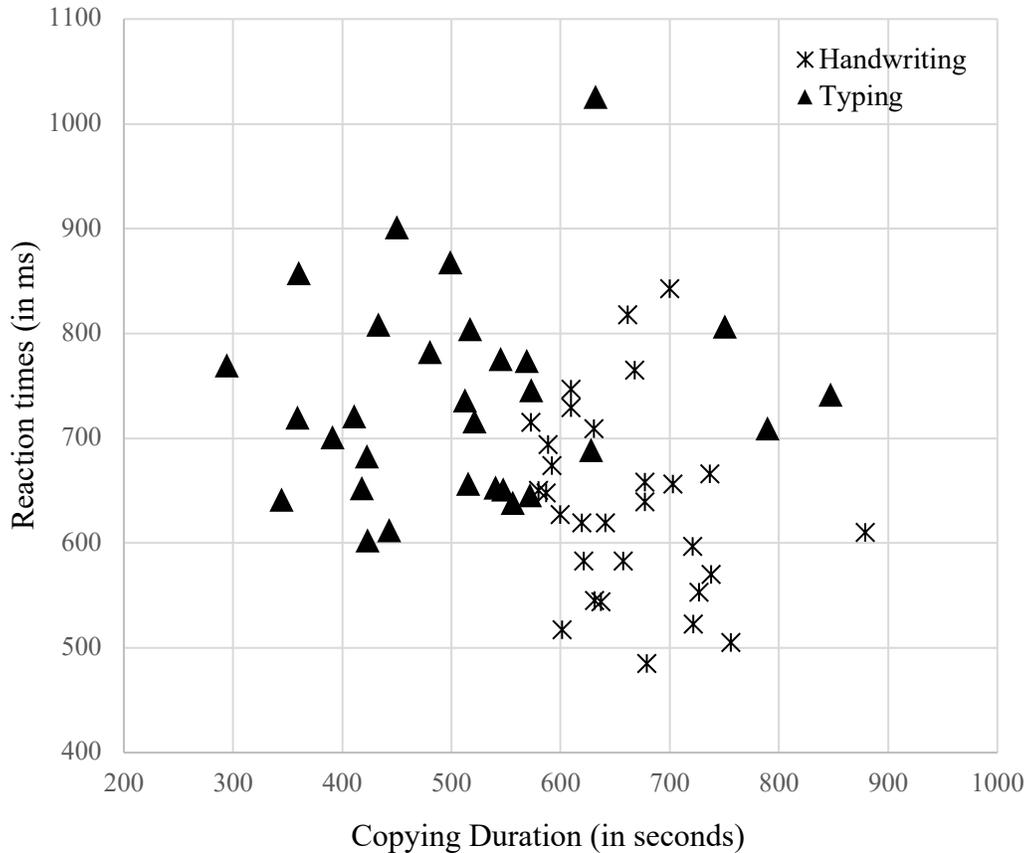


Figure 1. Scatterplot of copying duration and cognitive effort indexed by length of secondary reaction times when copying a text by handwriting or by typing.

4.3. Discussion

As expected, typing was faster than handwriting. This is a frequent finding in studies of text composition (Beers et al., 2017) and note taking (e.g., Mueller & Oppenheimer, 2014). Also, as expected, the analysis of RTs indicated that copying the text by typing was more effortful for students than longhand copying. The increase in cognitive effort could likely be explained by at least two reasons. First, it could be due to the faster speed of copying the text by typing relative to handwriting. By copying more words and letters per unit of time, typists may have more information to process than hand writers. For example, they can process more spelling information. Similarly, they may need to process more syntactic knowledge or semantic

information. This may require more cognitive effort than handwriting as it involves more information to be processed in working memory. Second, this increase in RT could also index the individual level of typing automatization. The students who participated in the study were French second-year undergraduate students, about 20 years old, who can be considered "digital natives", meaning that they grew up after computers became ubiquitous. They can therefore be considered as experienced typists. However, despite their individual practice, French students do not receive intensive formal training in typing, as in handwriting, which would lead to less automatized typing (with less robust associations between letters and keys, keys and fingers, or with a less efficient internal loop, Yamaguchi & Logan, 2014). This shorter learning curve may require more calculations to determine the correct keys, fingers and movements, instead of direct retrieval of these associations in long-term memory. To test whether the copying duration could explain the increase in cognitive effort, we calculated correlations between copying duration and RTs. We did not find any significant correlation, suggesting that the difference between output rates of handwriting and of typing may not be the cause of the increase in RT. In addition, several studies have shown that secondary RTs in writing activities are related to the level of automatization of targeted processes (for reviews, see Olive, 2004, 2012). Thus, it seems that RTs indexed the level of automatization of typing and was minimally affected by copying duration. It is noteworthy to signal that similar studies in other countries where the educational system operates differently might produce a different pattern of cognitive effort of typing.

Nevertheless, regardless of the reasons why typing requires more cognitive effort, that it takes up more resources means that one would expect fewer resources to be available for the central processing required by an ongoing task. We investigated this in Experiment 2, which

compared the effects of typing and of handwriting on students' performance of a short-term recall task.

5. Experiment 2a: Effect of Typing on Short-Term Recall

The effects of handwriting and typing in memory tasks were examined by investigating the effects of using a keyboard on the short- and long-term encoding of items. Despite the use of different tasks and methodologies, the studies have shown the detrimental effects of typing on the encoding of information compared to handwriting. For example, Mangen et al. (2015) showed that dictated words written by hand, by contrast with typed words, resulted in better immediate oral recall as well as in better visual recognition. Mangen et al. (2015) explained these findings by referring to theories of embodied cognition: handwriting involves sensory-motor processes that are specific to each letter, which is not the case with typists' movements. Consequently, handwriting leads to more distinctive traces in memory and therefore to better memorization and recall (see also Longcamp et al., 2003, 2005). Better oral recall of items encoded with handwritten compared to typed dictation was replicated with a word-copying task (Smoker et al., 2009), but also with a text-copying task (Frangou et al., 2018). This superiority of handwriting over typing seems to be stable over time. Frangou et al. (2018) showed that the recall performance of participants half an hour and a week after the experiment resulted in a better performance with longhand copying than when it was done on a computer. Aragón-Mendizábal, et al. (2016) also found that students were less able to recognize of word lists with a typed recall. They suggested that because typing is faster than handwriting, students process more information which is therefore less integrated in memory.

Accordingly, and based on the finding of Experiment 1, we hypothesized that typed recalled would be lower than handwritten recall in a short-term memory task. We tested this hypothesis using a within-subjects design in which participants were asked to memorize increasingly large sets of words and then recall them by handwriting and typing. This task was inspired by Bourdin and Fayol (1994) who showed that performance at a serial recall task was lower when transcription required more resources, for example in children compared with adults or when children had to write rather than speak the responses. Bourdin and Fayol suggested that because cognitive resources are limited, when transcription requires more resources, there are fewer resources available to memorize the words. Finally, it is important to note that unlike Mangen et al. (2015), Frangou et al (2015) and Smoker et al. (2018,) asking students to recall words by typing or handwriting as it was done in the present experiment did not manipulate item encoding, but their storage and retrieval.

5.1 Method

5.1.1. Participants

Twenty-seven French undergraduate students (24 women), aged between 18 and 23 years old, participated in the experiment in return for course credits. All students reported using physical and virtual keyboards on a daily basis for several years and the majority (over 90%) used a keyboard to take notes during class. Students who used a pen and paper to take notes reported using a keyboard to work and revise their notes. All the students also reported having more than five years of experience with keyboards. None had received formal typing instructions.

All students were treated in accordance with ethical guidelines: they gave free and informed consent before beginning the experiment, they were informed of their right to withdraw from the study, and the study guaranteed confidentiality. At the end of the study, the participants were debriefed about the goal of the study. All collected data were processed in accordance with the European Union's General Data Protection Regulation.

5.1.2. Serial recall task and procedure

Participants were tested individually. They performed a short-term word serial recall task twice, once for each input modality, either by handwriting the words to recall or by typing them on the keyboard of a computer (the words being visible either on the sheet of paper or on the computer monitor). Two 66-item lists of words were constructed in three series of four blocks from 4 to 7 words long. All words were controlled on length, number of syllables, and frequency (see Appendix B). Frequency values were taken from the *Lexique* database (New et al., 2004). In addition, to avoid possible effects related to orthographic processing of the words to recall (for example see Bourdin & Fayol, 1994), we also controlled orthographic consistency. Half of the words were orthographically consistent and the other half were orthographically inconsistent. Consistency scores were extracted from the Manulex infra database (Peereman et al., 2007). As we had no hypothesis related to orthographic consistency, consistency was not entered in the statistical analyses.

The experimenter specified to the participants that they had to recall the words in the order they were presented, by writing one word per line, and that they should use a dash to indicate each forgotten word. Participants were told that spelling of the words would not be considered. All words were presented, orally, in series, at a rate of one word per second. Each series started with a block of four words, followed by a block of five words and so on, finishing

with a seven-word block. After each block, the experimenter said “top” to inform the participant that he or she could begin recalling the words from that block. The length of time available for recall was not limited, but was recorded. The order of presentation of the recall modes and lists of words were counterbalanced. Before the beginning of each short-term recall task, the students were told which mode to use to recall the words.

We analyzed the number of words recalled correctly, in the correct position in the list, and the duration of each recall phase. Recall duration (in seconds) was recorded with a chronometer and corresponded to the time between the recall signal provided by the experimenter and the time when the participant finished recalling of a block of words.

5.2. Results and Discussion

One-sided paired *t*-tests were used to test the effect of writing mode on the number of words recalled and on recall duration. Table 2 presents the means and standard deviations. The order of presentation of the two recall tasks (handwritten/typed recall vs. typed/handwritten recall) was not significant ($F < 1$). There was no effect of recall mode on the number of words recalled, $t(26) = 0.42$, $p = .338$, Cohen’s $d = 0.08$. Participants recalled a similar number of words when handwriting and when typing. In contrast, recall duration was longer in the handwriting condition than the typing condition, $t(26) = 1.97$, $p < .05$, Cohen’s $d = 0.38$.

Table 2

Means and standard deviations of number of correctly recalled words and of recall duration as function of recall mode in Experiment 2a and Experiment 2b. Between parentheses, recall performance expressed in percentages.

	Handwriting		Typewriting	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
<i>Experiment 2a: Free recall rate</i>				
Number of words recalled correctly	48.8 (74%)	7.1	48.2 (73%)	5.1
Recall duration (in seconds)	281	85	253	80 *
<i>Experiment 2b: Fixed recall rate</i>				
Number of words recalled correctly	67.8 (60%)	8.8	62.8 (54%)	8.4 **

Notes. * $p < .05$; ** $p < .005$.

This experiment failed to show a difference between handwritten and typed recall, but recalling the words by typing was faster than doing so in handwriting. Since the trace of items stored in short-term memory deteriorates over time (Camos et al., 2009) we can assume that the memorized words were less accessible when participants recalled them by handwriting rather than by typing. If the recall rate were to be slowed down in the typing condition, a difference between the handwriting and typing conditions might emerge. We tested this in Experiment 2b by equating recall time in the typing and handwriting conditions. Specifically, we set an identical recall rate in the two conditions, based on the handwriting recall duration collected in Experiment 2a.

In addition, recalling lists of 4 to 7 words may indeed not place sufficient demand on short-term memory to reveal the additional effort of typing relative to handwriting. This explanation seems plausible, as the average recall performance was 74%. Accordingly, we

increased the difficulty of the task in Experiment 2b, by adding blocks of eight and nine words to each series.

6. Experiment 2b: Effect of Typing on Short-Term Recall at a Fixed Recall Rate

In this experiment, we imposed a fixed rate of recall and added two blocks of eight and nine words to each series. We expected typing to interfere more with the short-term memory demands of the task, leading to worse performance in the typed recall condition than the handwritten recall condition. We precisely expected an interaction between memory load and the writing modality: the difference between the two modalities should be higher with increasing load.

6.1. Method

6.1.1. Participants

Thirty French undergraduate students (28 women), aged between 18 and 22 years old, participated in the experiment in return for course credits. All students reported having used physical and virtual keyboards on a daily basis for several years and the majority (over 90%) used a keyboard to take notes during class. Students who used a pen and paper to take notes reported using a keyboard to work and revise their notes. All the students also reported having more than five years of experience with keyboards. None had received formal typing instructions.

All students were treated in accordance with ethical guidelines: they gave free and informed consent before beginning the experiment, they were informed of their right to withdraw from the study, and the study guaranteed confidentiality. At the end of the study, the participants

were debriefed about the goal of the study. All collected data were processed in accordance with the European Union's General Data Protection Regulation.

6.1.2. Task and material

We used the same task as in experiment 2a but with a fixed rate of recall of 6 seconds, derived from the median recall duration in the handwritten condition of Experiment 2a. A metronome beeped every 6 seconds to indicate to participants when to recall a word; they could only write or type one word per beep. We also increased the complexity of the recall task by adding blocks of eight and nine words to each of the three series of words per list, which resulted in 117 words per list (see Appendix C).

6.2. Results and Discussion

One-sided paired *t*-test indicated that recall mode affected the number of words recalled correctly, $t(29) = 3.22, p < .005$. The number of words recalled in the handwriting condition was higher than in the typing condition. The comparable recall rate in the handwritten and typed recall conditions and the increased memory load resulted in better recall by handwritten than by typing. This suggests that typing requires more working memory than handwriting in undergraduate students, and that this additional cognitive effort is detrimental to short-term memorization.

The relatively worse performance in the typed recall condition could be attributed to the fixed rate of recall or the increase in short-term memory load. To distinguish between these possibilities, we examined the interaction between recall modality and memory load. If the effect of modality in Experiment 2b resulted from the fixed recall rate, there should be a main effect of modality, regardless of memory load. If there was an effect of memory load, then the difference

should, at the least, be larger in the high-load condition, with this being reflected in an interaction between recall modality and memory load. We therefore conducted a repeated measures ANOVA on the percentage of words recalled with modality (handwritten, typewritten) and cognitive load (low-load: 4 to 5 words; high-load: 8 to 9 words) as within-subject factors (see Figure 2).

Because the number of words to recall was different in the two load conditions due to the different block sizes, using percentages allowed us to compare students' performances in the two load conditions directly, regardless of block size. This analysis also revealed a main effect of mode, with handwritten recall being superior to typed recall, $F(1, 29) = 14.76, p < .001$, partial $\eta^2 = 0.34$. There was also an effect of memory load, $F(1, 29) = 1464.90, p < .001$, partial $\eta^2 = 0.98$. Participants recalled more words from the low-load blocks than the high-load blocks. As expected, the mode x block interaction was significant, $F(1, 29) = 4.84, p = .036$, partial $\eta^2 = 0.14$. We therefore examined the mode effects in the two memory load conditions separately. Handwritten and typed recall did not differ in the low-load blocks ($t(29) = 0.65, p = .26$) but did differ in the high-load blocks, $t(29) = 4.35, p < .001$.

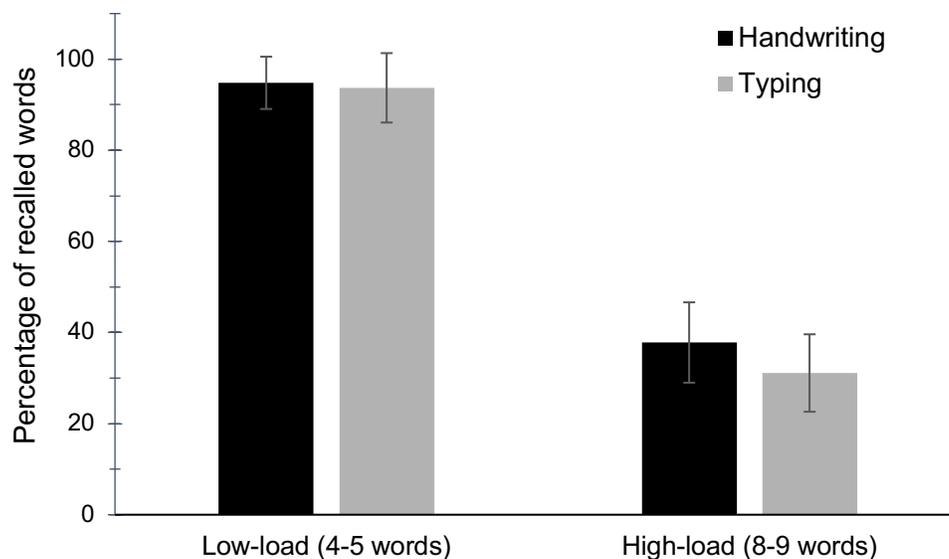


Figure 2. Mean percentages of correctly recalled words as a function of the load on short-term memory and mode of recall (handwriting vs. typing). Errors bars indicate standard deviations.

We carried out a final analysis of the effect of recall mode on recall of words in blocks of 4 to 7 words, as this was similar to the task used in Experiment 2a. A Student's *t* test did not reveal a significant difference between the handwritten and typed recalls when a fixed recall rate was imposed. This suggests that the absence of a mode difference in Experiment 2a was mainly due to the memory load being too low to demonstrate an effect of recall modality.

The difference in recall performance between the handwriting and typing conditions indicates that typing required more working memory, leaving insufficient capacity to support maximal recall performance. Students had to share their resources between effortful typing of the words they recalled and maintaining the remaining words in short-term memory, which had a detrimental effect on maintenance of the words in working memory. As the detrimental effect of typing was only apparent under a high load, it appears that typing is indeed more effortful than handwriting in undergraduate students, but this additional effort only has negative consequences under conditions of high cognitive load.

7. General Discussion

This study evaluated whether students' typing skills are as good as their handwriting skills. Although the students we investigated were second year university students - part of the millennial generation - and undeniably had some typing skills, few of them had received formal training in typing (which is typical in France). Compared to the long teaching of handwriting, this lack of training might lead to less efficient transcription of the text. We therefore hypothesized that typewriting would be more resources-demanding for undergraduate students than handwriting. We further examined whether the working memory capacity required for handwriting and typing had an impact on the ongoing activity. We reasoned that if typing is more

resource demanding and more effortful, then typed recall should need more working memory than handwritten recall, leaving less for retaining the words in working memory. We expected, therefore, that students would recall fewer words when typing.

The results confirmed our hypotheses. Experiment 1 showed that students expended more cognitive effort when copying the text with a keyboard than with a pen. Because students copied lines of texts that were present in their visual field, we minimized the short-term memory demands of the task and the main cognitive demands of the copying task could be associated with difference in input modality, i.e. with using a keyboard (and a screen) or a pen and paper to copy the text. However, we observed that copying the text by typing also led to shorter copying duration than when handwriting it. Therefore, the increase in cognitive effort may have come from the fact that students had more information to process at a given time when typing than when hands-writing. Because no significant correlation was found between copying duration and cognitive effort when typing, we rather suggest that the increase of cognitive effort associated to typing (relative to handwriting) was mainly determined by students' individual level of automatization of typing. Nevertheless, further studies are needed to investigate and understand how the higher output rate of typing, as opposed to those of handwriting, can affect the cognitive demands of typing, and consequently the on-going activity, both at the product and process level.

The higher effort related to typing might have resulted in changes to copying behavior. For instance, one way in which students could have adapted to the greater demands of typing is by holding shorter chunks of text in working memory (Rothkopf, 1980). The study design did not allow us to examine copying span. Eye movement studies could be used to capture changes in copying span. Hiding the original text and analyzing the number of times it is consulted would

also provide interesting information about how students adjust their copying strategy to cope with the additional effort required to type rather than write by hand.

In Experiment 2, we examined the impact of the higher demand of typing on a short-term memory recall task. We reasoned that, given limited working memory capacity, the extra demands of typing at the moment of recall would leave less working memory available for maintaining the list in short-term memory. As expected, students recalled fewer words when they were typing than when they were writing by hand, but the effect was only detectable under a high-load, suggesting that although typing does indeed require more resources than handwriting, the additional demands are limited, such that they only have a detrimental effect on ongoing task performance with very effortful tasks. The effect of mode on recall was only apparent when we controlled for recall duration, as both experiments confirmed that students' typing was faster than their handwriting.

In addition, the impact of typing on serial word recall was observed only for the highest memory load (when students had to remember more than five words). This suggests first of all that the additional demands imposed by typing, as opposed to handwriting, are relatively small. It also suggests that typing can interfere with ongoing activities, but only when these activities are very expensive and require the majority of available resources (McCutchen, 2000). For example, when composing a text, typing is likely to interfere primarily with planning and editing. Indeed, these two processes are the most resource-intensive (Kellogg, 2001; Olive, 2004). In addition, planning and revision are often activated during transcription (Alves et al., 2008; Olive et al., 2009). Thus, it can be expected that with fewer resources available during keyboarding, planning and revision will be more heavily solicited during pauses rather than simultaneously with transcription. Second, it can also be expected shorter execution periods

during typing than during handwriting. Indeed, it has been shown that increased transcription demands generally result in shorter bursts of language (e.g., Alves et al., 2007, 2011; Alves & Limpo, 2015). Further study is therefore needed to better understand how typing affects real-time supervision of writing processes. Similarly, the additional cost of keyboard typing can affect note-taking, especially the more expensive processes of note-taking (such as integration of information in long-term memory or comprehension). This could have repercussions on the quality of the information memorized by noters and as a consequence on its academic performance. As indicated in the introduction of this article, published research on the impact of keyboarding does not yet allow us to decide on its positive or negative effects on note-taking (Urry et al., 2020).

Beyond these effects of transcription modality on cognitive effort, it is important to point out that digital writing environments (i.e., input devices, monitors, software, tablets, smartphones...) present features that are different in nature than the pens and papers usually required for handwriting. Comparing writing activities carried out by hand or with a digital device requires investigating how these various dimensions simultaneously change with a digital writing tool. Although keyboards are the default input device in digital writing environments, newer digital writing tools such as those that require smart pens for example may be closer to the analog writing environment, and could offer a different experience of writing for students (Boyle & Joyce, 2019).

8. Educational Implications

The finding that the cognitive demands of typing may affect the ongoing activity is important for education. As a majority of students now use computers and tablet keyboards to

take notes and write academic texts, it is important to ensure that the way they interact with computers does not consume additional resources, relative to handwriting, at the expense of the learning activity. This is even more important as writing also supports learning.

Writing and note taking are effortful activities that overload students (Flower & Hayes, 1981; Olive, 2004, 2014). Importantly, even after long practice, writing still requires high cognitive effort. This is due to the fact that the processes of planning, formulating and revising text, which are fundamental to the creation of written discourse, can only be carried out effectively with effort on the part of the writer. In contrast, typing or handwriting that does not involve constructing a discourse can be automatized. As shown by writing research, one of the fundamental aspects of learning to write fluently is learning to manage the overload involved in constructing and recording written discourse by automating the transcription processes (McCutchen, 1996, 2000). This is why handwriting has to be learnt first, before spelling, planning and all the other processes involved in writing. The results of this study suggest that schools should devote more attention to ensuring students learn to type efficiently.

Importantly, writing is also used to assess knowledge and academic performance. The relatively greater amount of resources devoted to typing, compared with handwriting, may have repercussions for students' performance in examinations. Thus, poor performance may be falsely attributed to lack of knowledge instead of to the cognitive demands imposed by poor typing skills. Students should therefore be warned that unless they are proficient typists, using a keyboard may have a detrimental impact on their academic performance.

Finally, because poor typing skills can negatively affect the activities in which students are engaged, it is vital that students become skilled typists. Formal teaching of typing should become the norm in schools, because students who teach themselves to type often automatize

idiosyncratic, suboptimal finger-key associations. Formal education in typing should begin as early as possible, in primary school.

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