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PhD Thesis

DOES THE WAY WE INTERACT WITH TECHNOLOGY AFFECT COGNITIVE PERFORMANCE?

An in-depth analysis of writing devices

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General Introduction

"Writing *is* a technology", claimed Ong (1986). Writing is a means by which we materialize our thoughts through a combination of intellectual and manual skills. Therefore, writing is a complex skill indispensable for shaping language development and manual abilities in children and to contribute to the intellectual development of all of us. Writing is extremely interiorized in our culture and in each literate human being in the way that "we cannot separate it from ourselves or even recognize its presence and influence" (Ong, 1986, p.24).

An important point to mention is that writing is seen as a technology that can be possible only using technologies: when we write we need a tool to handle and a surface on which to imprint our thoughts. Yesterday as today, writing cannot be considered without reference to the devices thanks to which we write and, today more than yesterday, a large amount of writing devices are available. Precisely, the great influence of mass technologies has changed our writing modality that is moving from the traditional use of pen and paper to the domain of keyboards and recently to touchscreen tools, both in everyday life and in educational contexts. The digitalization of writing and of the texts we write, but also the ubiquity of digital technologies, should encourage a deeper understanding of the implications of the physical and sensorimotor changes in writing. Electronic means have expanded our writing production but the role of tangible devices for writing and their different haptic affordances are rarely considered in the study of language, in general, and of writing, in particular. In my opinion, it is fundamental to establish possible cognitive entailment of different types of writing modalities, to explicate their role in other linguistic tasks and to evaluate the possible implication on daily life and education. Theoretical, empirical and pedagogical considerations are fundamental to keep pace with the changes that digitalization and technological development are causing in literacy diffusion.

The main technological tools dedicated to writing can be divided into devices for handwriting and devices for typing. On the one hand, we can cite touchscreens and graphic tablets on which we can handwrite directly with a pen and, on the other hand, classical keyboards and touchscreen keyboards, with different sizes and configurations, on which we type with our hands or using other supports like touch pens.

Considering the different spatial, visual and tactile properties of each of these devices, it is intuitive that they allow different interactions that probably entail different cognitive performances. Nevertheless, the writing modalities they provide are those generally involved in traditional handwriting and in typing. In essence, the pen – on a paper or on a touchscreen – and the keyboard require different motor-perceptual mechanisms: on the one hand, in order to interact with handwriting devices we have to grasp a pen and manually draw letter by letter, on the other hand, in order to interact with typing devices we have to tap a set of keys that correspond to each letter.

To understand different and common mechanisms of the two writing modalities in depth, it is useful to consider general models of writing production. The general assumption, like in all higher-order motor actions, is that writing consists of central and peripheral processes. As Purcell, Turkeltaub, Eden and Rapp (2011) summarized (see Figure A), central processes are composed by the Orthographic Long-term Memory (or orthographic lexicon), the Phoneme-Grapheme Conversion and the Orthographic Working Memory (or graphemic buffer). These mechanisms guide perception and deconstruction of the phonological and visual input into abstract letter strings that are then converted into motor commands by peripheral processes. Central processes are involved in spelling and are shared by the two writing modalities.

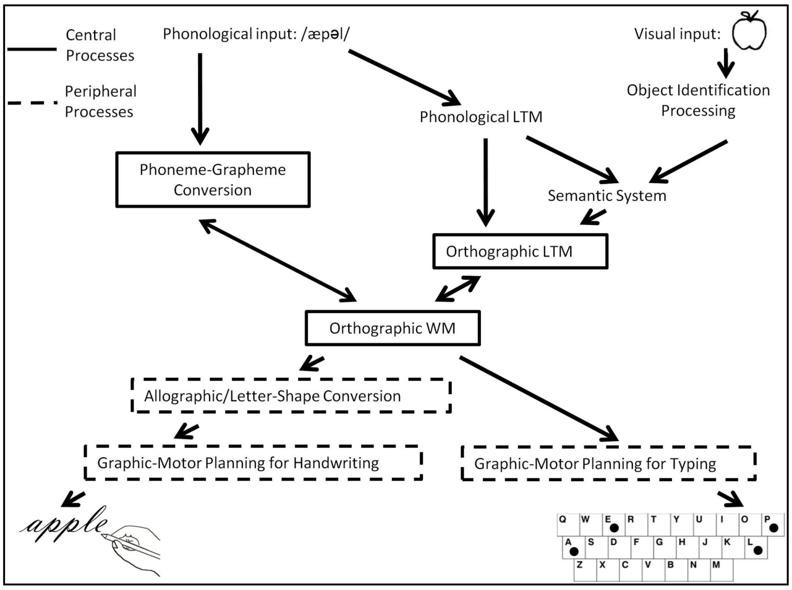

Fig. A. A schematic depiction of the cognitive architecture of the written word production system © 2011 Purcell, Turkeltaub, Eden and Rapp.

Peripheral processes are involved in the conversion of abstract letter strings into detailed motor information that is propagated down the motor system. This process is specific for different affordances depending on whether we have a pen and paper or a keyboard in front of us. On the one hand, during handwriting, specific letter forms are selected passing from the Letter-Shape Conversion to the Graphic Motor Planning process that assembles the letter forms. Then, an Effector-Specific Motor Program organizes the appropriate execution of the motor gesture. Typing, on the other hand, consists of a translation phase, during which the character is translated into a keypress schema that includes the planning of hand and finger motor commands, and, finally, an execution phase, during which the typing movement is executed.

Peripheral processes of writing differ substantially and operate as two different perceptual and motor mechanisms. As summarized by Mangen and Velay (2010), differences between the two writing modalities are manifold. Handwriting in general is uni-manual, while the passive hand and arm play a role in counterbalancing the motion of the active limb (Guiard, 1987). Through this writing modality, we therefore are the creators of the letter shapes. Conversely, the keyboard involves both hands without grapho-motor movements implicated, but a sequence of keypress schemata. Accordingly, motor execution programs constitute great differences. In detail, handwriting movements implicate the execution of graphic shapes, associating each letter or stroke with its specific movement, each visual shape with its motor program. In typing, there is an activation of keypress schemata that transforms the visual form of each letter into a movement of fingers, palms and arms to a given key. A good hand-writer reaches a high level of standardization of the idiosyncratic movement necessary to draw the letter; a good typist has to be fast and accurate in reaching keys with a precise association between ten fingers and letter positions (Mangen, 2014). Another difference regards visual attention. It is focused on one point in handwriting in the way that, during planning and execution of the movement, the regulation of spatiality contemporarily involves coordination and ego-centric and allo-centric reference frames (Purcell, Turkeltaub, Eden & Rapp, 2011). Conversely, writing trough the keyboard splits visual attention – focused on the screen – and the haptic input – focused on the keys. In this case, the spatiality of the limbs movement is associated uniquely with the position of the keys on the keyboard. In comparison with the classical PC, recent tablet technologies reduced the space between keys and screen, shortening the oscillation of visual attention, but no evidence demonstrated a benefit of this reduction (Mangen, 2014). Therefore, it is intuitive that the speed of writing differs: handwriting is typically slower. Skilled writers can produce a cursive script at a rhythm of six strokes per second (van Galen, 1990), whereas a skilled typist can reach a mean interval between keystrokes of 60 msec and 200 words per minute (Rumelhart & Norman, 1982).

Peripheral processes of writing are not extensively studied from a motor-perceptual point of view: there is no general consensus about the processes involved and about the different and common cognitive features in the process of converting abstract graphemes into the execution movements of typing and handwriting. Most of all, little is known about the interaction between central and peripheral processes of the two writing modalities. Furthermore, a rather unexplored field of research concerns the difference between writing technologies. Not only handwriting and typing have to be treated as two different processes, but also the different technologies for handwriting, on the one hand, and for typing, on the other hand, have to be compared in order to know if different devices and affordances affect these writing processes.

This thesis sustain that it is reasonable to think that the motor-perceptual differences between the two writing modalities can lead to different cognitive performances in linguistic tasks, depending on the writing movement that has to be performed but also on the experience that we have with this movement. Given the large diffusion of different technologies, it is more and more interesting to observe and analyze the differences that these technologies evoke not only in writing but also in other tasks where linguistic knowledge has to be mobilized. Is it possible that the use of digital devices for writing affects higher and lower cognitive processes? And if so, how is this influence characterized?

The aim of the present thesis is to analyze different behaviors while we use different writing technologies and to discuss the findings from a cognitive science point of view. The thesis is presented like a collection of papers, results of my research activity and experiences during my participation in the doctoral school. I divided my work in three separate chapters in which different research points of views are analyzed, different experimental procedures are used and different technological devices for writing are tested.

In **Chapter 1**, I report a study aimed at investigating whether technologically mediated linguistic performance reflects cross-modal interaction and whether it is modulated by the technology used. We compared the use of a pen on a touchscreen and of a classical keyboard during a writing task where semantic-spatial information has to be recovered and made specific reference to previous findings in the field of embodied cognition that were never tested in writing tasks before.

Chapter 2 comprises a set of studies conducted in collaboration with the Laboratoire de Neurosciences Cognitives, CNRS – Aix-Marseille Université, Marseille. The first part of the chapter (Paragraphs 2.1 and 2.2) is dedicated to a study we designed to investigate the influence of expertise in typing with an AZERTY keyboard, a classical French keyboard, on a set of linguistic tasks that required writing, reading and spelling. The main research question of this work was to investigate whether it is possible that a strong experience in typing influences our linguistic abilities. The second part of the chapter (Paragraph 2.3) is dedicated to a study that represents a new incentive to writing technologies research. We compared typing performances on a classical keyboard and on a mobile phone touchscreen keyboard to reason on the possibility that the two writing devices are used in a similar manner given the same configuration of keys in spite of the haptic differences during typing. The aim was to test if the typical bimanual advantage of typing on a keyboard can be observed also on a mobile device.

Mobile technologies are the argument of **Chapter 3** in which I present two theoretical papers dedicated to the potential of these devices for learning, in general, and for second language learning, in particular. This dissertation adds to the wider discussion on the influence of Information and Communication Technologies in education and on how the new and old technologies can be useful in those developmental situations where economic, social and educational resources are very limited.

Finally, the **General Conclusions** of the thesis aims to inspire future work to favoring a multidisciplinary research approach that includes the motor knowledge of writing with different technologies in literacy acquisition.

To conclude, this thesis does not have the ambition to be exhaustive on the broader and often unexplored topic of writing modalities, but aims to be a cause for reflection in the cognitive field in order to highlight the importance of taking into account technological devices that are widespread all over the world and are modifying our behavior.

Chapter 1

Handwriting versus typing: an embodied perspective

It is known that our movements organize our perception and help in shaping our spatial representations (Viviani, 2002). Starting from infancy, we learn to associate actions and the corresponding visual and tactile perception building coherent and unified representations of objects. Motor theories of perception and, in particular, the embodied cognition theory are relevant in this context. These theories support the idea of a mental simulation of actions, even when these actions are simply observed. In detail, the embodied cognition approach emphasizes the influence of the body on cognitive processes and considers that cognition is intrinsically built and shaped by body fundamentals derived from the direct experience with the world, therefore through perception and motor actions (for reviews see Anderson, 2003; Barsalou, 2008; Fischer & Zwaan, 2008; Grafton, 2009). To sustain this theory, numerous behavioural and neuroimaging studies locate cerebral motor structures that are activated during the visual presentation of images of objects to which a specific action can be attributed, but also during the observation of actions performed by others (for reviews, see Grèzes & Decety, 2001; Martin & Chao, 2001).

With regard to language comprehension, numerous studies suggest that the activation of motor-perceptual components plays a role in understanding words and sentences. Zwaan and Taylor (2006) identified this activation as “motor resonance” during comprehension. In detail, perceptual-motor characteristics are fundamental to understand words or objects that refer to tactile, auditory and visual domains and to words and objects associated to specific movements. The motor system involvement was observed in speech perception, lexical access, and in sentence and discourse comprehension (see, among others, Zwaan & Yaxley, 2003;

Šetić & Domijan, 2007; Estes, Verges & Barsalou, 2008; Fischer & Zwaan, 2008; Nazir, Jeannerod & Hauk, 2008; Pecher, van Dantzig, Boot, Zanolie, & Huber, 2010).

With regard to writing, Longcamp, Anton, Roth and Velay (2003; 2005a) focused on alphabetic characters, that according to these authors are treated as objects to which we associate specific writing movements. They examined the relationship of the peripheral motor components of writing letters and characters to the subsequent recognition performances, sustaining that the cerebral representation of letters, instead of being strictly visual, can be based on a complex neural network that includes motor-perceptual components acquired through the concomitant learning of reading and writing. In detail, these authors discovered an activation of motor patterns usually involved in handwriting during the recognition of previously learned letters and characters (see also Ouellette, 2010; Shahar-Yames & Share, 2008; Bosse, Chaves & Valdois, 2014; Bara & Gentaz, 2011). In the typing domain, a similar automatic activation of motor patterns was observed in skilled typists that it has been attributed to the overlearning of keypress patterns. For example, the work of Rieger (2004) showed a strong effect of congruency during the discrimination of letter colors: skilled typists were faster when the responding finger for the color discrimination task was the one usually used to type the respective target letter (see also Van den Bergh, 1990; Beilock & Holt, 2007; Yang, Gallo & Beilock, 2009). Further discussion on this topic is addressed in Paragraph 2.1.

Regarding different peripheral processes of writing, the comparison of handwriting to typing can tell us if different writing movements can affect recognition performances. Some studies analyzing the distinction between handwriting and typing in pre-school children (Longcamp, Zerbato-Poudou & Velay, 2005b; James & Engelhardt, 2012) and in adults (Longcamp, Boucard, Gilhodes & Valey, 2006; Longcamp, Boucard, Gilhodes, Anton, Roth, Nazarian & Velay, 2008) discovered that the letters and the characters learned through typing are recognized less accurately than those learned through handwriting. This can be attributed to the simultaneous learning of reading and handwriting and could imply that typing has a different impact on the cerebral representation of letters and on their functional organization in long-term memory.

The cited studies about the impact of different writing modalities on letter recognition stand isolated in the panorama of writing research and of the embodied cognition approach. Furthermore, there is a shortage of studies that investigate the recovery of semantic and sensorimotor information during language production (Nazir et al., 2008).

In the present chapter, I report a study that aims to contribute to closing this gap in writing modalities research and in the embodiment approach to language comprehension in using a comparison of different writing tools in a production task. Our hypothesis claims that semantically relevant representations are recovered during the production of written code. In particular, we compared handwriting and typing technologies – in detail a pen on a touchscreen and a classical keyboard – in a cross-modal interaction task where we tested the presence of the spatial iconicity effect, which indicates the systematic encoding of the representation of stimulus location during perception.

In Paragraph 1.1, I report the original paper of this study whereas in Paragraph 1.2 some further analyses and subsequent implications are discussed.

1.1

Technology and Cognition: Does the device we use constrain the way we retrieve word meanings?

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Abstract. *We examined the possible implication of two different technological tools, the touchscreen and the keyboard, on cross-modal interaction in writing. To do this, we revisit experiments (e.g. Šetić & Domijan, 2007) that investigated the recovery of spatial iconicity in semantic judgment and applied them in writing to dictation. In the present experiment participants had to type or to handwrite on a touchscreen, in the upper part or in the lower part of the screen, words whose referents are typically associated with the top or the bottom part of space. In this way congruent (e.g. "cloud" at the top of the screen) or incongruent (e.g. "cloud at the bottom of the screen) conditions were created. The hypothesis was that incongruent conditions give rise to a delay in starting to write more pronounced for touchscreen session than for the keyboard one. Results are discussed in terms of embodied cognition theory.*

Keywords: Typing, handwriting, writing technologies, spatial iconicity

Introduction

Do technologies shape cognition, and/or does the way people use and interact with technologies affect their performance in cognitive tasks? The response to both questions are clearly positive if we consider broad levels of analyses (e.g. Pezzulo, Barsalou, Cangelosi, Fischer, McRae & Spivey, 2013), but empirical evidence is still lacking for more focused, fine-grained analyses of specific tasks. In this paper we report a study aimed at investigating whether technologically mediated linguistic performance reflects cross-modal interaction and whether it is modulated by the technology used. To do so we will focus on some effects that have been motivated by the embodied approach to cognition.

Accounts of embodied cognition propose that perceptual and motor aspects of a word meaning are intimately related, and this may have implication for language processing as well as for language representation. Specifically, the view that language is closely linked to perceptual and motor representations allows postulating that perceptual and motor aspects of meaning are activated during language processing and may thus interact with the actual processing of the linguistic message. To illustrate, recognizing a word or a sentence would require the re-enactment of the perceptual and motor-related processing performed during actual learning and everyday experiences with the concept the word refers to (see, among others, Zwaan & Yaxley, 2003; Šetić & Domijan, 2007; Estes, Verges & Barsalou, 2008; Pecher, Van Dantzig, Boot, Zanolie & Huber, 2010).

Several studies have been performed to test the embodied view of language processing. In particular, several experiments have shown systematic effects due to (a) perceptual factors such as concepts' typical position and the actual position of the stimulus word on the screen such that congruent trials (e.g. the word "cloud" presented on the top of the screen) are responded to faster that incongruent trials (e.g. the word "cloud" presented at the bottom of the screen) (see, e.g. Šetić & Domijan, 2007); (b) response direction, such that the direction of the response with respect to a person's body interacts with the sentence the person is exposed to. This is best exemplified by the action-sentence compatibility effect (ACE) (Glenberg & Kaschak, 2002): when a sentence implies action in one direction (e.g., "Close the window") and participants move their hand in the same direction (i.e. away from the body) to respond responses are faster than in the condition in which the sentence meaning and the direction of the response are incongruent; (c) response position, such that congruency between the directionality of an action implied by a verb and the location of the response key with respect to the body speed up response time (Job, Treccani & Mulatti, 2011).

While accounts of these results have been offered that did not make reference to the embodied approach (e.g. Job, Treccani & Mulatti, 2011; Lakens, 2011) the pattern show a congruency effect between the meaning of the words and the locations of the stimuli on the screen.

Most of the studies have focused on reading (and comprehension) while only few have addressed writing (and production). Among the latter, Jasmine and Casasanto (2012) have reported the QWERTY effect, named after the disposition of the keys on the keyboard. Some words are spelled with more letters on the right side of the keyboard and others with more letters on the left side, and the authors found a relationship between the emotional valence of the words and key position so that words with more letters on the right were rated as more positive than words with more letters on the left. Interestingly, the effect was stronger for more recently coined words.

In this study we report an experiment in which we investigated whether the interaction between perception and language reported by Šetić and Domijan (2007) would emerge in writing. Furthermore, we investigated whether the technical device used for writing modulates the participants' performance. Specifically, we used both a touchscreen and a keyboard, on the assumption that the use of the pen on the touchscreen would favor the asymmetry between congruent and incongruent location effect while the keyboard would be less prone to let the effect to emerge.

Methods

Participants. Twenty-four Italian native speakers (mean age = 23), students and researchers of the University of Trento, Italy, were recruited for free participations or for course credits. In a brief pre-experimental sessions each participant completed a short questionnaire about his/her habits of writing with pen, keyboard and touchscreen in order to expunge participants unfamiliar with any of these devices.

Procedure. A set of 40 Italian words referring to animals and 40 referring to objects were selected. In each category, half of the concepts had a typical location at the top (i.e. eagle, sky) and a half at the bottom (i.e. mouse, carpet) of space. All 80 words were vocally registered with Cool Edit Pro 2.0 reducing rumor and hiss and controlling the length of the silence at the beginning and at the end of each word (120 ms).

The experimental procedure consisted of two writing conditions performed in succession by each participant. In the first condition, participants had to manually write with a pen on a touchscreen (LG FLATRON T1910); in the second condition, participants had to write with the keyboard with the support of the same screen used as a normal computer screen.

All of the 80 words were automatically dictated by the computer in each condition.

The procedure of stimulus presentation and the collection of data (reaction time) in both conditions were done using E-Prime 1.1.4.1, with a similar configuration of the visual cues presented on the screen to make them comparable as much as possible. Specifically, in each writing condition, at the end of each word dictated by the software, a visual cue, precisely a line, was presented at a fixed point at the top or at the bottom of the touchscreen where participants have to directly handwrite the stimulus, or to type the word they heard. The line where the words have to be written, in both conditions, appeared at the middle of the audio file of the presented word. (See Figure 1.A for a schematic pattern of the experiment).

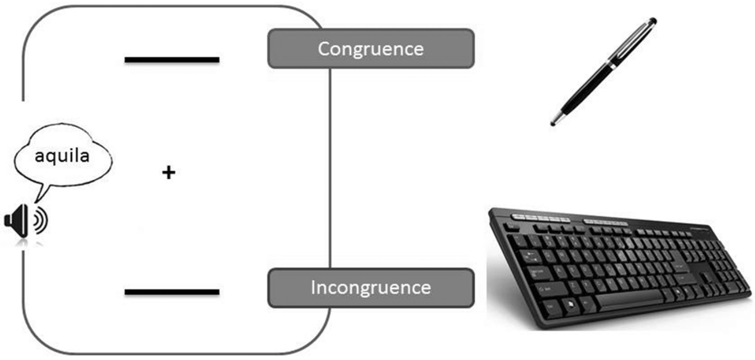

Fig. 1.A. Schematic pattern of the experimental design

Each word was presented twice so that one time it was written at the top and one time at the bottom of the screen for each writing condition (pen vs. keyboard) for a total of 160 stimuli divided into four blocks per condition. In this way, a congruent (i.e. eagle at the top of the screen) and an incongruent (i.e. eagle at the bottom of the screen) condition was devised. Words presentation was random for each block and for each participant with the only constraint that the same word did not appear in the same block or in consecutive blocks.

The difference between the procedures of the two conditions consisted in the input system of writing. For the handwriting condition, the experimenter fixed the screen in a sloping position in order to facilitate writing on the screen and to prevent fatigue of the arm. During the experiment, the participant had to position the pen at the center of the screen, on a specified fixed point. When the software recorded the position of the pen, the audio of the word started. In this way we are able to control the position of the participant for every trial. Then, when the participant finished writing, he/she had to return to the central point to stop the current trial and to begin the next.

During the keyboard session, the screen was positioned vertically and the keyboard in front of the participant. To build a graphical design similar to the handwriting condition, in the middle of the screen were put a fixation point that the participant had to fix before starting to write. Furthermore, to control the position of the hands and to avoid that they were put on the letters of the keyboard, the participants were instructed to put the hands on the space bar and to keep it pressed. This input activated the audio of the word and, once the line appeared on the screen, the participants had to release the bar and write the corresponding word. The end of the trial coincided with the press of the enter key and then the return to the bar space to hear the next word.

Participants were instructed to be fast an accurate. Reaction time from the presentation of the to-be-written-on line to the beginning of writing was registered and collected. At the beginning of each condition, a brief training was administered that contained, unlike the experiment, some comprehension questions to verify access to the meaning of the dictated words. The stimuli were seven words, without any specific reference to the top or to the bottom of the space. Associated with three of these words we used three simple yes-no questions ("is it an object?", "is it an animal?", "has it the wings?") that the participant answered orally, for handwriting condition, and pressing the corresponding keys, for the keyboard condition. Erroneous responses were very few (. 17), confirming access to semantics in this condition.

Results

Response times (RTs) shorter than 250 ms and longer than 2000 ms (3%) and errors (0,13%) were eliminated and did not enter into any of the following analyses. RTs for correct responses are plotted in Figure 1.B, separately for touchscreen and keyboard, as a function of the condition (congruent vs. incongruent) and block (1 to 4). A repeated measure ANOVA with device (touchscreen and keyboard) and location congruency (congruent and incongruent) was run on the RTs. The effect of the device is significant ($F1_{(1,23)} = 16.9$, $F2_{(1,79)} = 48.6$), with responses via keyboard being faster than response via touchscreen. The effect of the location congruency is not significant ($Fs < 1$): independently from the writing device, words written in a congruent or in an incongruent location were equally fast.

A piecewise linear model shows that there is an effect of block, indicating a learning curve which is modulated by the writing device: for the touchscreen performance is increasing continuously across blocks while for the keyboard, after an increased from block 1 to block 2 there is no further increase from block 2 to block 4 (paired t-test: t (23) = 3.44, p < .002).

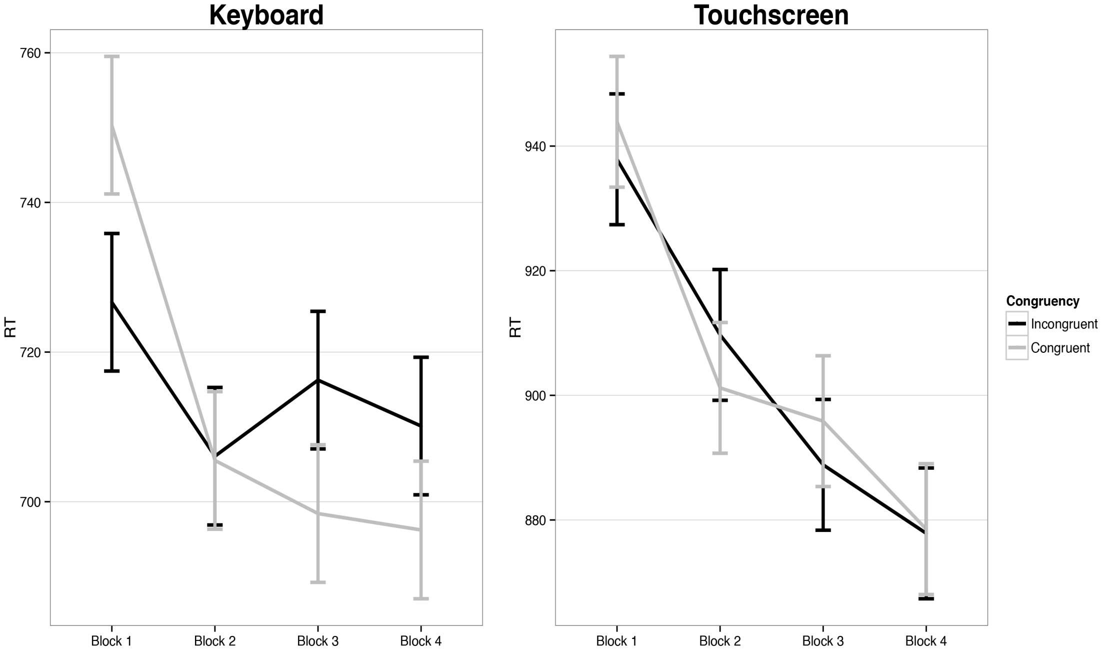

Fig. 1.B. Plot of the RT means along the four experimental blocks

Discussion

Two main findings emerge from the study. First, the expected difference between the two conditions of writing emerges, confirming the hypothesis of a different modulation of performances as a function of the device used. Such difference may be attributed to the fact that the pen and the keyboard allow for idiosyncratic movements and correlated differences in the time writing is initiated and deployed. This is true in general, and in our experimental setting in particular, as in the touchscreen condition participants had to move the hand from the central point to the indicated line while, in the keyboard condition, they had to move the hand(s), and the finger(s), from the bar space to the key corresponding to the first letter of the stimulus words.

Thus, the difference between the two different writing modalities may be ascribed to the different manual skills involved in each. Mangen and Velay (2010) point out that in handwriting we use only one hand and we are the maker of the shape of the letters but the keyboard involves both the hands without grapho-motor movements implicated.

Another difference regards visual attention that is focused on one point in handwriting, whereas writing trough the keyboard split visual attention - focused on the screen - and the haptic input - focused on the keys.

It is plausible to hypothesize that these manual variances have different cognitive consequences. Several studies show that memory for figures, alphabetic characters, and pseudo-characters are improved thanks to previous handwriting experiences, given the directed experimentation of the shape of the proposed stimuli in comparison with both the previous keyboard or the sole visual experiences (Longcamp, Zerbato-Poudou & Velay, 2005b; Longcamp, Boucard, Gilhodes & Velay, 2006; James & Atwood, 2009).

Furthermore, different cerebral structures mediating performance in the two writing modalities, and their links with other linguistic process – for example reading – have been identified (e.g. Longcamp, Hlushchuk & Hari, 2011; James & Engelhardt, 2012).

These theoretical proposals can be seen in connection with the embodied cognition approach, as they assume that the perceptual mechanisms involved in language are bounded with motor actions, here the action of writing.

The second finding from the study regards the issue of spatial iconicity in writing. Our attempt to replicate in writing the results reported by, e.g., Šetić and Domijan (2007) was not successful.

Our prediction that the congruency between the location of stimuli and the typical position of the corresponding referent would generate faster response times compared to incongruent condition is not supported by the data. This was not true even for the touchscreen condition, the condition we thought was more likely to yield the effect because of the fewer constraints on movements and the greater overlap between meaning and movement. However, the results of the presented study show no difference between congruent and incongruent condition in either the devices.

This pattern suggests either that in linguistic production there is not a recovery of spatial iconicity of the produced words, irrespective of the writing tool or that structural constraints of the experiments, such as timing, may have prevented the effect to emerge. Further data are needed to disentangle this result.

An interesting, and unexpected, finding is the dissociation between the learning curve of the two writing conditions, with a continuous improvement in the touchscreen condition but a flat performance after block 2 in the keyboard condition. This pattern may reflect a "floor" constraint for the latter condition, such that the planning and execution of the writing performance have reached maximum speed by the end of the first block. An alternative, not necessarily inconsistent, account would allow for the fine-grade adjustment for the trajectory movement in reaching the indicated line in the touchscreen condition, adjustment that requires time to reach the optimal standard.

To conclude, we did not find a spatial congruity effect in writing in neither of the two devices used, the touchscreen and the keyboard, in spite of significant time differences in performing the task in the two conditions, which may have allowed detection of the effect either at an early or a late onset. Interestingly, the speed to perform the task across the experiment varied markedly as a function of the devised used, with increased speed up to the last block for the touchscreen condition but an increase between the first and second block only for the keyboard condition.

1.2

Movements count: further analyses of the meaning-location congruency

The experimental procedure of this study was not easy to realize given the technical complexity of programming a similar design with a touchscreen and with a keyboard.

The two writing modalities, handwriting and typing, required two different movements to perform the task. After the visualization of the to-be-written-on line, in the touchscreen condition participants moved the pen from the central point directly to the line while, in the keyboard condition, they moved the hand from the bar space to the first key. This requires to separate the writing movement from the perceived line on which the text appears. In the original paper, presented in the previous paragraph, the analyses used the RTs related to the time difference between starting to write (the first point on the touchscreen or the first keypress) and the appearance of the to-be-written-on line. We chose to consider this measure because it includes a set of processes – the time necessary to process (a) the presented word and its meaning, (b) the spatial information, encapsulated in the meaning, (c) the congruence or the incongruence between the meaning and the location of the line on the screen and (d) the time necessary to start writing – that together provide a comprehensive level of analysis of the writing process.

Given the fact that the time necessary to start writing (d) is a measure that in our study estimated two different movements, we consider useful to split the original RTs into two separate measures in order to provide a more movement-free measure of the writing process.

In detail, we performed two further separate analyses. In the first analysis, we considered as RTs the time elapsed between the appearance of the to-be-written-on line and the moment participants started the movements: when they pulled the pen off the central point in the touchscreen condition, and when they lifted the fingers from the bar space in the keyboard condition. We named these RTs as “Processing time”. In the second analysis, we considered only the movement. To do so, we measured the time between the moment participants moved from the central point, or from the bar space, and the beginning of the writing performance – the first point on the touchscreen or the first keypress on the keyboard. We name these RTs as “Movement time”.

The main idea is that if we compare results with these two different reaction times, which corresponded to different moments in the task performance, we might gain important insights in how the writing in the two conditions is accomplished.

Results

The results are plotted in Figure 1.C and Figure 1.D for the Processing Time and the Movement Time, respectively.

For both analyses, RTs that were minus or plus 2.5 standard deviation from the mean, were removed (2% for Processing time; 1.4% for Movement time). Errors were just removed in the original sample (Paragraph 1.1) previously to outliers detection. A repeated measure ANOVA with device (touchscreen and keyboard), location congruency (congruent and incongruent) and blocks (1 to 4) interaction was run for each type of departed measures. For the Movement Time an analysis that compares R2 adjusted of segmented and linear regression models fitted to the two writing condition was also performed.

The Processing Time

The effect of the device was significant ($F1_{(1,\ 23)} = 15.9$, $p < .001$, $F2_{(1,\ 79)} = 49.1$, $p < .001$), with responses via touchscreen being faster than responses via keyboard. The pattern emerging from this further analysis is opposite to the pattern emerged in Cerni & Job (2013). Neither the effect of location congruency nor of blocks was significant ($p > .05$). Interestingly, the interaction between device, location congruency and blocks, on the one hand, and of location congruency and blocks, on the other hand, were not significant in the by-subject analysis, but they reached significance in the by-item analysis: F2$_{(3,\ 1262)}$ = 2.9, p < .05 and F2$_{(3\ ,1262)}$ = 3.0, p < .05 respectively.

To investigate in more detail these results, we analyzed separately the data sets for the keyboard condition and the one for the touchscreen condition. The interaction between location congruency and blocks proved significant only in the keyboard condition (F1$_{(3,\ 69)}$ = 3.2, p < .05, F2$_{(3,\ 632)}$ = 5.3, p < .01). Figure 1.C shows that, in the fourth block, congruent responses were faster than incongruent ones (t (23) = 2.8, p < .01). No significant results were found in the touchscreen condition.

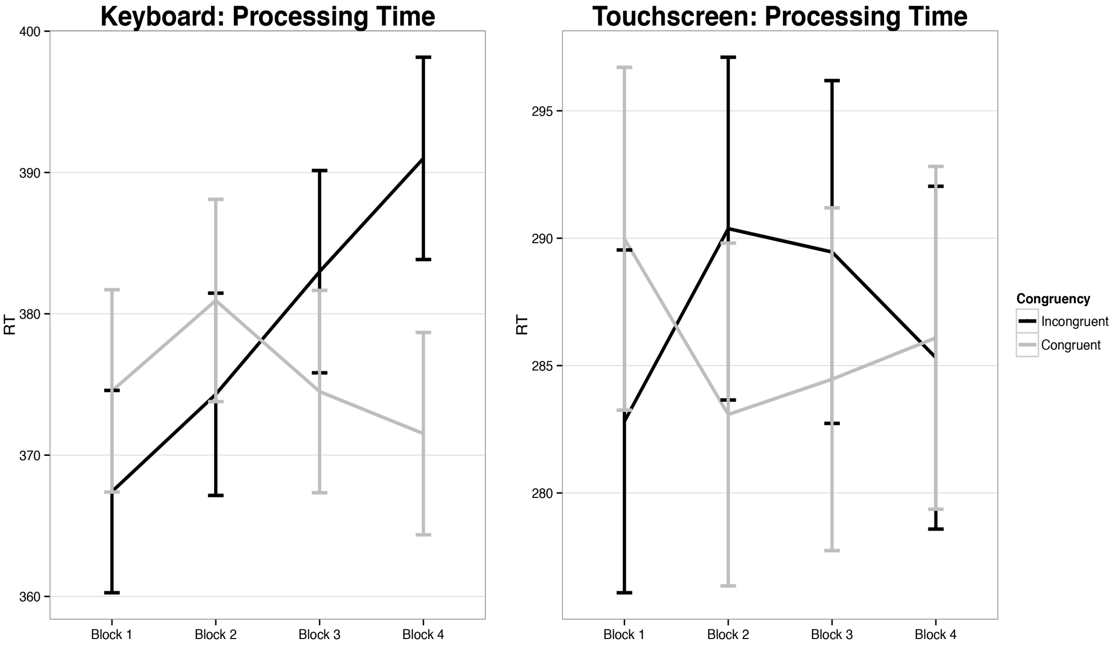

Fig. 1.C

The Movement Time

The effect of the device was significant (F1$_{(1, 23)}$ = 18.5, p < .01, F2$_{(1, 79)}$ = 431.5, p < .01), with responses via keyboard being faster than responses via touchscreen. Contrary to the Processing Time analysis, this result was equal to the analysis in Cerni & Job (2013). Also the effect of blocks was significant (F1$_{(1, 23)}$ = 12.4, p < .01, F2$_{(1, 79)}$ = 26.1, p < .01).

The effect of the location congruency was not significant and also none of the interactions were significant (p > .05).

The comparison between segmented and linear regression models did not reach significance for the learning curve effect showing that the performances with both devices are not linear.

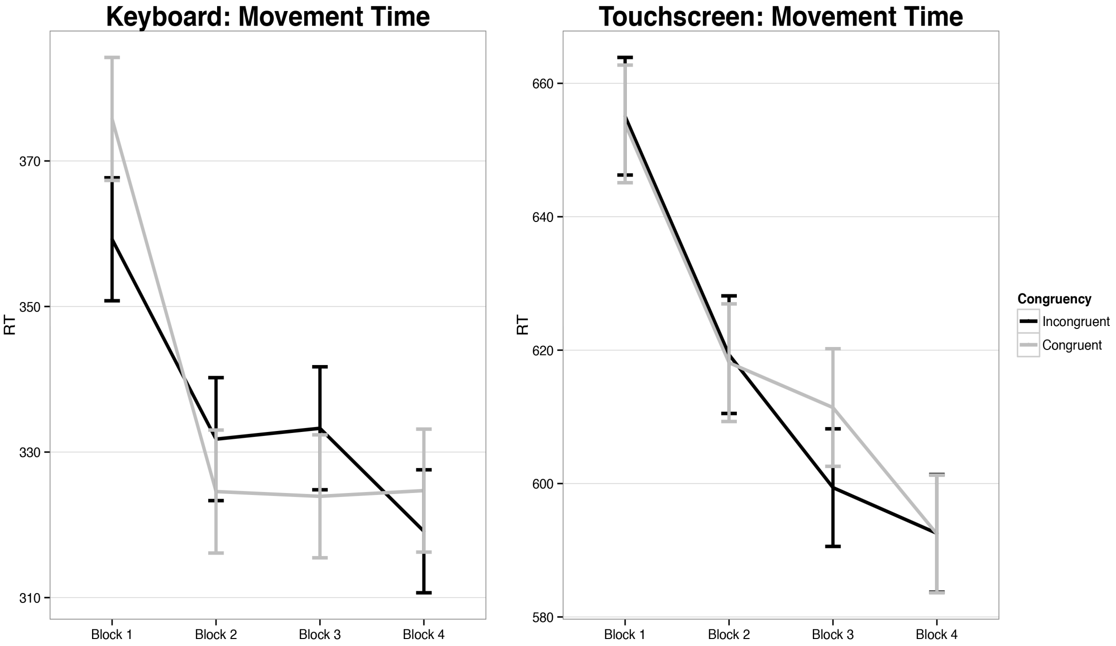

Fig. 1.D

Discussion

The two additional analyses present some interesting results that allow to better clarify the location congruency effect in writing but also to better characterize the diversity of movements between the two writing devices.

First, the different modulation of performances with the two devices is confirmed by both the additional analyses. The Movement Time analysis, replicates the original findings by Cerni & Job (2013): responses via keyboard were faster than responses via touchscreen. In contrast, the results obtained in the Processing Time analysis shows an opposite pattern with the touchscreen condition being faster than the keyboard condition. We interpreted this pattern of data as showing that the mechanisms involved in the processing of the stimulus and the planning of the response are faster when writing on the touchscreen, but the whole writing response, including the movement, is faster when writing on the keyboard.

The comparison of these two new findings leads us to suppose that the slower responses of the touchscreen performances in the previous analyses are due to the amplitude of the movement across the screen, from the middle point to the to-be-written-on line. Since the spatial arrangement of the two conditions were similar, and required to initiate the response by pulling off from a fixed point – the central point of the touchscreen and the bar space of the keyboard –, we argue that the device-related difference in the Processing Time is linked to differences in the attention processes in the two writing condition (see Mangen & Velay, 2010). The account rests on the assumption that, in the touchscreen condition, attention is focused on the screen and the screen is also the location of the haptic response. In this way, there is congruence between the visual and the haptic locus of attention. This allows participants to detect the line and immediately to start the movement on the same surface. On the other hand, in the keyboard condition there is a divergence between vision processes, centered on the screen, and the haptic processing, centered on the keyboard. Thus, participants had to visualize the line on the screen and then they had to start the movement on the keyboard with the attentional focus on the screen delaying the release of the bar space.

With regard to the iconicity effect, our original hypothesis rested on the assumption that the overlap between the movement and the meaning (up and down) in the touchscreen condition can be a strong factor for the activation of the iconicity effect. Lachmair, Dudschig, De Fillippis, de la Vega & Kaup (2011) found results that lead us to suppose this overlap. In three lexical decision task experiments participants were exposed to words with reference on the top or on the bottom of the space. The response system required them to perform either an up or a down movement starting from a middle point. Results indicated that responses were faster when the response direction matched the referent's location. Our experimental procedure in the touchscreen condition was similar to these tasks, but did not report a significant effect neither in our first analysis (Paragraph 1.1), nor in the analysis of the Movement Time.

Interestingly, Lachmair et al. (2011) conducted a further analysis considering separately the movement times as dependent variable. They reported no significant results for these measures suggesting that the congruency effect emerged prior to the response movement. In addition, they reported the location congruency effect in a fourth experimental session, where the response system was the traditional button press and hands stayed rested on the respective buttons. These further results are consistent with our findings in the keyboard condition where we reported the congruency effect in the Processing Time and no effects in the Movement Time. On the contrary, in the touchscreen condition the congruency effect did not emerge neither in the Processing Time analysis where the movement was not counted.

The explanation of the presence of the iconicity effect in the keyboard condition and the absence of the effect in the touchscreen condition in the Processing Time analysis may be ascribe to both the subsequent required movements and to the task demands. In detail, the touchscreen condition required to program and then to perform a complex movement up or down on the screen that could interfere with the emergence of location-congruency effect. The reason is that the attention toward the location of the to-be-written-on line could be modulated by the movement and this may attenuate the attention to the processing of the stimuli. This fact can explain the slower Processing Time in the touchscreen condition than in the typing condition. On the other hand, the keyboard condition does not require such an ample movement and so, after an initial adaptation to the task during the first three blocks, in the fourth block the attentional processes can be directed to the visualization of the line, which may induce the location congruency effect.

In the Movement analysis, the fact that the iconicity effect did not reach significance supports the idea that the word meaning and the possible congruence/incongruence with the to-be-written-on line are processed before the movement.

The last results to discuss concern the different patterns of the learning performance in the two writing conditions. In the original analysis by Cerni & Job (2013) the keyboard performance showed a pattern such that, after an acceleration of RTs during the first block, performance became flat within the following blocks. In the touchscreen condition, performance continued to increase linearly during the four blocks suggesting a fine-grade adjustment for the trajectory movement during the task.

The Movement Time analyses do not show the same results and indicate that the learning curves of both the touchscreen and the keyboard are segmented. The similarity of Figure 1.B (Paragraph 1.1) and Figure 1.D suggests that the slopes of the curves found by Cerni and Job (2013) are mainly driven by the movement performances. The keyboard condition presents the same learning curve found in the original analysis, but the learning curve in the touchscreen condition presents a major discrepancy between the first and the others experimental blocks than the curves of the original analysis. It is possible that, in the touchscreen condition the Processing Time and the Movement Time interfered more than in the keyboard condition in the adjustment to the task suggesting that not only the movement but also the time necessary to start the movement had a role in shaping the learning curve found by Cerni and Job (2013).

To conclude, the diversity of the two writing modalities in general, and in our tasks, in particular, leads to different performance. Our findings show the complexity of comparing two different writing tools, driven by the difference in the movements they allow. Indeed, in the two writing conditions, the movements, linked to the structural characteristics of the writing devices, allow for different attention allocation to the interaction between words meaning and location, and to different learning curves during the task.

The novelty of the task used in our study to investigate location congruency effect and the similarity and dissimilarity between our findings and the previous studies on this topic need further experimentations to confirm any conclusion. To overcome structural constraints of this study, a more specific semantic context that usually has facilitated the access to the searched effect can be constructed. Specifically, in previous research on spatial iconicity the tasks were usually linked to semantic judgments. For example, Šetić and Domijan (2007) instructed participants to press a key if the target word referred to flying or no-flying instances, inducing a specific access to meaning to answer the question. Meier and Robinson (2004) presented words that have a typical positive or negative valence, on the top or on the bottom of the screen and recommended to participants to make an evaluation of positivity/negativity. Estes, Verges and Barsalou (2008) used a context word (e.g. cowboy) followed by an upper-location (e.g. hat) or lower-location (e.g. boot) cue that appear at the center of a screen. Taking into account these previous experiments, we can hypothesize that the use of a contextual reference into the tasks can encourage a more deepened semantic processing that may facilitate the emergency of the effect, also in the touchscreen condition.

Chapter 2

Typing, mobile typing and motor expertise

Nowadays, typewriting is becoming the most practiced output modality in written communication. Many of us know how to type without a formal training, with an association between keys and fingers that remains personal and non-systematic (hunt-and-peck typing). Conversely, typing expertise is characterized by a strong and systematic association between hand and finger movements, and keys. Based on the fixed division of the left and right sides of the keyboard and on the stable motor representation, all ten fingers are used so that each word is typed exactly in the same way by all experts, but with variable associations between fingers and keys by non-experts (Rieger, 2012).

Typing does not consist only in these behaviors of experts and non-experts; therefore, it does not depend only on experience and schooling, but also on the devices designed for typing. Nowadays, if we speak about typing in general, we should include new text entry methods designed for mobile typing devices. A great amount of writing activities that a personal computer allows is now present also on mobiles. For example, word processors, spreadsheets, schedulers, web search, blogs and other desktop applications are adapted to mobiles of every size: from tablets to smartphones. Consider that one of the activities that make mobile phones popular is text messaging, indeed, a text entry activity. Therefore, typing on mobile platforms is a daily situation for many of us (MecKenzie & Soukoreff, 2002).

Today, the most common keyboards in mobiles are touchscreen QWERTY keyboards. If we think about the last models of smartphones and tablets, all of them are touchscreens and furnished with a QWERTY. Recent lines of research in human-computer interaction are analyzing the impact of mobile keyboards. For example, some studies focus on the comparison of small QWERTY keyboards with other mobile typing methods (i.e. Clawson, Lyons, Starner

& Clarkson, 2005), on alternative mobile typing modalities (i.e. Wilson & Agrawala, 2006; Bi, Chelba, Ouyang, Partridge & Zhai, 2012) and on the expertise level of mobile typing (i.e. Clarkson, Clawson, Lyons & Starner, 2005). Nevertheless, a standard in mobile typing comparable to the standard of touch typing does not exist, which renders the comparison of users' performances difficult.

Furthermore, in the field of cognitive science and linguistic studies, there is an absence of investigations on the cognitive implication of mobile typing in the models of writing. If we know little about peripheral processes of handwriting and typing, we know almost nothing about mobile typing.

At the basis of the studies presented in this chapter lies the concept of bimanual advantage: a remarkably stable feature of typewriting movements, which was among the first phenomena observed in experimental studies of expert typists. In detail, the cross-hands (bimanual) interkeystroke intervals – the elapsed time between two successive keypresses – are shorter than within-hand (unimanual) interkeystroke intervals (i.e. Shaffer, 1976, 1978; Terzuolo & Viviani, 1980; Rumelhart & Norman, 1982; Ostry, 1983; Larochelle, 1984; Salthouse, 1986; John, 1996; Wu & Liu, 2008). For an expert, a word containing only alternations between the left and right hand is much easier to type than a word containing letters associated with the same hand, because skilled typists move their hands in parallel (Gentner, Grudin, & Conway, 1980). This pattern is not present in novice typists (Larochelle, 1983).

This important difference between expert and non-expert typists is at the heart of the first part of the present chapter (Paragraphs 2.1 and 2.2) in which I present a study dedicated to test the impact of motor expertise of writing on linguistic performances where spelling knowledge has to be mobilized.

In this study, typewriting is considered a good model to investigate the "embodiment" of reading and the possible influence of writing motor information on spelling: the number of bimanual transitions per word offers a powerful estimate of the motor difficulty of that word for experts. In detail, we designed a set of French words where the amount of cross- and within-hand transitions was manipulated as a continuous variable. The experimental design consists of four tasks: a typing to dictation task, a lexical decision task, a spelling task and a handwriting task. Our hypothesis sustains that in these tasks, words that are usually typed with more bimanual transitions may be written, spelled and recognized faster that words with less bimanual transitions by expert typists compared to non-experts.

In Paragraph 2.1, I present a paper that addresses the influence of the bimanual motor advantage in typing on a lexical decision task. The aim was to test whether lexical decision performance showed a differential effect of motor difficulty in expert and non-expert typists. In Paragraph 2.2, I discuss the extra results of the spelling “probe” task where we tested the influence of the bimanual advantage on spelling recovery. Unfortunately, data of the handwriting task are not available herein, but the experimental design is briefly discussed.

In the last session of the chapter (Paragraph 2.3), I present a paper focusing on the comparison between touch typing and mobile typing with the assumption that strategies typical to standard typing can be found also in mobile typing. In detail, the study tested the possibility that motor knowledge of typing, which concerns the bimanual transition advantage and the unimanual disadvantage, can have an impact on both computer and mobile keyboards. Is it possible that typing with ten fingers on a classical keyboard has the same motor constraints as typing on a mobile with only one index or two thumbs?

2.1

Motor expertise for typing impacts word recognition

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Abstract. *Handwriting is still widely taught in elementary schools worldwide, yet typing is clearly becoming the dominant writing modality in adulthood and even earlier. This massive shift of writing habits in the general population calls for better understanding of the possible consequences of typing practice on reading. Here we directly tested whether word recognition, indexed by the primary task of lexical decision, is impacted by typing expertise and typing properties of words. We found that the response times to lexical decision varied as a function of the ratio of bimanual transitions per item, an index of motor difficulty for alternating keystrokes. This effect followed the trend observed when participants were actually typing the words, and was therefore different for expert and non-expert typists. This result demonstrates for the first time that motor representations built during the repeated typing of words have a collateral effect on visual word recognition.*

Introduction

Reading and writing have typically been studied separately, as if they were encapsulated systems. Yet some researchers have hypothesized the existence of specific directional influences of the motor aspects of writing on reading, the rationale being that reading acquisition and practice is supported by contemporary performance of writing gestures (Tan, Spinks, Eden, Perfetti & Siok, 2005; James & Engelhardt, 2012; Mikulak, 2014). Empirical evidence in favor of such an influence has been reported for handwriting. Knowledge of graphic movements specific to characters impacts their visual recognition and the associated neural substrates (Velay & Longcamp, 2012 for review). Letter recognition being the very first step in word reading, motor knowledge is likely to affect skilled reading beyond single letters. Handwriting is still widely taught in elementary schools worldwide, yet typing is clearly becoming the dominant writing modality in adulthood and perhaps even earlier. This massive shift of expertise in the general population calls for better understanding of the possible consequences, if any, of typing practice on reading.

To this date, typing practice has revealed no measurable effect on single character recognition, presumably because the movement performed to strike a given key bears no relationship with the shape of the character to be recognized (Longcamp et al., 2005; 2008; James & Atwood, 2009; Tan, Xu, Chang & Siok; 2012). These observations suffer from two limitations though. First, the participants tested were hunt-and-peck typists displaying moderate skills and variable associations between fingers and keys. Second, the experiments focused on single characters, whereas typing expertise relies on stable motor representations of each keystroke and their sequence (Rumelhart & Norman, 1982; Rieger, 2004). Indeed, while the shape of the characters is fundamental in handwriting, a critical dimension of typing is the sequence of keystrokes.

A few studies suggest that typing expertise can lead to the activation of specific motor patterns in non-motor tasks: skilled typists spontaneously "like better" and memorize more accurately pairs of letters usually typed with two different hands relative to pairs typed with the same hand (Van Den Bergh, Vrana & Eelen, 1990; Beilock & Holt, 2007; Yang, Gallo &

Beilock, 2009). This effect is thought to origin from motor coordination properties of letter pairs: alternating between hands to type a pair is easier and faster for experts (Shaffer, 1976; Rumelhart & Norman, 1982; Ostry, 1983). Yet the evidence remains scarce and the possible consequences of typing expertise on visual word recognition are not apparent.

Here we directly tested whether word recognition, indexed by the primary task of lexical decision, is impacted by typing expertise and typing properties of words. The motor transition effect implies that for an expert, a word containing a majority of bimanual transitions is much easier to type than a word containing more unimanual transitions (Gentner, Grudin, & Conway, 1980). This pattern is not present in novice typists (Larochelle, 1983). We designed a set of French words in which we manipulated the number of cross- and within-hand transitions. We tested whether lexical decision performance for those words and matched pseudowords showed a differential effect of motor difficulty in expert and non-expert typists.

Methods

Participants. The experiment was designed to include sixteen participants per group. This number was set to optimize the counter-balancing of the tasks and response matching. To reach this number, twenty expert typists (formally trained for touch-typing), French native speakers, had to be tested. Four of the typists of the initial group of 16 produced errors rates in the typing task above 40% of the trials and an had to be replaced by another 4 typists. The control group was composed of 16 participants without a major experience of typing, selected to match the typists for age, gender, education and handedness. Non-experts used to type with a maximum of three fingers per hand and they had not had any formal training with a standard typing method. None of the participants in the control group had to be discarded but one turned out to be an expert (see below).

For all participants, we checked the declared degree of typing expertise with a questionnaire on the writing habits (Table A) and a computerized typing pretest, programmed with Presentation® 16.3. The test yielded estimates of typing rate and accuracy based on two short texts that participants had to transcribe at their normal typing rate. Accuracy was defined on a per word basis. Typing rate was calculated as words (5 characters) typed per minute (MacKenzie, 2013) (results in Table A). Finally, we recorded videos of the participants while they did the typing pretest to ensure that experts and non-experts used the number and position of fingers expected for each group.

One of the non-expert participants was finally affected to the experts group, given her very good typing performance and use of 10 fingers despite her self-report of typing habits. Eventually then, the expert group included 17 participants (1 male/16 female) and the control group included 15 participants (1 male/14 female; Table A).

Table A

Features of the sample

	Experts	Non-experts
N	17	15
Mean age	41.7	43.6
Daily handwriting time (minutes)	60.7	97.1
Daily typing time (minutes)	265	137.5
Typing experience (years)	24	16.6
Right handed (%)	70	90
Typing accuracy (%)	90	90
Typing rate (wpm)	40.6	28.5

Stimuli. We searched the Lexique database (Article Reference) for words that were typed with variable proportions of bimanual typing transitions on the standard French AZERTY keyboard (Table S1 in the Supplementary Material). The words never included the left-hand letters “x”, “w”, “c”, nor “v” because these have no right hand counterpart in the AZERTY keyboard. They were all 6 to 8 letters long. The experimental words were divided into 15 transition ratio categories (from 14%, for example "**pompi**_ste_" to 85%, for example "**h**_a_**bi**_t_**u**_e_**l**"; bold letters being typed with the right hand on the AZERTY keyboard). Across these 15 categories, the items were matched for: the hand used to type the first letter, the average number of letters typed with the left and right hand, lexical frequency, number of syllables and phonemes, presence of homophones and homographs, frequency of bigrams, number of phonological neighbors, and lastly orthographic regularity. Table S2 in the Supplementary Material summarizes these properties, and shows that only bigram frequency and orthographic Levenshtein distance (old20) were significantly different across transition ratio categories. These selection criteria resulted in 120 experimental words.

For the lexical decision task, we also prepared a list of 120 pseudowords, created by changing a letter from each of the experimental words. The substitute letter respected the bimanual transition structure of the base-word and lead to a minimal trigram frequency given its position of 10.

To these strictly controlled lists of stimuli, we added 36 words and 36 pseudowords with transition ratios 0 and 100% (i.e. typed with a single hand or hand transitions at every letter). These served as fillers and were not further analyzed. It was not possible to identify in the ‘LEXIQUE’ database (or toolbox) sets of words with 0 and 100% transitions that respected the matching criteria described above for the experimental items.

Procedure. This report is part of a larger study of written language processing in expert and non-expert typists, where each participant was involved successively into 4 different tasks that used the same set of words: a typing to dictation task, a handwriting to dictation task, a lexical decision task and a spelling task. Task order was counter-balanced across participants in a pseudo-random manner (Latin square). Here we report the specific methods and results of typing to dictation task and the lexical decision task. We ensured that task order had no significant effect on the performance in the two tasks of interest, and that it did not interact with the main factors.

The equipment included headphones to present audio stimuli, a QWERTY DirectIN Millisecond Accurate Keyboard (http://www.empirisoft.com/), adapted as an AZERTY keyboard with stickers on the keys, for collecting responses; high quality sound and video cards, and a CRT screen with a 70 Hz refresh rate. Stimulus presentation and response recordings were controlled by the software Presentation® 16.3 (http://www.neurobs.com/). The audio stimuli were recorded from a native female French speaker in an anechoic room and segmented with Audacity 2.0.3.

Tasks.

Typing task. Participants typed the words dictated one per trial in a random order. Each trial started by a fixation cross in the center of the screen, along with the auditory word presentation. Participants were instructed to start typing as soon as they had identified the word. Typed letters were displayed on-line on the center of the screen, replacing the fixation cross. The duration of each trial (stimulus plus input) was set to 4000 ms for experts and 5000 ms for non-experts. The task was split into two blocks separated by a brief pause.

A response was considered incorrect if participants pressed either the backspace or a wrong key. The remaining correct responses were used to calculate the response times (RTs: time between the beginning of the trial and the first keystroke) and the average interkeystroke intervals (IKIs) per trial.

Lexical decision task. Participants had to decide as fast as possible whether or not the visually presented letter string formed a word they knew. The stimuli were presented in Times New Roman on the center of the screen. The size of the letters covered 3 to 4 degrees of the visual field. At the beginning of each trial a fixation cross appeared at the screen center for 500 ms; then, a word (or a pseudoword) was presented until the response was given. After the response, a blank screen was displayed for 1000 ms. The order of presentation of the words and pseudowords was randomized and differed across participants. Responses were given by means of the two F1 and F2keys of the same Millisecond Accurate Keyboard, covered with a plastic board so that only the 2 response keys (F1 and F2) were visible. Participants used their right index (F1) and right middle fingers (F2) and the association between finger and response (word vs pseudoword) was counterbalanced across participants. We collected response times and error rates.

Data processing and statistical analysis. In the *Typing task*, we excluded the errors (18.7% for the expert group; 13.8 % for the non-experts group – tot 16.4%). Outliers were considered after errors detection. For each participant, response times above and below 2.5 standard deviations from their mean were considered as outliers and discarded from the dataset (.03% replacements for the experts, and .03% for the non-experts). The same was done with IKIs (18.2% replacements for the expert group, and 16.8% for the non-experts group – tot 17.5%).

In the *Lexical decision task*, errors in discriminating words and pseudowords were discarded from the dataset (4.5% for the expert group; 4.2 % for the control group – tot 4.4%).

Outliers were considered after error detection, for each participant as reaction time above and below 2.5 standard deviations from the mean (2.7% for the expert group; 2.5% for the control group – tot 2.6% for lexical decision) and the corresponding reaction times were also discarded from the dataset.

The resulting RTs and IKIs were log-transformed (Baayen, 2008) and examined with linear mixed regression models (Baayen, 2008; Baayen, Devidson & Bates, 2008; software R, package lmerTest for models processing and p-values). Transition ratio values were modeled as a continuous predictor. We constructed models for each task separately, and in all models, subjects and items were considered as random-effects while group (expert vs non-expert), bimanual transitions ratio and the interaction between the two were considered as fixed effects. Furthermore we included in the models all the linguistic and task-dependent variables that reached significance, discarding those that failed to reach significance.

Error rates in both tasks were also analyzed and the results are reported only when significant.

Results

A summary of findings is presented on Figure 2.A.

Typing Task. The error analysis on the typing task showed a significant effect of group ($\beta = -.59$, $SE = .28$, $z = -2.06$, $p < .05$).

IKIs

We included in the final model the number of letters in the word, frequency, bigrams frequency, the orthographic Levenshtein (old20) distance and the hand used to type the first letter.

In this task all the variables of interest reached significance: IKIs differed significantly between groups ($\beta = .2$, $SE = .06$, $t = 3.3$, $p < .01$) and were modulated by transition ratio ($\beta = -.002$, $SE = .0003$, $t = -6.7$, $p < .001$). Finally, the interaction between group and transition ratio was highly significant: $\beta = .003$, $SE = .0002$, $t = 16.6$, $p < .001$.

Splitting the two groups into two separate databases allowed us to test if the effect of transitions ratio is significant or not for each group.

The effect of bimanual transitions ratio, was highly significant for both groups, yet in opposite directions: with experts, IKI's increased as the bimanual transition ratio increased ($\beta = -.002$, $SE = .0003$, $t = -5.7$, $p < .001$); with non-experts, the IKIs decreased as bimanual transition ratio increased ($\beta = .001$, $SE = .0003$, $t = 5.1$, $p < .001$).

The complete results of the models are reported in Table S3, in the Supplementary Material.

Response times

We included in the final model the number of phonemes in the word, frequency, the bigrams frequency, the orthographic Levenshtein distance (old20) and the hand used to type the first letter.

No effect of transition ratio was observed. Furthermore, the interaction between group and bimanual transition ratio did not reach significance. The only effect that reached significance was the difference between the groups: β = .2, SE = .04, t = 5.5, p < .001.

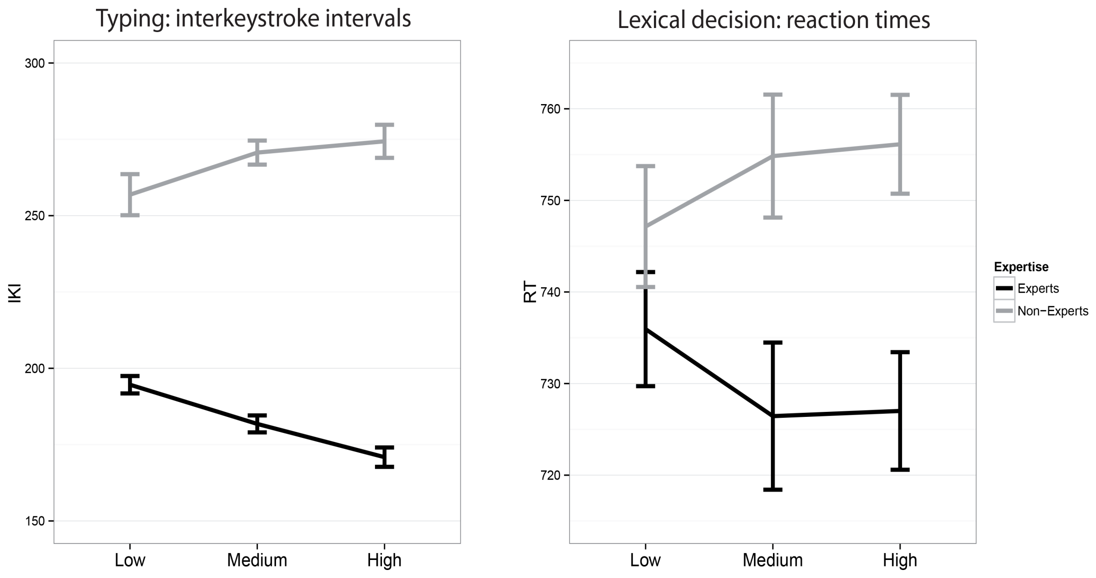

Fig. 2.A

Note. *Summary of chronometric performance in typing to dictation and lexical decision. For clarity, the data have been pooled from 15 into 3 categories of bimanual transition ratio: words with a low ratio of bimanual transition (14 to 33%), a medium ratio (40 to 60%), and a high ratio (66 to 85%). The error bars represent the within-subject confidence intervals (Morey, 2008), further statistics reported in the main text.*

Lexical Decision Task. We included in the model: trial rank, frequency (of the word or of the base-word for pseudowords, Perea, Rosa & Gomez, 2005) and number of letters.

Detailed effects on response times are reported in Table S4 in the Supplementary Material. As expected, we found an effect of lexicality (β = -.16, SE = .03, t = -5.9, p < .001). Furthermore, no effects of group or bimanual transition ratio were observed.

The interaction between group and bimanual transition ratio was significant (β = .0006, SE = .0003, t = 2.45, p < .05), showing the same trend than in the typing task. On the other hand, the two-ways interaction between lexicality, group and bimanual transition ratio approached significance ($\beta = -.0007$, SE = .0004, t = -1.8, p = .06).

We then analyzed word and pseudoword datasets separately to estimate the interaction between group and ratio of bimanual transition in two different models. Detailed effects on response times for words and pseudoword are reported in Table S4 in the Supplementary Material.

Pseudowords

The final model included the trial rank and the number of letters in the word.

No effects of group or bimanual transition ratio were observed.

The interaction between group and bimanual transition ratio reached significance ($\beta = .0006$, SE = .0002, t = 2.6, $p < .01$), showing the same trend than in the typing task. For experts, detecting pseudowords tended to get faster as the number of transitions increased, while for non-experts the trend was opposite.

Words

The final model included the trial rank, frequency, and the orthographic Levenshtein distance (old20).

No effects of group or bimanual transition ratio were observed.

The interaction between group and bimanual transition ratio did not reach significance.

Discussion

Experts produced the expected pattern in the typing task: a reliable decrease in mean IKIs as the ratio of manual transitions increased, and no effect of this variable on RTs (see Introduction). Surprisingly, and at variance with the hypothesis of unreliable strategies in non-experts (Larochelle 1983), the bimanual transition ratio strongly affected the IKIs of this group in the opposite direction. This differential effect on motor execution in typing sets the ground for the central result of the study, namely that the ratio of bimanual transitions had a significant effect on RTs in the lexical decision task. Word recognition processes appear related to the motor representations associated with the usual production of the same words on the keyboard. The influence of typing knowledge could stem from an early stage of orthographic processing, where letter strings are visually processed. Given previous evidence of motor-perceptual interactions for written visual stimuli (Velay & Longcamp, 2012), it is possible that in experts, visual perception of letter strings triggers the parallel activation of associated patterns of hand and finger typing movements, which could in turn exert an influence on the recognition processes. The stability of the motor patterns for typing would accordingly modulate the RTs. The effect is mostly driven by pseudowords whose processing takes more time and presumably relies on noisier evidence (Ratcliff, Gomez & McKoon, 2004; Dufau, Grainger & Ziegler, 2012). The influence of motor representations could be stronger in this case (for a similar argument in speech, see Du, Buchsbaum, Grady & Alain, 2014).

Despite a tradition of separate investigations of reading and writing, some authors assume shared cognitive components (Caramazza, Capasso, & Miceli, 1996; Rapp & Lipka, 2011). In the specific case of typing, brain regions known to process orthography and phonology of single words are commonly activated by reading and typed spelling (Purcell, Napoliello & Eden, 2011). For instance, the graphemic buffer, is involved in reading letter strings through the grouping of single letters into an ordered set of graphemes via the sublexical route (Perry, Ziegler & Zorzi, 2007), and is also a fundamental component of the cognitive architecture of written production (Rapp, 2002). This serial process of building graphemes nodes from letters could be a possible vehicle for the activation of motor information.

To conclude, our study demonstrates for the first time that motor representations built during the repeated typing of words have a collateral effect on visual word recognition. Besides the theoretical implications for current models of reading and writing, this finding has important practical implications for adapting typing training when learning how to read and write (Mikulak, 2014). Further investigations are now required to identify the exact locus of this interaction between reading and writing.

2.2

Motor expertise in spelling recovery: the spelling probe task

In the introduction of the chapter, I cited the fact that the typing tasks and the lexical decision task were inserted into a broader experimental design that comprehended in addition a handwriting task and a spelling task.

In this paragraph, I want to introduce briefly the handwriting task, even though we have no data analysis. Then, I describe in more detail the aim of the spelling task, the method we used and, finally, the results. Both these two additional tasks used the same set of words and were performed by the same participants during a unique experimental session. All of the four tasks are counterbalanced between participants.

The handwriting task. In summary, in the *handwriting task*, participants have to handwrite under dictation all the stimuli with a specific pen on a paper fixed on a Wacom Tablet Intuos 3, format A4. The stimuli presentation and the registration of the inputs are regulated by the software MovAlyzeR (NeuroScript).

During a single trial, a word, selected in random order, is dictated by the system and the participant had to write it in cursive one below the other, following dedicated boxes that are prepared on the white paper. Each trial lasted 3200 msec. The task is divided into 2 blocks. As dependent variable we measured the latency in starting to write, the duration of motor execution of the words and the error rate.

The scope of this task was to examine if typing expertise (experts vs non-experts) and the subsequent performances with bimanual transitions can interfere with handwriting performances.

It has to be specified that data processing and statistical analysis are being performed by an expert in MovAlyzeR (Neuroscript), at the Laboratoire de Neurosciences Cognitives, CNRS - Aix-Marseille Université, Marseille. Unfortunately, I cannot provide the results in this dissertation.

The spelling "probe" task

The task aims to determine the possibility that typing motor experience can influence the aspects of the highest level in the processing of written language, in particular spelling. To this end a recent line of research in writing investigates if an interaction exists between peripheral-motor processes of writing and the central processes of spelling. As just cited in the general introduction of this thesis, central processes have a role in the deconstruction of the visual/oral stimulus into abstract letters that are then converted into motor command by peripheral processes (Purcell, Turkeltaub, Eden & Rapp, 2011). Considering handwriting, Delattre, Bonin and Berry (2006) found that writing irregular words needs more time in latency and duration of the writing movements compared to writing regular words. These results suggest that central processes of assembling spelling are not finished during motor execution. The same conclusions were proposed by Roux, McKeeff, Grosjacques, Afonso and Kandel (2013). Authors found that letter duration was longer for irregular than for regular words, an effect that is modulated by the position of the irregularity in the stimuli.

In this experiment, we focused on the possibility that this interaction between central and peripheral processes can be seen as bidirectional to give a contribution to the hypothesis that writing is a complex process that is not limited either to motor command or to linguistic processes, but characterized by an interaction between the two. In this way the motor constraints of writing, related to the peripheral processes of writing, may have influence on the central processes, intended as processes involved in retrieving, assembling and selecting orthographic representations (Delattre, Bonin and Barry, 2006).

The spelling "probe" task we used was inspired by Rapp and Lipka (2011). It consisted in identifying if a visually presented letter (the "probe") belonged or not to a dictated word with the assumption that participants have to access the spelling of words to give their answer. To perform the task, it is necessary to access to the orthographic representation of the word in the Orthographic Long-Term Memory (O-LTM) and/or the involvement of sub-lexical processing. Later the Orthographic Working Memory (O-WM) is responsible of the effective verification of the presence of the letter. Lexical and sub-lexical processes are clearly categorized as central processes in spelling, whereas the O-WM, identify also as graphemic buffer, is classically associated to central processing, but can be seen in the interface between central and peripheral processes and across writing modalities (Purcell, Turkeltaub, Eden & Rapp, 2011). The role of the O-WM consists in maintaining active the abstract letters, basis for the activation of keypresses subsequently performed by peripheral processes.

Given this pattern, in this study, we tested the possibility that motor constraints of typing, when associated to a great experience with this writing modality, can influence central processes independently from the letter conversion into keypress.

We used the same words we selected in the previous tasks, where we manipulated the amount of bimanual transitions, testing if the bimanual facilitation influences spelling of words when motor execution is not required. We tested this hypothesis comparing the two groups of expert and non-expert typists, expecting a facilitation of spelling in function of the increase of bimanual transitions ratio only in experts, who possess an automatism in the typing movements.

Materials and methods

Participants and Stimuli. The same participants, divided into a group of experts and a group of non experts typists, and the same stimuli of the previous study (Par. 2.1) were used in this task.

In addition to the controlled variables, presented in Table S2 in the Supplementary Material, we balanced between transitions ratio categories also the position of the probe in the words – a continuous variable from 1 to 8 – the hand used to type the probe – counting the number of right probes – and if the probe made a bimanual transition with the previous letter in the word – e.g. if we presented the words "madame", the probe "D" (left key) does not constitute a transition with the previous letter "A" (left key) and it was categorized as "No transitions". Conversely, the probe "M" (right key) constitutes a transition with the previous letter "A" (left key) and was categorized as "Transitions". For this last variable we counted the number of "Transitions". These additional variables can be viewed in Table S5 in the Supplementary Material.

The task was programmed in Presentation 16.3 and was conducted with the support of the same equipment of the typing and lexical decision tasks. The presented audio files were the ones used in the typing task.

Procedure. At the beginning of each trial, a central fixation-cross appeared and, after 300 msec, an audio word was presented. After the sound presentation an upper case letter replaced the cross for 1000 msec and was followed by a blank response screen for 2000 msec. Participants had to press a designed key (F1 or F2) if the letter belonged to the heard word or the other designed key (F2 or F1) in the opposite case. The response system was alternated between participants and was identical to the one we used in the lexical decision task.

Two lists were created so that half of the words were associated with a yes response in one of the list and with a no response in the other. Then, the two lists were counterbalanced between participants. We assigned probes to words in order to counterbalance their position along the words, choosing from the first to the last letters. Then, for the probes not present in the words we manually assigned the letters to words.

We collected the reaction times in identifying the presence or the absence of the probe in the word and the error rates.

Data processing and statistical analysis. The procedure and the software for the analysis was the same used for typing task and lexical decision task. I briefly summarize the main steps.

In the Spelling Probe task errors in choosing if the presented letters belong or not to the heard word were discarded from the dataset (5.8% for the expert group; 5.1 % for the control group – tot 5.8%).

Outliers were considered after errors detection for each participant as reaction times above and below 2.5 standard deviations from the mean (2.4% for the experts and 2.2% for the non-experts – tot 2.3%) and the corresponding reaction times were also discarded from the dataset. Error rates were also analyzed but results did not show any significant effect of interest and were not reported.

Reaction times were log-transformed for the analysis. We used linear mixed models where we inserted all the transitions ratio values, modeled as a continuous predictor, the item-related variability and associated linguistic parameters. In all models, subjects and items were considered as random-effects while group (expert vs non-expert), bimanual transitions ratio and the interaction between the two were considered as fixed effects. Furthermore, we included in the models all the linguistic and task-dependent variables that reach significance, discarding those that failed to reach significance.

Results

Completed results of the model are reported in Table S6 in the Supplementary Material. Graphical representation can be consulted in Figure 2.B.

The final model was composed by the following linguistic and task dependent variables: trial rank, the hand used to type the first letter of the word and the number of syllables.

The results confirmed the absence of an effect of group ($p > .05$) and of transitions ratio ($p > .05$). Then, reaction times for "yes" responses were shorter than reaction times for "no" responses ($\beta = -.08$, $SE = .02$, $t = -3.2$, $p < .01$) showing a facilitation in answering when the letter was present in the word.

Furthermore, the interactions yes/no answer x group x transitions ($p > .05$) and group x transitions ($p > .05$) did not reach significance.

As in lexical decision task, yes and no responses were split into two separate databases to confirm the absence of an effect for the interaction between group and transitions ratio.

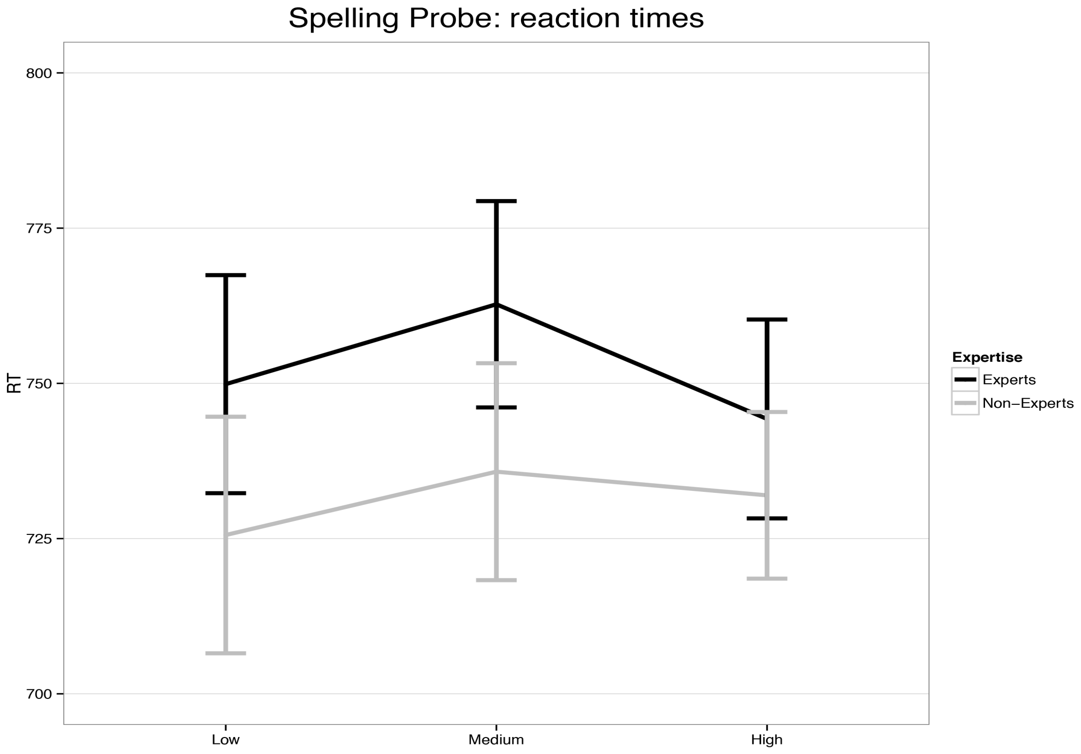

Fig 2.B

Note. *Summary of chronometric performance in the spelling probe task. For clarity, the data have been treated as in Figure 2.A, in Paragraph 2.1*

No responses. In the final model that considered only reaction time for no responses, where the probe was not present in the word, we allowed as extra variable only trial rank.

The interaction between groups and transitions ratios did not reach significance (p > .05). In the same way, no significance was found for effect of group (p > .05) and transitions ratio (p > .05).

Yes responses. Considering only the sample of yes responses, where the probe was present in the words, we inserted in the final model as extra variables the trial rank, the number of phonemes, the number of syllables and the position of the probe into the word.

As in the previous model for No responses, the interaction between groups and transitions ratios did not reach significance ($p > .05$). In the same way, no significance was found for effect of group ($p > .05$) and transitions ratio ($p > .05$).

Discussion

Results of the spelling probe task did not confirm our hypothesis of a recovery of typing motor information – represented by the transition ratio manipulation – during spelling independently from the experience we have with typing.

We have different explanations for the absence of the transitions ratio effect in this task.

First, we can deduce that motor information on bimanual coordination is limited to peripheral processes, so to motor execution. Models of typing usually divide the process of typing into two or more phases (Salthouse, 1986; Rumelhart & Norman, 1982; Jhon, 1996; Wu & Liu, 2008). For example, Salthouse (1986) divided typing process into four components: an input phase and a parsing phase that are responsible of receiving the text into the system and segmented it into characters. Then, a translation phase and an execution phase translate characters into keypresses and execute the writing movements. More recently, Logan and Crump (2009) divided the system of typing in two phases: an outer loop, that extract words from the input text, and an inner loop that translate the words in the corresponding keypresses. In their studies, they proposed that these two steps are encapsulated and that the process of typing is hierarchical. Their assumption comes from a set of studies designed to understand the specific role assigned to the outer and inner loops. They discovered that when skilled typists had to type only letters with the right or with the left hand, discarding from a word the letters of the opposite hand, the performance in typing decreased substantially. In a similar task, where letters to be typed with the designed hand are colored, the effect of inhibition disappeared. These findings demonstrated that the attention to hands caused the slowing down of typing process. Authors sustained that the high speed of the typing execution suggests that the outer loop usually do not control the inner loop output, but only the input (the whole word or colored letters). In other words, the inner loop is responsible for manual coordination; meanwhile the outer loop is unaware of motor commands.

In another work, Crump and Logan (2010) presented a task similar to our spelling probe. Their participants had to typewrite a probe after the visual or auditory presentation of words. When the probe was present in the words, it was typed faster than when it was not present. They sustained that a word-level representation causes the activation of letters and keystrokes in parallel. Despite the similarity of the task, the fundamental difference was the absence of a typing action in our spelling probe task.

The necessity of two separated loops in typing can be the explanation of the absence of motor information about hand alternation in our spelling tasks. Seeing typing as a hierarchical process seems to be reasonable to explain the quickly and efficiently coordination of perceptual, cognitive and motor systems. On the one hand, the speed of typing in experts does not allow that the outer loop interferes with the inner loop in planning hand movements. On the other hand, non-experts have not the reasonable experience to possess any standard motor information in spelling memory.

The second possible reason of the absence of a recovery of motor pattern during spelling can be linked to auditory presentation of words. Given the results of the lexical decision task, where words were visually presented, we can hypothesize that a visual input could lead to an activation of motor information possibly maintained during subsequent spelling. Conversely, the auditory input activates the orthographic information but no motor information is recalled.

Finally, a problem in the spelling probe task is the self-terminating strategy used to give a "yes" response. In detail, once the participant found the letter in the word, he/she stopped the spelling and gave the answer. The significant effect of the "position of the probe" variable explain us that if the probe is equal to one of the first letters in the target word, it is recognized faster compared to probes that correspond to the last letters of the stimulus (see results in Table S6 in the Supplementary Material). Furthermore, "no" responses were generally slower than “yes” responses and it is plausible to suppose that participants spelled all the word when they did not find the probe. The self-terminating strategy prevented that the entire word were processed, at least when the probe was present, nullifying the percentage of transitions we assigned to the whole word.

In conclusion, the spelling probe task leaves some doubt about the possibility of a bottom-up interaction of central processes of writing and peripheral process of typing. In my opinion, the question about the existence of this interaction is an open field of research and it would be interesting to explore in more detail, and with fine-grained experimental design.

2.3

Two thumbs and one index:
A comparison of manual coordination in touch typing and mobile typing

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Abstract. *It is extensively demonstrated that in touch typing, manual alternation is performed faster that manual repetition, meanwhile manual repetition speed depends on the distance between successive keys. In this experiment, we tested if the manual alternation and repetition constraints, typical of touch typing performances, can be seen in mobile typing, despite the different use of hands and fingers that the two writing tools required. We recruited two groups of skilled touch typists and tested them in a typing to dictation task with both a classical keyboard and a mobile keyboard. The "one-hand" group usually types with one index on the mobile, so through manual repetition; the "two-hands" group uses two thumbs taking advantage of bimanual alternation. Stimuli were selected according to the percentage of bimanual transitions necessary to typed them, from unimanual words to bimanual words. Results show that manual alternation and repetition behaviors work in the same way in both touch typing and mobile typing. On the one hand, when we use one hand on the mobile, the greater the distance between the keys, the slower the mobile typing performance, on the other hand, when we use both hands, the bimanual advantage influences both mobile typing and touch typing behavior. Furthermore, the advantage increases as the skills level of participants increases.*

Keywords: touch typing, mobile typing, bimanual coordination, manual alternation, manual repetition.

Introduction

Commonly when we think about typewriting, we think about a classical keyboard placed in front of a screen. Nowadays we should enlarge our idea of typing to a set of new and widely used tools: the mobile devices. In this paper, we focus our attention on mobile phone devices, widespread in daily life all over the word, comparing typing strategies performed with these "new" tools and the touch typing strategies performed with classical computer keyboards.

The computer keyboard and the mobile keyboard differ from each other in their physical and interactive features. A great difference consists in the interaction that they allow. The classical keyboard is devised for "touch typing", the typing method based on a standard association between each of the ten fingers and a subset of keys. In this way, typing is a bimanual action where simultaneous coordination between hands and fingers is required and where the right and the left hand never interfere with each other given the fact that they are assigned to the corresponding part of the keyboard (i.e. Shaffer, 1976, 1978; Terzuolo & Viviani, 1980; Rumelhart & Norman, 1982; Larochelle, 1984; Ostry, 1983; Salthouse,1986).

On the other hand, we usually grasp a mobile device and type on it with either one or two hands. It is possible to write with the index or the thumb of the dominant hand, or with the two thumbs of the two hands and, rarely, with the two indexes placing the device on a surface. Therefore, mobile typing can be unimanual or bimanual.

Bimanual coordination was extensively studied in the past and more recently in neuroscientific research (for review i.e. Cardoso de Oliveira, 2002; Swinnen & Wenderoth, 2004). In motor control studies, a bimanual interference exists when we have to give a simultaneous response with the right and the left hand. In this case, bimanual alternation becomes slower than one hand repetition because coordinating simultaneous movement between hands require more cognitive processes than coordinating within-hand movements (Adam et al., 1998; Miller, 1982; 1985; Adam & Pratt, 2004; Hazeltine, Aparicio, Weinstein & Ivry, 2007).

Conversely, typing requires a different mechanism of manual interaction that typically entails bimanual advantage.

Research on typing (Shaffer, 1976, 1978; Terzuolo & Viviani, 1980; Rumelhart & Norman, 1982; Ostry, 1983; Larochelle, 1984; Salthouse, 1986; John, 1996; Wu & Liu, 2008) suggests that bimanual alternation is a recurrent motor constraint in skilled typists: the interval between two keypresses (interkeystroke intervals – IKIs) is faster when performed with hand alternation than with hand repetition. This mechanism is supported by the fact that skilled typists move their hands in a parallel manner (Crump & Logan, 2010). In this way, when they alternate hands in two successive keystrokes, the movement of the second hand initiates before the other hand has finished to press the previous key (Gentner, Grudin, & Conway, 1980; Flanders & Soechting, 1992). In the case of within-hand interkeystrokes, typing rate appears to be a function of the distance between keys: the greater the distance, the greater the IKI (Rumelhart & Norman, 1982). Furthermore, IKIs are performed sequentially by the motor system when the same finger has to be used, since a keystroke begins only after the previous one (Soechting & Flanders, 1992). The difference between a cross-hand IKI and a within-hand IKI is greater when the latter is performed with the same finger. Rumelhart and Norman (1982) claim that this happens because the activation of two successive within-hand keystrokes interfere with each other: when one keypress is activated the next is inhibited. Conversely, if the second keystroke is performed with the other hand, it is likely that there is a higher activation on that hand.

The touch typing between-hands mechanism is probably due to the extensive practice of typists and it is difficult to reproduce in manual control studies. For example, Trapp, Lepsien, Shem, Villringer and Ragert (2012), in a serial reaction time task (SRTT), designed to test learning-related changes in reaction times, unexpectedly reported faster between-hands transitions than between finger alternations of the same hand. The task consisted in reproducing a sequence of letters associated with the index and middle finger of both hands. They suggested that this result was due to the fact that participants performed a single sequence repetition while the sequence to be pressed is visually presented on the screen.

Interestingly enough, the switch cost between hands decreased during the time course of learning.

Therefore, between-hand transitions are slower when various responses are possible and an overlap in the mappings of the responses of the two hands occurs (Rosenbaum & Kornblum, 1983). For example, no overlap between hands was found in non-expert (hunt-and-peck) typists (Larochelle, 1983) probably because more cognitive processes have to be monitored when typing is not an automatic skill.

Although Trapp et al. (2012) did not make specific reference to typing, it can be hypothesized that bimanual alternation in skilled typing is due to the activation of the keypress sequences and the connected motor response. For example, when typists are encouraged to pay attention to the hands by typing only letters of the right or of the left side, the bimanual advantage disappears because typists have to monitor the response (Logan & Crump, 2009). Furthermore, Crump and Logan (2010) showed that typing is controlled by a hierarchical process in which words cause a parallel activation of letters and their motor responses for keystroke execution.

In this study, we proposed to investigate if the bimanual advantage, typical of touch typing performances, can be seen in mobile typing, despite the use of only two thumbs per hand, or if the bimanual coordination is consistent with the disadvantage demonstrated by motor control studies (Adam et al., 1998; Miller, 1982; 1985; Adam & Pratt, 2004; Hazeltine, Aparicio, Weinstein & Ivry, 2007). For this reason, we recruited skilled touch typists, with experience in mobile typing with two thumbs, and tested them in a typing to dictation task with both a classical keyboard and a mobile keyboard. Stimuli, specifically words, were selected according to the percentage of bimanual transitions necessary to be typed, from 0% (unimanual words) to 100% (bimanual words).

We hypothesized that in both the computer-typing task and the mobile-typing task, the IKIs decrease as a function of the increase of bimanual transition in the stimuli, considering that the alternation of hands in mobile-typing proceed in parallel as in touch typing.

Furthermore, we proposed that the experience in typing with a standard keyboard could affect typing on the mobile. For this reason we collected a sample of participants with different skill levels, operationalized as typing rate (Salthouse, 1984), and analyzed this rate in the interaction with bimanual transition ratio in both the tasks. In the computer-typing task we expected a decrease of IKIs as a function of the increase in the transition ratio for the fastest participants, confirming the fact that the switch cost between hands decrease with experience (Gentner, 1983). We expected an analogous effect on the IKIs performance with the mobile, demonstrating an effect of key position knowledge.

Finally, we recruited a group of expert typists, but with little experience with the mobile, in the way that they use only the index of the right hand to type. We hypothesized that IKIs in mobile-typing task with one hand decrease as bimanual transitions decrease in the same way that unimanual keystrokes in touch typing are a function of the distance between keys. Indeed, passing from the left to the right part of the keyboard with one hand should transform the bimanual transition into a unimanual transition with a longer distance between keys, unusual in touch typing method.

Methods

Participants. Twenty-four participants, Italian native speakers, volunteered. Before the experimental session they filled in a questionnaire in order to collect: a) age and b) manual preferences. We selected only right-handed or ambidextrous participants. Then, we collected their writing habits c) with the keyboard, d) with the mobile keyboard and e) with the pen on the paper in order to select participants who used the keyboard for a suitable amount of hours per day and to ensure that they have mobile typing experience. Finally, we ask them to estimate their experience with the classical keyboard by asking f) how many years they used the computer and if they attended g) a typing course in the past.

In order to collect a quantitative measure of typing experience and to ensure that all the participants are skilled touch typists, we used a typing pretest, designed by means of Typing Test TQ 6.3 software (© Giletech e.K.) where participants had to type with the computer keyboard two short visually presented texts. Order of the presentation of the two tests was counterbalanced between participants. This software is able to record typing accuracy (calculated as the total amount of words in the text minus the number of errors divided by the total amount of word) and typing rate. We considered Net speed output as typing rate, calculated as words (5 characters) typed per minute minus the number of mistyped words. Finally, we recorded participants during the pretest to ensure that they use ten fingers and that they respect the division between right and left keys of the keyboard. Thanks to these procedures we were able to establish that our sample was composed by good touch typists with a minimum typing rate of 40 wpm. In order to test our two experimental hypotheses, we considered two groups: the "one-hand" group and the "two-hands" group. The first group comprehended 8 participants that were expert typists with the keyboard but used only one hand – in particular the index finger of the right hand – on the mobile. This group had only a moderate-to-low daily mobile typing.

The remaining 16 participants set up the second group given that they have a greater experience with the mobile phone in general and they use two thumbs to type on the mobile. In this group there was more heterogeneity than in the first group with respect to typing experience. Nevertheless, thanks to the typing pretest and the recorded videos we ensured that they used ten fingers and that they respect the division between right and left keys. In Table B we reported the complete data collected by the questionnaire and the typing test.

Table B

Features of the sample

	"One-hand" group	"Two-hands" group
N	8	16
Mean age	47	31.5
Right-handed (%)	95.9	82.5
Daily typing time (minutes)	275	441.95
Daily mobile typing (minutes)	12.5	157.9
Daily handwriting time (minutes)	50	63.75
Typing experience (years)	26.9	15.3
Typing course in the past	8/8	5/16
Typing accuracy (%)	95.9	96.5
Typing rate (wpm)	61.7 (SD 9.2)	53.9 (SD 14.1)

Procedure. Participants were asked to perform two tasks: a *computer-typing to dictation tasks* and a *mobile-typing to dictation task*, performed by participants in a counterbalanced order. In both tasks, the same word set was used and randomly presented. We recommended participants to be as fast and accurate as possible.

Stimuli. As experimental stimuli we presented 136 Italian nouns from 6 to 8 letters, selected from phonItalia 1.1 lexical database (http://www.phonitalia.org/). Words were controlled calculating the amount of bimanual transitions in typing on the QWERTY keyboard. Bimanual transitions ratio is calculated considering the number of transitions in the word divided by the number of interkeystrokes times 100. In this way, we obtained a total of 17 categories of bimanual transitions ratio: from 0% – words that are written with only the left or right hand – to 100% – words that are written interchanging hands for each letter (details in Table S7 in the Supplementary Material).

To consider the same amount of letters per row on the left and right side of the keyboard, we avoided left-hand letters “z”, “x”,”c” and “a” in the stimuli because of the absence of a counterpart on the right side of the keyboard, also we avoided double letters, because of the hypothesis that they are usually processed as a single key schema (Rumelhart & Norman, 1982), and stressed letters (e.g. “è”).

Main linguistic variables that can affect writing performances were balanced between the transitions ratio categories. Table S8 in the Supplementary Material provides a list of these variables.

Tasks. The two tasks had an identical design. Participants had to type each word auditory presented to them. On each trial a fixation cross in the middle of the screen was presented during the audio stimulus. Participants started to write after the identification of the word, during the stimulus presentation, and the typed letters appeared immediately in the place indicated by the cross, which instantly disappeared. After they finished typing the word, participants pressed the <Enter> key to stop the trial and to start the next. We instructed participants to avoid pressing of the <Backspace>, so no correction at any misspelling was possible. Participants were allowed to pause after processing half of the task.

We collected reaction times, recorded at the first letter pressing, and the average duration of interkeystroke intervals (IKIs). Accuracy was also recorded. A trial was considered an error if the target word was misspelled.

Before the beginning of the each tasks, we encouraged participants to accommodate the chair taking a comfortable position. To perform the *Computer-typing task*, participants sat in front of the screen, with the keyboard placed in front of them. In the *Mobile-typing task*, participants were instructed to hold the phone in one of the two ways: participants in the “one-hand” group held the phone with their left hand and typed on it using the index finger of the right hand; participants in the "two-hands" group held the phone with two hands and type on it using both thumbs.

Equipment. Both typing tasks were programmed with Opensesame 2.8.1 (Mathôt, Schreij & Theeuwes, 2012) an open source software able to run on both computer operating systems and Android mobile devices.

The *computer-typing task* was run on a PC with an LCD screen (Dell 1905FP) with a refresh rate of 75 Hz. The screen was positioned at a fixed distance of 65 cm from the participants. The resolution was set to 1024 px x 768 px and the characters were presented in white on a black screen with a font size of 18 pt. To collect responses we used an Italian QWERTY keyboard (Logitech Internet 350).

The *mobile-typing task* was run on a Nexus 5 (http://www.google.com/nexus/5/), Android version 4.4.4. The resolution was set to 12 px x 800 px and the characters were presented in white on a black screen with a font size of 30 pt. We chose a major font size for this task because the font size we used in the computer task resulted too little and threatened the visibility of typed letters. Data were collected by means of the standard touchscreen QWERTY keyboard of the mobile device displayed in horizontal position, a default option provided by Open sesame software.

The audio stimuli were recorded by a female Italian speaker and segmented with Cool Edit Pro 2.0. and were presented by means of headphones.

Data processing and statistical analysis. There was 9.4% errors in the *computer-typing task* for the "one-hand" group and 11.5% for "two-hand" group, and 11.8% in the *mobile-typing task* for the "one-hand" group and 15.4% for "two-hand" group.

In both tasks, outliers, i.e. interkeystrokes that were minus or plus 2.5 standard deviation from the mean, were detected for each participant after errors removal and were eliminated. In the *computer-typing task* we removed 2.1% of the total amount of interkeystrokes for the "one-hand" group and 2.1% for the "two-hands" group. In the *mobile-typing task* we removed 1.9%

for the "one-hand" group and 2.1% for the "two-hands" group. The means interkeystrokes per words were computed and used in the data analysis.

For RTs, the outliers were identified as those trials whose RTs were less or exceed 2.5 standard deviation from the mean (*computer -typing task*: 2.4% for "one-hand" group and 2.3% for "two-hands" group. *Mobile-typing task*: 2.6% for "one-hand" group and 2.4% for "two-hands" group).

For statistical analysis, IKIs and RT were log-transformed and processed using linear mixed models (Baayen, 2008; Baayen, Devidson & Bates, 2008, software R, package lmerTest for models processing and p-values and package LMERConvenienceFunctions for graphical representations). We constructed separate models for the two groups of participants, and in all the models, we considered subjects and items as random effects while the bimanual transitions ratio – considered as a continuous predictor – the tasks (*computer* vs *mobile*) and the interaction between the two were considered as fixed effects. For the "two-hands" group we considered also the interaction of the typing rate, collected in the pretest, with the variables of interest, given the different typing rate distribution between participants.

Furthermore, to control for possible variables that can interfere with the hypothesized effects we included in the models all the linguistic and task-dependent variables that reach significance.

For error analysis, we used the same procedure to construct the models using generalized mixed model and considering errors as a binary dependent variable with a binomial distribution.

Results

Interkeystrokes intervals

"One-hand" group

Results for the "one-hand" group are summarized in Table S9 in the Supplementary Material and represented in Figure 2.C.

In the final model we included trial rank, typing rate, number of right letters, word frequency, number of characters and phonemes, orthographic neighborhoods mean frequency, orthographic Levenshtein distance, and the bigrams frequency.

The effect of Task ($\beta = .8$, SE = .02, t = 48.46, $p < .001$) and of Transitions ratio were highly significant ($\beta = -.002$, SE = .0002, t= -8.29, $p < .001$). Also, the interaction between Transitions ratio and Task reached significance: $\beta = .005$, SE = .0003, t = 19.57, $p < .001$).

The significance of the interaction of interest allowed us to split the database between the *computer-typing task* and the *mobile typing task* to ensure that Transitions ratio reached significance in both tasks. The statistical models confirmed that IKIs mean significantly decreased as Transitions ratios increased in the *computer -typing task* ($\beta = -.002$, SE = .0002, t= -7.87, $p < .001$). Conversely, in the *mobile-typing task* the IKIs mean significantly increased as the Transitions ratio increased ($\beta = .004$, SE = .0002, t = -17.01, $p < .001$).

“Two-hands” group

Results for the “two-hands” group are summarized in Table S10 in the Supplementary Material and represented in Figure 2.C.

In the final model we included trial rank, typing rate, number of right letters, first letter, orthographic neighborhoods mean frequency, orthographic Levenshtein distance and bigrams frequency.

The effect of Task ($\beta = .5$, SE = .01, t = 41.44, $p < .001$) and of Transitions ratio were highly significant ($\beta = -.001$, SE = .0002, t = -6.26, $p < .001$). Also, the interaction between Transitions ratio and Task was significance: $\beta = .0007$, SE = .0002, t = 3.45, $p < .001$).

When analyzing the databases of the separate tasks, we found a significant effect of Transitions ratio in both the typing tasks: $\beta = -.01$, SE = .0002, t = -4.96, $p < .001$ in the *computer-typing task* and $\beta =-.0005$, SE = .01, t = -2.64, $p < .01$ in the *mobile-typing task*.

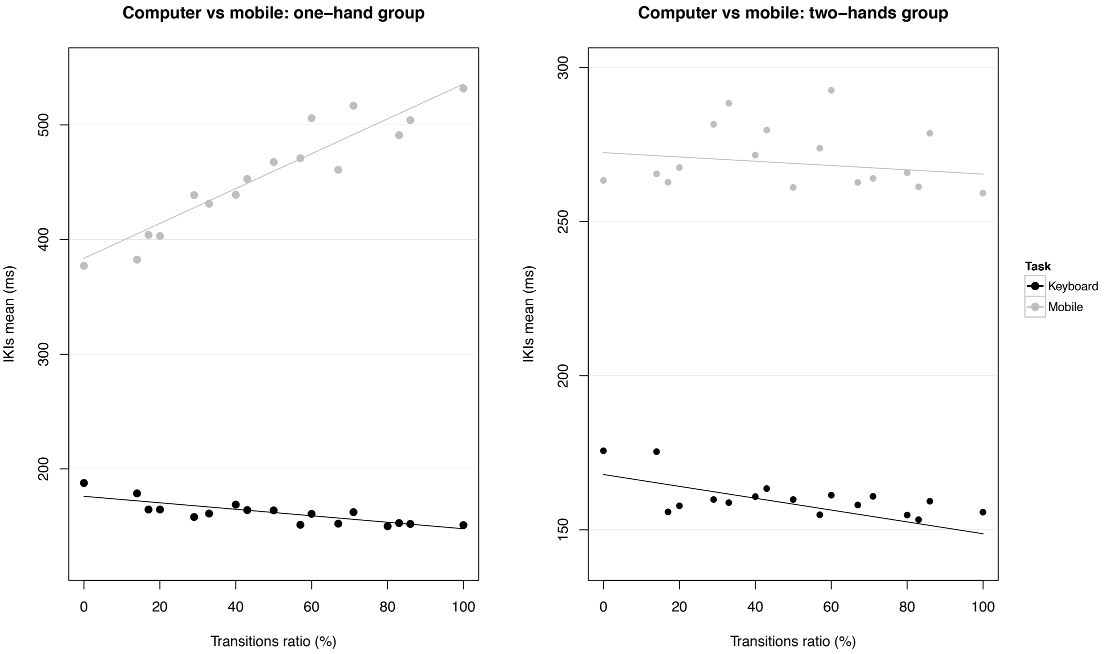

Figure 2.C

Note. *Summary of chronometric performance of computer-typing and mobile-typing of the "one-hand" group (panel a) and the "two-hands" group (panel b).*

Effect of typing rate

Given the interindividual variability of the typing rates in the "two-hands" group, we inserted the interaction of this variable with Transitions ratio to test if the Typing rate had an influence on the effect of Transitions ratio, usually a performance that increases with expertise in typing. Results are plotted in Figure 2.D.

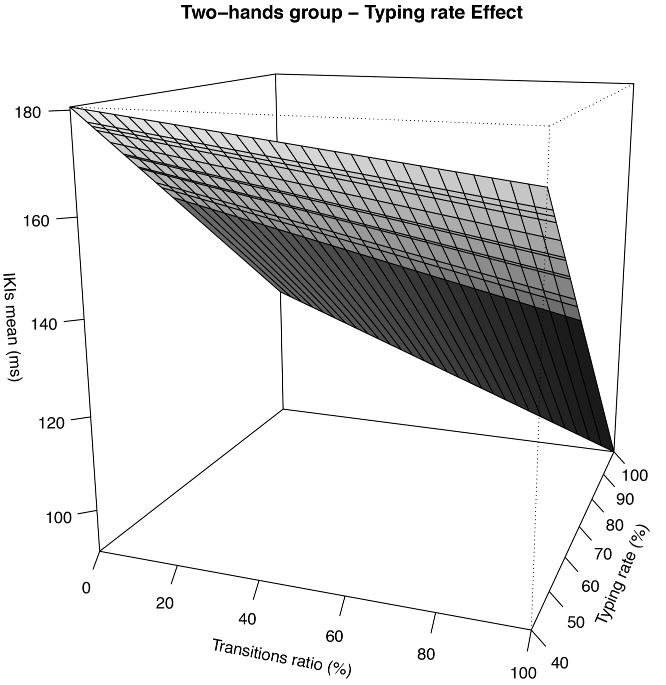

Fig 2.D

Note: *Plot of the interaction between Transition ratio and Typing rate. Computer-typing and mobile-typing datasets have been pulled.*

In the general model the interaction between Typing rate, Tasks and Transitions ratio did not reach significance ($p > .05$) suggesting that there is no difference between the two tasks in the interaction between typing rate and transitions. The interaction between Typing rate and Transitions ratio was significant ($\beta = -.00004$, $SE = .00001$, $t = -4.02$, $p < .001$). Also the effect of Typing rate was significant ($\beta = -.006$, $SE = .002$, $t = -2.3$, $p < .05$). The effects of Transitions ratio and of Tasks were not significant, as the interactions between Typing rate and Tasks and between Transition ratio and Task ($p > .05$).

Reaction times

Reaction times results are reported in Table S11 in the Supplementary Materials.

In both groups, no influence of Transitions ratio on reaction time was found ($p > .05$). Also the interaction between Task and Transitions ratio was not significant ($p > .05$). A significant difference existed between the tasks in both groups, indicating that pressing the first key of the dictated word needed more time on the mobile device that on the computer keyboard ($\beta = .04$, $SE = .01$, $t = 37.21$, $p < .001$ for the "one-hand" group; $\beta = .3$, $SE = .009$, $t = 29.66$, $p < .001$ for the "two-hands" group).

Errors

Errors analysis is reported in Table S12 in the Supplementary Material.

Both groups reported a significant difference between the tasks demonstrating a large amount of errors in *mobile-typing tasks*. Results were respectively: $\beta = .7$, $SE = .3$, $z = -2.46$, $p < .05$ for the "one-hand" group, and $\beta = .6$, $SE = 3.9$, $z = -2.3$, $p < .01$ for the "two-hands" group.

The only relevant result regarding transitions ratio was found in the "one-hand" group that reported an increment of errors with the increment of Transitions ratio in the *computer-typing task* ($\beta = .008$, $SE= .004$, z value $= 2.04$, p value $< .05$).

Discussion

Motor behavior in touch typing and in mobile typing have both different and common features. Generally, touch typing is devised for the QWERTY keyboards, but in the last decades mobile devices require typists to adapt their typing habits to smaller, and often touchscreen, keyboards and to abandon the ten finger method. Indeed, mobile typing is performed with one finger per hand, commonly the index of the dominant hand or the thumbs of both hands.

In this study, we tested whether manual motor constraints of touch-typing with a standard keyboard can be observed in mobile typing with one or two fingers.

First, we found that in the *computer-typing task,* for both one-hand and two-hands groups, the IKIs mean decreased as a function of the increase of bimanual transitions per word. This finding largely confirms the bimanual advantage in touch typing (Shaffer, 1976; Terzuolo & Viviani, 1980; Rumelhart & Norman, 1982; Ostry, 1983; Larochelle, 1984; Salthouse, 1986; John, 1996; Wu & Liu, 2008; Crump & Logan, 2010).

In the case of mobile typing with one hand, we observed an increase of mean IKIs as the transitions ratio increased. This pattern can be accounted for by assuming that the execution of two successive keystrokes with the same hand transformed every bimanual interval of the words stimuli into a unimanual interval, with a longer transition from a key in the left side of the keyboard to a key on the right side, and vice versa. Therefore, mobile typing with the index finger of the dominant hand reflects the principle that the IKIs depend on the distance between keys, as previously found in within-hand IKIs (Rumelhart & Norman, 1982). Furthermore, findings in typing within-hand keystrokes are consistent with the view that the same finger of the same hand is moved sequentially in such a way that a keystroke begins only after the previous one has been performed (Soechting & Flanders, 1992). Since programming of different movements with the same finger causes interference – when one keypress is activated the next is inhibited (Rumelhart & Norman, 1982) – we claim that such inhibition affects one-hand typing strategies on mobile devices.

In the two-hands group, we found a similar trend when comparing the *computer-typing task* and the *mobile-typing task:* IKIs mean increased as bimanual transition ratio decreased. This result is consistent with our hypothesis: bimanual alternation in mobile typing reflects touch typing behavior and not more general motor preferences in bimanual coordination (Adam et al., 1998; Miller, 1982; 1985; Adam & Pratt, 2004; Hazeltine et. al, 2007). Clearly, in both computer and mobile typing cross-hands intervals between two keystrokes are faster than within-hand intervals. We deduce that bimanual advantage typical of touch typing behavior can be extended to mobile typing. Specifically, also mobile typists move their hands in parallel, programming hand alternation faster than hand repetition because the second hand receives the highest activation in triggering keystrokes compared to the inhibition common in hand repetition (Gentner, Grudin & Conway, 1980, Flanders & Soechting, 1992).

As for the difference between mobile typing, in which only two thumbs are used, and in touch typing, in which all fingers are involved, our results indicated that bimanual advantage in mobile typing, and probably in touch typing, is not due to alternation between fingers, but mostly to an interplay between the right and the left hand to which the corresponding part of the QWERTY keyboard and specific letters are assigned. However, the bimanual advantage remains stronger when the ten fingers are involved, as attested by the interaction between transitions ratio and the two tasks. When manual responses cannot be programmed in advance, the alternation between hands is slower than hand repetition because of the major cognitive operations required (Adam et al., 1998; Miller, 1982; 1985; Rosenbaum & Kornblum, 1983; Adam & Pratt, 2004; Hazeltine, Aparicio, Weinstein & Ivry, 2007). In typing, manual responses can be programmed in advance. Crump and Logan (2010) propose a hierarchical process of typing where an "outer loop" is involved in the processing of words and an "inner loop" in the deconstruction and execution of keystrokes in parallel. Thus, a sequence of keypresses is activated and the corresponding motor program is simultaneously executed. Furthermore, when typists are encouraged to pay attention to the hands by typing only letters of the right or of the left side, the bimanual advantage disappears because the typists had to monitor the response, thus disrupting the parallel process of keypress execution (Logan & Crump, 2009). In bimanual motor control studies, Trapp et al. (2012) unexpectedly discovered slower reaction times in bimanual alternation than in hand repetition when participants had to perform a serial reaction time task, i.e. reproducing a sequence of letters associated with the index and middle finger of both hands on designed keys. Interestingly, the switch cost between hands decreased during the course of learning. The authors explained the bimanual advantage by the fact that the sequence of letters is visually displayed on the screen. Despite the absence of a specific reference to typing, we can see this result associated to the findings of Crump and Logan, 2010. If the sequence of letters is programmed in parallel, the presence of sequence of keypress in the inner loop can be linked to the bimanual advantage. This pattern can be interpreted as showing that the cognitive and motor processes involved are common to both touch typing and mobile typing.

The influence of typing rate in touch typing on mobile typing was previously investigated by Salthouse (1984). The author analyzed the effect of skill level, measured as words per minute, in different parameters of keystrokes pressing. Typing rate was positively correlated to the bimanual IKIs. The higher the experience of a typist, the higher the speed in switching hands. Previously, Gentner (1983) claimed that the finger movements become less sequential and more overlapping with practice.

In line with this finding, our results confirm that in the *computer-typing task* the increase in the typing rate gave rise to an increase of the bimanual advantage: a reduction of IKIs mean as the transition ratio increased was more pronounced in more skilled typists.

The novel and somewhat surprising result is that the same effect arises also in the *mobile-typing task*: typing rate, measured in the pretest with a standard keyboard, influenced bimanual advantage in mobile typing. Salthouse (1984, 1986) proposed that experience plays a role in the precision of the movement specification and coordination, and in a higher synchronization of processes that eliminate the uncertainties of movement of unskilled performances. Given the effect of typing rate in mobile typing, we can consider that the knowledge of the key position is another crucial factor in bimanual alternation. Motor learning research also indicates that learning new movements may be simplified by the combination of previously learned movements. For example, Gordon, Casabona and Soechting (1994) discovered that in typing, when some keys are switched with other keys, the movement pattern and the speed of the new learned disposition and the normal one are similar. Furthermore, participants were generally faster if the overlapping movement of the two hands was maintained.

Finally, we observed slower reaction times and the larger amount of errors in mobile typing compared to touch typing from both one-hand and two-hands groups. These findings may be ascribed to different causes related to the different interaction and physical constraints of the two types of keyboard. As previously demonstrated, the smaller the keyboard, the slower is the typing rate (Sears, Ravis, Swatski, Crittenden & Schneidermann, 1992). Furthermore, capacitive touchscreen have been shown to be the slowest technology to respond to touch (Carroll, 1989). One reason for this pattern is that the different size of the two types of keyboards allows different precision in the movements. With a touchscreen device, the less precision in pressing the right keys might be the justification of higher amount of errors in mobile typing. Connected to this, the different pressing feedback that touchscreen tools provide might increase the error rate. Moreover, the shorter distance between keys probably reduces the precision in pressing the first key causing slower reaction times. Furthermore, the different posture of hands in touchscreen keyboards might also slow down reaction time. Indeed, in a classical keyboard, typists usually position their hands along the home row while in a mobile touchscreen keyboard fingers are far from the screen at the beginning of the movement.

In conclusion, this study reported a similar pattern of movement in bimanual alternation a unimanual repetition in both a classical keyboard and a mobile phone touchscreen keyboard. This strongly suggests that the cognitive and motor processes involved in touch typing transfer to mobile typing. To our knowledge, our study is one of the first that directly compares touch typing and mobile typing on small devices.

We are convinced that further research in the field of mobile typing is necessary given the large diffusion of these devices in everyday life. Interactive and physical features of mobiles have to be analyzed from a cognitive perspective to completely understand, on one hand, user performances and, on the other hand, cognitive processes involved.

Chapter 3

Mobile technologies and learning

Nowadays it is difficult to imagine our daily life without mobile phones or other mobile devices like portable laptops and tablets. Mobiles are widespread all over the world and are utilized in an extended number of fields. It is sufficient to think about the huge amount of applications devised for smartphones: they cover activities ranging from everyday organization to social contact, from games to learning activities.

In this last chapter, I focus on a different line of research compared with the previous chapters, which, however, is closely related: the social and educational influence of Information and Communication Technologies (ICT) on literacy acquisition and language learning, with particular attention to the potentials of mobile devices.

I present two theoretical papers that were published in two different proceedings of international conferences. The first paper (Paragraph 3.1) considers the effectiveness and the potentials of ergonomics applied to ICT in educational environments, especially in situations where it is necessary to improve educational resources, as in developing countries where literacy diffusion and school settings are still poor. We generally consider both writing and reading as two fundamental skills for each individual and, sometimes, we take the mastery of these abilities for granted. Primary education is dedicated to the acquisition of these skills and technologies offer new possibilities for extending the power of classical educational methods. Teachers may use ICT as a helpful tool in the school setting (integrative tool), but ICT may also be a tool in those cases in which teachers and schools are not present (substitutive tool). In this regard, ICT can be effective in developing situations where people often do not dispose of schools, skilled teachers and well-organized educational methods. Technology allows to reach individuals and groups that are far in space and time thanks to its digital features; it is long-lasting, multisensory, and flexible in terms of the information it can deliver. For these reasons, it may compensate for the shortage of teachers and educators and capitalize on motivation and curiosity by children if its use is correlated to an appropriate pedagogical program.

Mobile devices may add some useful advantages: for example, they are increasingly cheap, compact, personalized, user centered, networked. The educational scenario is slowly integrating such devices that are contributing to shape the recent eLearning environment, adding the advantage of ubiquity and simultaneity. Thanks to these features, mobiles are altering the nature of learning, freeing users from the time and space anchors. In this way, users can independently self-regulate the device and their learning process.

The second paper (Paragraph 3.2) focuses on mLearning: eLearning with mobile technologies and, specifically, on Mobile assisted Language Learning (MALL). Several technological examples were examined in order to reason about how mobile devices are suitable for language learning. In detail, we paid attention on the cognitive mechanisms involved in second language acquisition: (a) spaced repetition, (b) multisensoriality, (c) incrementality, (d) situated cognition and (e) socio-cultural sharing.

The underlying purpose of both papers consists in proposing the use of these mobile tools as a possibility of redemption and educational equality in developing countries where people, for cultural reasons and for shortage of resources, have no guaranteed access to adequate instruction and where linguistic pluralism forces individuals to learn in other languages rather than their mother tongue.

3.1

Ergonomics: Possible Roles in Helping Literacy Acquisition in Developing Countries

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Abstract. *Ergonomics, and the implementation of psychologically-tailored technologies, may prove helpful in the process of literacy acquisition. In this paper we discuss the possible role of ergonomics in allowing a greater number of children to get access to formal education, focusing on literacy acquisition through the use of ICT. In this perspective, ergonomics not only allow for better design of educational settings, and enhance the physical learning environment, but may promote the use of communication technologies as important learning tools. We briefly review some ICT based programs aimed at enhancing the acquisition of reading and writing skills launched in several countries. We then discuss the modulating effects of several factors in the use of ICT in this endower, ranging from e.g. socio-economic conditions to language use and status, from technological constraints to teachers' and family attitudes. Finally, we argue for several possible roles of ergonomically based ITC in literacy acquisition for children growing up in developing countries.*

Introduction

Ergonomics, and the implementation of psychologically-tailored technologies, may prove helpful in tackling areas of criticality in modern societies. It may also play an important role in helping the acquisition of literacy by both children and adults. It may do so in several ways, either directly or indirectly, and it may be a driving force for other developments as well.

Access to literacy and numeracy are basic rights for a person not only because written communication is widespread and pervasive in contemporary society but also because literacy is linked, among other things, to non-formal learning and other development activities such as health interventions, family planning, agricultural extension and the formation of self-help groups (Alam, 2002).

In spite of this, literacy is a dramatic divide in today world. Of the 182 countries listed in the 2011 United Nations Development Programme (UNDP) Report, 102 have a literacy rate of 90% or above, 12 are below 50%, and the remaining 68 are in between. There are many factors that hinder access to literacy. Among them, data show a strong correlation between household poverty and illiteracy. "Evidence indicates that people who come from low-income households, and therefore lack adequate nutrition and hygiene, are less likely to acquire and use literacy skills. This implies that when implementing literacy education activities targeting low-income households, it may be necessary to first address the basic nutritional and health needs of the target group" (UNESCO, 2005).

Literacy diffusion in developing countries is crucial for achieving a solid balance between language, education, and economic development. In fact, the human, economic and social capitals are considered multiplicative: a weak economic base affects education (human capital) and social cohesion (social capital) (Williams & Cooke, 2002).

Ergonomics and Acquisition of Literacy

Why is Ergonomics Important

While adult illiteracy is an important issue that requires a research impetus to find solutions that would be beneficial to both individuals and societies, in this paper we will focus on the possible role of ergonomics in allowing a greater number of children to get access to ICT learning tools and environments that may improve literacy acquisition. In doing so, we should be aware not only of the large cross-lingusitic differences among writing systems (see, e.g. Job, Peressotti, & Mulatti, 2006) but also of the social implication of literacy (see, e.g. Ogbu, 1990).

Ergonomics may play a pivotal role in improving educational environments at both the physical and psychological level. Recently, Andrée Woodcock (2011) has proposed a four-fold categorization of such benefits:

1. Good ergonomic design can protect the health and well being of the children and teachers
2. Good ergonomics design can enhance learning and teaching
3. Behaviors learned in schools during early years can have a cross over into family and later life
4. Ergonomics can provide a way of linking diverse initiatives undertaken to enhance the learning environment – such as curriculum innovation, use of ICT.

Thus, ergonomics can be effective at several level, from the design of the furniture of the school, that should enhance correct seating and limit the possibility of wrong postures during lessons, to the structuring of the class context, favoring different types of interaction (for some activities a face-to-face setting is better than the traditional row-behind-row setting of most classes); from the long-lasting effects of ergonomically congruent behaviors that would be beneficial for both the individual as well as the society to the role of ergonomics as a source of change in the learning environment by providing new tools and, as a consequence, tuning the pedagogical approach to instruction. This latter is the perspective we are interested in in this paper. Specifically, we discuss how ergonomic principles may enhance the use of ICT in setting up programs of literacy acquisition in developing countries.

A role of ICT?

ICT has been widely used as an instrument for literacy acquisition for several reasons. Technology allows to reach individuals and groups that are far in space and time; it is long-lasting, multisensory, and flexible in terms of the information it can deliver; it may compensate for the shortage of teachers and educators, if appropriately used; it can capitalize on motivation and curiosity on the part of the children. ICT may be used as a helpful tool by teachers in the school setting (integrative tool), but it may also be a tool where teachers and school are not present (substitutive tool).

Several studies have investigated the possible role of ICT as an integrative tool in literacy acquisition, both in western and in developing countries, with mixed results, leading Cummins, Brown and Sayers (2006) to conclude that such "data do serve to debunk the I belief that technology infusion by itself will transform students' educational progress".

On the one hand, Carroll, Krop, Arkes, Morrison and Flanagan (2005) showed no gains in literacy achievement in California between 1990 and 2003 despite major curricular reforms and significant technology investment. Analogously, Goolsbee and Guryan (2006) examined the impact of the federal e-rate program and concluded that although the program had certainly increased access, there was no evidence that Internet investment had any measurable effect on student achievement.

On the other hand, Machin, McNally and Silva (2006) evaluated the effects of ICT investments in England and found a positive impact on students' performance, particularly in English.

Finally, on the basis of a study involving more than 100,000 15-year-old students in 31 countries, Fuchs and Woessmann (2007) argue that access to computers might exert a negative impact on students' achievement. Analogously, Angrist and Lavy (2002) report data from a survey of Israeli school teachers who received an influx of new computers funded by money from the national lottery. The new computers appeared to increase teachers' use of computer-aided instruction but there was no evidence that this translated into higher test scores. In fact, the trends were in the opposite direction.

In commenting these, and similar studies, conducted in developed countries, He, Linden and MacLeod (2007) and Linden (2008) claim computer assisted learning programs have limited utility in educational environments that work well. Such outcome probably originates because technology insertion competes with functional teaching tools. On the other hand, in developing countries, where trained teachers are not always available, ICT could make the difference in literacy acquisition (He, Linden & MacLeod, 2007). In fact, evidence suggests that the application of technologies that change pedagogical methods can have very large effects. Indeed, information literacy and classical literacy can proceed in a concomitant way with reciprocal benefits starting from the first years of schooling. This is possible through analysis of pedagogical methods that take advantage of technology in the classroom, but especially outside the classroom, as an extracurricular instrument. With respect to this, Linden (2008) maintains that if computers substitute more productive arrangements of resources, students may learn less than if the same programs were used as supplement to existing efforts out of the classroom, in individual programs.

The role of ICT as a substitutive tool is quite complex. Literacy acquisition is part of an educational process that goes behind learning to read and write and learning numeracy. Thus, the pedagogical relationship within a learning community is very important. However, where such community is difficult to build, for whatever reason, ICT can become a unique pedagogical method and may substitute the classical educational system tools, enabling to reach large part of the population, including the disadvantaged. In this perspective, ICT can replace low-skilled teachers and assist in the course of education in areas that lack teaching materials and school buildings.

Of course, there is a correlation between poverty level and literacy acquisition, as mentioned in the introduction. Analogously, another crucial world gap, the so-called "digital divide", is concerned with the diffusion of information technologies and the disparity of access to them. These two kinds of divide, literacy and digital, are somehow connected because the lack of acquisition of literacy skills is often linked to the absence of technology use, including informational and educational content access. According to Chinn and Fairlie (2010), one of the main factors responsible for the low rate of technology penetration in developing countries is human capital, measured by years of schooling. Although computer and internet diffusion rates among developing countries have risen dramatically over the past several years, the difference between developed and developing parts of the world is still quite large. Thus, without an innovative intervention that takes into account the effects of globalization and technological advancement the gap will only increase, providing the richest with all aspects of educational and communicational power of ICT and excluding the uneducated poor and leaving the latter without the necessary skills to secure their well-being (Kim, Miranda & Olaciregui, 2008).

The challenge we are forced to face is how to use ICT for literacy acquisition in situations in which ICT itself is not readily available.

A review of two cases

The case of Interactive Radio Instruction (IRI) in Zambia

The Directorate of Open and Distance Education of Zambia's Ministry of Education has developed alternative basic education programs at lower basic (Grades 1-4), middle basic (Grades 5-7), and upper basic (Grade 8) levels. Such programs for lower and middle basic education are delivered to learners countrywide using Interactive Radio Instruction in community-supported learning centers of two types: center that are dependent entirely on radio lessons and mentors, and community schools that use IRI methodology wherein children learn by following a radio lesson under the supervision of a mentor (Zambia Ministry of Education, 2006).

As reported by Siaciwena and Lubinda (2008) the program is a partnership between the Ministry of Education and different organizations – among which there are local community-based organizations, international non-governmental organizations, and churches and aims to reach out-of-school children who have no basic education, nor the ability to access the formal school system due to inadequate provision or insufficient facilities, poverty, distance to the nearest formal/government school, increasing parental disinterest in school education, and the impact of HIV/AIDS.

The Interactive Radio Instruction (IRI) program was launched in July 2000 as a pilot project catering for Grade 1 learners at 22 IRI learning centers. The program has been expanding rapidly as shown by the increase in both the number of schools using IRI radio broadcasts, up to 1,058 in 2006, the number of community schools adopting IRI methodology, up to 497 in 2006, and the number of learners, up to 81,324 in 2006, reflecting a 44 percent increase (Zambia Ministry of Education, 2006).

Data about the achievement of educational goals for the individuals involved are not available (to the best of our knowledge), but Siaciwena and Lubinda (2008) list three main achievements that can be considered indexes of success of the program. First, the IRI accounts for a significant portion of the schools offering basic education – i.e., 893 IRI centers out of a total 7,256 schools offering. Second, IRI have helped to improve the quality of education in community schools, as shown by the fact that teachers uses IRI to supplement teaching materials and that IRI assists untrained teachers to manage their lessons adequately. Third, "the IRI programme is promoting equity and equality in educational provision" (Siaciwena and Lubinda, 2008) by (a) increasing the number of school in rural areas, (b) providing educational opportunities to girls as well as to boys; (c) increasing access to education for orphans.

One Laptop Per Child (OLPC)

OLPC is a nonprofit organization whose aim is to design, produce and distribute low-cost computers so that every child in developing countries have access to knowledge and computer literacy with the hope of reducing the digital divide in the planet. As suggested by Kraemer, Dedrick and Sharma (2009), the case of OLPC can be seen as a study in general diffusion of technology in developing countries.

The laptop is designed to be shock and water resistant and it adapts to the exposure to sunlight, being equipped with a display that can be used either in black and white or color, allowing good outdoor visibility. It is designed with particular attention to energy saving, and it is particularly suitable for conditions where electricity is not readily available (Buchele & Owusu-Aning, 2007). Furthermore, OLPC has been designed in such a way as to enable a connection even when there are no close access points. This is made possible by a mesh network that allows to automatically connect a laptop that has access to the network in a sharing signal system (Buchele, 2009).

The educational framework of the project relies on the constructionist view of learning, developed by Papert (Papert & Harel, 1991). Within the OLPC project, the laptop is viewed as an useful tool in the construction of both individual and shared knowledge (Buchele & Owusu-Aning, 2007; Apiola, Pakarinen & Tadre, 2011). Therefore, the development of educational programs following this system should ensure a child's learning through direct interaction with the instrument in a situation of peer-to-peer learning.

Since 2007 OLPC has spread in many developing countries. Half-dozen countries have reported positive changes, but also critical issues, in their pilot studies. As reported by Kramer, Dedrick & Sharma (2009), enrollment in schools grow, absenteeism decreases, discipline and participation in class increases. A study conducted in Uruguay on the usability and functionality of the OLPC laptop has reported that connectivity is still a challenge, especially when children are not in school. Then, there are problems with input devices, in particular with touchpad and keyboards. The interaction with the interface is not always intuitive – for example, because of the bad language translation or the difficulty in concept understanding and content localization (Hourcade, Beitler, Cormenzana & Flores, 2008). Unfortunately, evaluation studies on the use of OLPC are rare, given the novelty of the project. In addition, they often tend to have a formal imprint since they are funded by ministries, who are the direct intermediaries between OLPC and schools (Nugroho & Lonsdale, 2010).

In an ergonomic prospective, the lack of usability measures about the device is unfortunate, and it is not clear how well the laptop fits into the specific contexts in which it is used (Martinazzo, Patrìcio, Biazon, Ficheman & Lopes, 2008; Leaning, 2010). Cuts of production and a sale curve less dynamic than predicted are sometimes interpreted as cues of difficulties of the project (Kraemer, Dedrick & Sharma, 2009; Leaning, 2010).

At a more theoretical level, Leaning (2010) is concerned with the fact that OLPC provides both a hardware and a software but not a proper educational program, despite the stated goal. Indeed, the educational program and the actual method of use in the classroom are left to the specific country and the specific school in with the laptop is placed. On this issue, Apiola, Pakarinen and Tedre (2011) see two opposing forces: omitting specific educational guidelines is useful for inserting laptops in the context of use, but lack of teachers' skills in the educational framework within which OLPC has been developed is detrimental. Also lack of teacher training on the specifics of the laptop may also affect the program (Kraemer, Dedrick & Sharma, 2009).

The two cases reviewed are at the opposite ends of an ideal continuum that range from "collective" to "individual" technologies. The radio is a unidirectional, one-to-many technology, while the laptop is, to some extent, interactive, and a one-to-one tool. Both have strengths and weaknesses that are related to their context of use, availability of resources, and the educational support they can rely on. The two cases were instrumental in showing that there is no "optimal" technology, that each tool can support learning and teaching in some conditions better than in others, and that in order for ICT to play a role it must take into account a set of variables and intervening factors at different levels of complexity.

A framework for literacy acquisition and ICT

In order to propose a long-term strategy for exploiting ICT in literacy acquisition in the developing countries it is important to consider both its potentials and its limitations as an educational tool. Before any proposed educational program can be implemented, an institution must take into account not only the technology in itself, but also the economic, political, and social aspects that modulate its use in actual contexts. We organize these factors in three areas:

(a) economic and social factors
(b) human resources
(c) differences among technologies

Economic and social factors (a)

There are several potentially positive social and economic factors involved in the use of ICT in literacy acquisition. Some are linked to individual and collective motivation to acquire competences that can be used in adulthood; to perceived self-efficacy and social reward; to peer influence and imitation behavior; to the perceived possibility to achieve a higher social status and, with reference to poor people, to improve their own and their family life conditions. At a more global level, administrations can support and actively implement ICT as a tool for economic growth.

However, there are also social constraints that may limit the use and diffusion of ICT in developing countries. These mainly concern the actual reduced availability of economic means and infrastructures, reflecting the digital divide between and within countries, but they also concern gender differences in access to literacy and to ICT use, as well as peoples' attitude and beliefs, such as the belief that technologies are for educated people only.

Among the economic problems we may mention the level of the services offered and the physical resources available, such as problems with electronic systems due to intermittent voltage drops or spikes in electrical power sources (Steinmueller, 2001), problems that are more severe in rural areas (Kim, Miranda & Olaciregui, 2008; Geldof, 2008). This limitedness of use is aggravated by the scarce network connection and its high cost, as well as by higher operational costs such as maintenance and transportation (Dymond, 2004). Urban zones are less affected due to large monetary investments that coincide with major infrastructures, and the richest and more educated population brackets in urban zones have access to, and can use, technology-mediated information (Dighe & Reddi, 2006).

Indeed, the difference between rural and urban networks remains such that fixed rural networks are still at least 6 to 10 times more costly than urban ones (Dymond, 2004). Thus, the digital and educational divide is not only "global" but also "local", within the same country (Gulati, 2001; Alam, 2002). In the poorest zones, insufficient physical conditions and poor social conditions, such as meager financial resources for paying and using technologies, are all limitations that increase the divide (Geldof, 2008).

For all these reasons, as well as a general lack of education, impoverished conditions, and the high cost of technology, Internet and telephone connections are not well developed in many areas. The most widespread technological instruments in the developing world are radios, which can be bought by a large part of population and do not have high network costs (Kenny, 2002). Moreover, with regard to power supply, radios can run on batteries, so they are not dependent on electricity.

Another relevant fact is that ICT impacts women and men differentially, especially in developing countries. Women are discriminated in many aspects of social life, including employment, income and education (Dighe & Reddi, 2006; Hilbert, 2011). This condition may stem, along other causes, from the unequal access to literacy in childhood in which women are disadvantaged. It has been claimed that the increasing socio-economic importance of ICT may provide a unique resource in fighting the existing inequalities (Hilbert, 2011); however, women are still disadvantaged in access to ICT, and this may impact even more negatively on their access to literacy.

Human resources (b)

Human resources, with respect to the use of ICT in literacy acquisition in developing countries, can be considered both from the point of view of the technicians needed for the technological development and support and the point of view of skilled teachers needed for support the education process of students by means of technology.

While software developers, system engineers, communication and network engineers, computer teachers and operators (Waema, 2002) will eventually increase in number and abilities in developing countries, the lack of skilled manpower in ICT implementation in all sectors from school to industry who can create dedicated technologies or maintain the existing ones suggests that using ICT for literacy acquisition should be based on simple-to-operate, shock resistant, and user-friendly devices.

In this sense, a positive cycle could be activated such that the use of ICT favors literacy acquisition that, in turn, may favor technological literacy. One of the first steps to consider is that governments should make ICT training available in all schools, to allow people to grow a basic ICT literacy. Another step is to introduce and improve training in secondary and higher school to train a class of workers capable of exploiting and developing new technologies that meet national development requirements (Waema, 2002). Thus, the growth of human resources depends on each institution's capacity to achieve a favorable environment for learning (Kimaro, 2006).

Teachers are important too, as they play a pivotal role in the educational system with reference to both knowledge acquisition and training and to the adoption of ICT in such system.

As reported by Glewwe and Kremer (2005) teacher quality and availability is a common issue in developing countries. Indeed teachers often have weak incentives and little supervision, and a great level of absenteeism is registered. Moreover the teachers incentives are often focused on exam score; for this reason instruction is often based on rote learning, copying from textbooks onto the blackboard, and having students copy from the blackboard. The authors claim that only 90 percent of primary school teachers and 69 percent of secondary teachers are trained and the required training for these teachers is general lower than that of rich countries (Glewwe & Kremer, 2005). The lack of skilled teachers is a serious problem for the development of literacy that, according to He, Linden and MacLeod, (2007), can in part be overcame by the use of computers in school. This statement needs some qualification, as computers cannot substitute teachers, not even bad ones. It is true, however, that for less skilled teachers, and for poor schools, computers can provide educational programs that can integrate lectures and other didactic activities.

The introduction of ICT alone cannot change the pedagogical framework; rather, the very possibility of improving literacy and education performance with computers in schools is linked to appropriate changes in pedagogy: effects of the computers and associated training for the teachers teaching methods have to be combined (Barrera-Osorio & Linden, 2009). Using ICT in schools as an integrative tool requires to view teaching as shifting from a teacher-centered perspective to a learner-centered perspective (Trucano, 2005). It is typical to consider teaching as the center of the learning process but it is actually learning that must be central. So, for ICT to be functional to literacy acquisition they should be design to reflect this change in perspective.

Differences among technologies (c)

The expansion of ICT in developing countries must comply with the context in which it is implemented, i.e. it is useful to invest in an appropriate technology in reference to the context of use. The physical and social constraints that we have discussed do not allow the diffusion of all type of ICT tools in a generalized way. For example, if network and electricity are not always available some tools are automatically excluded, and a technological diffusion plan has to consider possible alternative technologies that can reach potential users. Analogously, if there is a disparity between rural and urban zones and, accordingly, a disparity in education in these zones, technological tools appropriate for the different situations must be considered in order to maximize the possibility for all children to have access to such technologies.

As reported by Dighe and Reddi (2006), in earlier decades the use of traditional media, such as radio and television, for educational purposes was extensive. These mass media, the most diffused and known in most developing countries, transcend the illiteracy barrier and can be used to reach a lot of people. But the new ICT must not be neglected because it may reach niches not yet involved, and they may prove to be flexible tool for literacy acquisition. Indeed, while traditional media are unidirectional communication tools, and are often controlled by corporations, the new digital media are potentially more open and can be used either individually or collectively (Dighe & Reddi, 2006). Moreover, the new ICT tend to enhance multisensory and multi-channel information transmission, through images, audios, videos, tactile, and texts. Among these new ICT tools, the mobile technology seems to play a relevant role (Chigona, Beukes, Vally & Tanner, 2009).

Mobile technology can reach vast segments of population, as it does not require bandwidth connections, and this might be an asset in developing countries. So, distance learning using multimedia through mobile technology seems to be a viable way to reach billions living in difficult-to-reach rural areas of many countries (Deb, 2012).

Rapid mobile communication technology development has given opportunities for economic and social development in developing countries. As reported by Shrestha, Moore and Abdelnour-Nocera (2010), for a large group of people mobile phones are the first and only interactive digital media they directly operate and experience. Mobile technologies are related to mobile learning or mLearning, a relatively young educational technology paradigm. It can be defined as a form of eLearning that can be pursued at any time and in any place using ubiquitous technologies (Muyinda, Lubega, Lynch & von der Weide, 2010). Typical examples of the devices used for mobile learning include cell phones, smartphones, palmtops, and handheld computers; tablet PCs, laptops, and personal media players (Deb, 2012).

One of the important challenges for mobile technology is building applications that can function offline, thus dealing with the disconnected nature of mobility (Shrestha, Moore & Abdelnour-Nocera, 2010), and without direct supervision or tutoring. For these reasons, each program must be built on educational, social, and technological principles that may allow the program to be successful. The local stakeholders, including educators and technicians, must be involved in the process, for the program to be pragmatically and socially viable (Deb, 2012).

While in principle mobile technology is an innovative and inclusive tool that allows children unable to attend classes to acquire literacy with minimal professional supervision, is it actually functioning when implemented in real situations? Kumar, Tewari, Shroff, Chittamuru, Kam and Canny (2010) have used mobile phones as a tool for learning English as a second language in a rural area of India. Eighteen children aged between 10 and 14, belonging to different social castes, were loaned cellphones with preloaded educational games, based on traditional village games, that targeted different English competencies spanning across both oral and written modalities. At the end, participants, on average, had learned 46 new words over a span of 16 weeks, and the Authors argue that it is reasonable to expect each participant to cover over 150 words in a year. Given the social and educational context, this compares well with the estimated typical learning of 500 new second language words per year in good learning condition (Cameron, 2005). These results seem encouraging and support the view that mobile phones were an active and productive tool of learning in this study. At a more general level, on the basis of their analysis of social interaction with the mobile tool, the Authors argue that mobile learning games can create a shared context that encourages the development of new social ties across different caste binderies.

Some of the features that may account for the positive outcome of the Kumar et al.'s (2010) participant observation seem to be unrelated to the fact that mobile learning is interactive, involves substantial human contact, supports personalized and situated learning that recognizes diversity between individuals, and it can be quite context-specific (Traxler, 2007). Rather, it seems that the mobile tools activated pro-social behaviors, like mentoring and "expert" interventions, social routines, and a sense of responsibility within the community.

The current limitations of mobile technologies are several, as illustrated by Deb (2012): physical attributes of mobile devices, such as small screen size, inadequate memory and short battery life; content and software application limitations, as the difficulty of adding applications; network speed and reliability and, lastly, physical environment issues such as problems with using the device outdoors. However, the rapid improvement of this kind of technologies is comforting, and is paralleled by developments of the open source mobile system, that will reduce costs and improve networks capabilities. Open hardware and open software can also lower the costs and thus increases the possibility of offering sustainable services in the future (Shrestha et al., 2010). Once the costs are lowered and the technical limitations are overcome, the mobile devices and educational programming must fit together in and out of the classrooms. Therefore, any mobile and technological application cannot ignore the need for well-studied pedagogical tools linked to this type of technological tools.

Conclusions

ICT can in principle play a role in the process of literacy acquisition by children in developing countries both as an integrative tool when schools and teachers are available and as a substitutive tool where formal education conditions are unavailable. For the former types of environment, several technological tools may be adequate as a support to teachers. For the latter types of environment, small, mobile, and easily-rechargeable technologies seem to be a promising learning tool that may complement classic medias as the radio.

In order for ICT to play a significant role, the technology chosen must be not only compatible with, but also functional to, the contextual conditions of use, defined in terms of, physical socio/economic, and human resources available, as well as the socio-motivational aspects of the user.

An ergonomic approach requires both the pedagogical aspects and the technological aspects to be considered jointly, in order to favor productive learning environments and to provide effective teaching tool. Distance education, active role of the learner, and multi-channel learning may converge to create adequate learning environment.

The existing digital divide between and within countries is an obstacle to the diffusion of knowledge as well as to the social, economic and cultural growth of individuals and societies. ICT is at the same time a cause and a product of the digital divide; however, the rapid diffusion and innovation of ICT, that lowers the cost of devices and makes them more durable and easier to use even for people who cannot read and write, seem to make them more feasible to the context of developing countries, characterized by physical and socio-economic barriers to ICT.

3.2

Cognitive-Educational Constraints for Socially-Relevant MALL Technologies

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Abstract. *Mobile technologies may play a pivotal role in language learning in situations where multilingualism may be a key factor in personal and societal development. We review some Mobile Assisted Language Learning (MALL) studies and show that when such technologies take into account cognitive constraints and rely on a coherent pedagogy model they foster the learning process and allow to frame it in the socio-cultural environment of the learner.*

Introduction

The sociolinguistic status of most countries is quite complex, as several languages may coexist within the country, each having specific functions, with one or some of them having a privileged status while the others(s) being used in daily life interaction within groups of different status. Such a situation has several important implications at the political, social, and individual level, as the country official language may not coincide with the set of idioms spoken by the majority of the population, a portion of the population may not know the official language (Geldof, 2008), the different languages may act as a barrier between groups – yielding inequity and discrimination, and individuals may have the necessity to learn several languages in order to reach their life goals. To cope with this problem, and to try to limit illiteracy, individuals' frustration, minorities' discrimination, as well as school drop out, several countries have adopted language policies for bringing in the mother tongue at least in the first years of schooling. For example, following a research by the Zambia Ministry of education showing that only the 3% of children in Grade 1 could read at an acceptable level, in 1996 the Government introduced a new language policy allowing the teaching of reading through the students' mother tongue (one of the country seven official languages). Except for this new measure, English remains the main medium of instruction in the country (Tambulukani & Bus, 2012). In South Africa over 80% of the population speaks indigenous African languages and less than 1% speaks English at home. In spite of this, English and Afrikaans are the dominant institutional languages. With the adoption of the new constitution official status was given to 11 languages, but many South-African teachers would prefer maintaining English as the unique medium of education (Casale & Posel, 2011). Finally, in Bolivia, where one third of the population speaks the official Spanish language and where 70% of the population is indigenous, the Education Reform Law of 1994 introduced all the indigenous languages into primary bilingual schooling and intercultural education to create understanding among students (Benson, 2002).

For many persons being multilingual is a necessity rather than an option in order to fully achieved citizenship, and for many countries improving multilingualism may be beneficial for social development. However, most of the people, and the countries, that would benefit from multilingualism lack the necessary economic resources and structures, such as access to school and formal education. In this paper we review the possible role of mobile technologies to promote language learning as a means to overcome individual and institutional limitations and to foster personal as well as societal development.

mLearning

Information and Communication Technologies (ICT) are routinely used as educational tools. Job and Cerni (2012) list several reasons for this: technology allows to reach individuals and groups that are far in space and time; it is long-lasting, multisensory, and flexible in terms of the information it can deliver; it may compensate for the shortage of teachers and educators, if appropriately used; it can capitalize on motivation and curiosity on the part of the children. Teachers may use ICT as a helpful tool in the school setting (integrative tool), but ITC may also be a tool where teachers and school are not present (substitutive tool).

The added value of Mobile devices is that nowadays more people possess a personal technological device thanks to the rapid evolution of computing and price lowering. The market, and the correlate request by users, is providing more and more complex and compact devices that have the features of being personalized, user centered, networked, ubiquitous, and durable (Motiwalla, 2007). Mobility is one of the main characteristics associated with these devices; indeed, cellular phones, PDAs, audio devices, Smartphones, netbooks and tablets alter the traditional configuration of time and space by providing access to electronic resources and multimedia communication between users anywhere and anytime. The educational scenario is slowly integrating such devices, and they contribute to shape the recent eLearning environment adding the advantage of ubiquity and simultaneity (Muyinda, Lubega, Lynch & van der Weide, 2010). The opportunity to access educational resources not only "just-in-case" but also "just-in-time", "just-enough" and "just-for-me", which alters the nature of learning, freed users from the time and space anchors defined by the computer location or by external stakeholders, and allow them to independently self-regulate the device in his/her location and time frame (Traxler, 2007).

Following the distinction between ICT as an integrative tool and ICT as a substitutive tool, aimed at individual and self-regulated learning without the support of a teacher or a formal institution, we see mobile technologies as powerful tools for the last type of functional role. However, many of their potentialities have not been tested and/or used yet. Kukulska-Hulme and Schield (2008) point out that the major use made of mobile technologies for learning is pedestrian, uncreative, repetitive and teacher-led, while less attention has been paid to the features of mobility, peer connectivity, and communication. In this sense, the crucial features of mLearning have not been fully exploited and the tool is used as just another technology for WBT (web-based training) that is static, non-flexible and time consuming (Morita, 2003), ignoring e.g. the possibility to cut the content into smaller segments providing a learning process that lasts one minute or less and the ad hoc, context-specific use of the device. The interaction between mobile devices potentialities (e.g. mobility, portability, individuality) and limitations (e.g. small screen, limited message length, limited power) as well as user's potentialities (e.g. intelligence, motivation, problem solving abilities) and constraints (e.g. attention and memory limitations, time and contextual constraints) may be a contributing factor for the development of creative solutions.

In order to fulfill an educational role, mLearning must be coupled with a congruent pedagogical model and consistent learning methods. Scharples, Taylor and Vavoula (2005) claim that "in the era of mobile technologies, education become conversation in context built through and with personal and mobile technology." This assumption underlies the potentiality of social-constructivist theory, which considers learning as an active process of building knowledge and skills through practice and within a supporting community. Furthermore, mLearning devices must be sensitive to the cognitive constraints involved in learning so that they can favor rather than hinder the learning process. We will briefly review some of these cognitive factors with reference to the mLearning devices devoted to language learning.

MALL

MALL is an implementation of mLearning applied to language learning. The language learned is, typically, a second language (L2) and learning is supported by portable technologies, emphasizing continuity and spontaneity of access and interaction across different contexts of use (Kukulska-Hulme, 2009). Through MALL, students may feel a sense of freedom from time and place, so they can take advantage of the opportunity to learn L2 when they desire and where they are (Miangah & Nezarat, 2012).

We propose that language learning through mLearning is highly compatible with some of the cognitive mechanisms involved in language acquisition, specifically: spaced repetition, multi-sensoriality, incrementality, situated cognition, socio-cultural sharing.

Spaced repetition. A notion originally proposed in the area of memory studies (Melton, 1970) it refers to the fact that learning is more effective when content is presented over time rather than in quick succession. There are several factors that modulate the effects of spaced repetition (see, e.g. Edge, Searle, Chiu, Zhao & Landay, 2011 for lexical learning), but by and large a learner retains more information (e.g. words or sentences) when the input is provided at spaced intervals.

Edge et al. (2011) proposed that space repetition can be an inherent attribute of MALL. Indeed, if mobile technology allows learners to connect to learning content across moments of free time, it is possible to create microlearning content opportunities over time. Microlearning, a technique inspired by eLearning, breaks up learning task into a series of quick learning interactions in different time periods. The strong point is the possibility of exploiting temporally-space presentation that has been shown to achieve higher learning goals than a heavier learning method. Furthermore, short interactions are the best design for mobile technologies. Thus, the system should manage the spacing of occurrences of each item, as well as the co-occurrences of items.

Combining micro-content and the possibility of accessing the database in different moments of the day, Cui and Bull (2005) propose TenseITS, a mobile intelligent tutoring system for the use of tense in English. TenseITS is designed primarily for Chinese learners and it allows them to study English during their daily routine, without interfering with other activities. TenseITS as an intelligent tutoring system offers (a) individualized adaptations according to the learner's knowledge, abilities, weak points, and misconceptions by means of individualized learning material and a learner model; (b) individualized adaptations according to the learner's location and needs in that location (e.g. Restaurant, home, etc), by means of multiple context inputs, such as the amount of time available (less than 15 min, between 15 and 30 min, etc.), and, finally, (c) portability that allows the user to connect in different time and place conditions, e.g. the concentration level and the frequency of interruption (High, Medium, Low). In this way, the system may keep track of where the users are, as well as of relevant features of the learning situation, thus allowing different types of learning instruction – e.g. new lessons, repetitions of lessons, lesson plus exercises, exercises only, etc., to be uploaded.

Multisensoriality. Learning entails building knowledge encompassing different modalities, and utilizing different sensory modalities can make learning very powerful, as claimed, among others, by the Paivio's dual-coding theory (see, e.g. Mayer & Sims, 1994; Lotto, Job & Rumiati, 1999). Mobile technologies are well suited to provide integrated perceptual, visual, and auditory inputs, and some additional utilities may be implemented to enhance this aspect, e.g. repertoires of environmental sounds, tactile and/or symbolic smell icons, and so on.

Ketabi, Zarei and Khazaei (2011) compared a traditional in-class method of language learning with a blended method through mobile phones, precisely through sending SMS and MMS with or without the addition of pictorial annotations, and showed that Iranian semi-illiterate adults learning English benefited more from the blended method, with words presented with a related image being recognized and recall better than words without pictorial annotations (for similar results in a school setting see, e.g. Tonzar, Lotto & Job, 2009). Two other studies are relevant here. Chen and Hsieh (2008), with Chinese speakers learning English, and Taki and Khazae (2011), with Farsi speaker learning English, classified their participants in four groups according to their visual and verbal abilities: high visual and high verbal; high visual and low verbal; low visual and high verbal and, finally, low visual and low verbal. They presented to-be-learned words in different conditions: (1) printed words together with pronunciation, grammatical class, and the corresponding meaning in L1; (2) words as in (1) with the addition of an example of a sentence and the corresponding translation; (3) spoken words with pictorial annotation. Chen and Hsieh (2008) also use a condition in which words have both written and pictorial annotations. In both studies, there was a positive effect of congruency between type of presentation and verbal and visual characteristics of the learners.

This pattern highlights the fact that different features of words concur in fixating learning of the lexicon, with different modalities contributing as a function of the learners' individual difference, and that multisensoriality can be adequately implemented in mobile technologies.

Incrementality. Language is built on incrementality (Brown-Smith & Hanna, 2011), that can be viewed according to two perspectives, one referring to the progression from a limited to a more complex knowledge of language elements, e.g. from the lexical, to the sentential and textual level, and one referring to the level of proficiency, in terms of the productivity in processing, considering also figurative language processing.

MALL technology must take into account the actual level of the user but also his/her progression, adapting the material provided in real time. An interesting tool to measure and enhance learner performance is PIMS, or Personalized Intelligent Mobile Learning System (Chen & Hsu, 2008). This software can appropriately recommend news English articles to learners based on the learner's reading abilities evaluated by the fuzzy Item Response Theory (IRT). In the mobile program proposed by Chen and Hsu (2008), IRT is implemented in the so-called Client Mobile Learning System that provides a user interface for collecting learner's learning responses, an English vocabulary learning interface, and a checking vocabulary interface to confirm acquired vocabularies. A feedback agent is able to compute learners' difficulty levels as well as comprehension measures about the articles, and this information allows the system to recommend the article(s) with an appropriate level of difficulty. When the user makes progresses, the procedure is repeated. The evaluation of the system by the participants in a five-week period showed that the scores increased significantly from pre- to post-test mostly for those participants with low pre-test scores.

Situated cognition. According to situated cognition theory, learning is rooted in social practice and in the adaptation to the natural and cultural environment (Barsalou, 2008). This kind of learning is viewed as fast and context-specific, being a product of the activity, context and culture in which it is developed and used (Ogata & Yano, 2003; Traxler, 2007; Reinders & Cho, 2010) and should be analyzed from the perspective on what the learner is doing during a specific task or activity in a given socio-institutional context (Mondada & Pekarek Doehler, 2004).

In developing MALL systems, Ogata and Yano (2003) have stressed the need to provide users with the possibility to be localized in a specific place, for example through GPS, and to attune the learning material and the linguistic expressions to that specific place. Their system, CLUE, provides a repertoire of sentence but also of polite expressions in Japanese, introducing characteristics of the interlocutors. Another feature of CLUE is vocabulary learning through tagging real objects with Radio Frequency Identification (RFI) sensors, allowing the system to infer contextual information about the user movements and interactions with these objects which, in turn, allows the system to tailor the linguistic input the learner is presented with by scanning the RFI tag.

In a similar perspective, Beaudin, Intille, Manguia Tapia, Rockinson and Morris (2007) have developed a prototype based on RFI. The basic system design consists of an "always on" mobile phone application connected to objects sensors distributed in a house via GPRS. This application responds to user touch and movements with objects providing object-related audio-played English and Spanish phrases and their translation on screen.

Socio-cultural sharing. Learning a language implies not only to increase one's vocabulary and grammatical competencies, but also to know, and being sensitive to, cultural and social aspects of that language. This means that learners should have the possibilities to interact with other member of the learning community. In this perspective, mobile technologies allow users to interact with other people either directly or indirectly. Chat, forum and calls can be used for connecting directly, while mobile devices can increase social interaction among peers via networking.

Wong and Looi (2010) developed a system to learn Chinese idioms that were tested in a primary school classroom interaction. Students used the handhelds to take photos, composed sentences about the idiom connected to the photo, shared the artifacts in a wiki platform and carried out asynchronous peer reviews. In this way students could interact with each other at the distance, commenting on photos of others and sharing materials for learning. An even stronger social sharing due to mobile technologies has been reported by Kumar, Tewari, Shroff, Chittamuru, Kam and Canny (2010). These authors have used mobile phones as a tool for learning English as a second language in a rural area of India. Children aged between 10 and 14, belonging to different social castes, were loaned cellphones with preloaded educational linguistically-relevant games based on traditional village games. Apart from the satisfactory number of L2 words learned by the children, the authors emphasize that the mobile learning games created a shared context that encouraged the development of new social ties across different caste boundaries.

Some of the features that may account for the positive outcome of the Kumar et al. (2010)'s study seems to be only tangentially related to the fact that mobile learning is interactive, involves substantial human contact, supports personalized and situated learning that recognizes diversity between individuals, and it can be quite context-specific (Traxler, 2007). Rather, it seems that the mobile tools activated pro-social behaviors, like mentoring and "expert" interventions, social routines, and a sense of responsibility within the community.

Concluding remarks

Traditional media tend to be unidirectional communication tools, and are often controlled by corporations while mobile technologies are potentially more open, can be used either individually or collectively, and tend to enhance multisensory and multi-channel information transmission. They can reach vast segments of population, as they do not require bandwidth connections. This can be an asset in developing countries and in difficult-to-reach rural areas of many countries (Deb, 2012).

One of the challenges for mobile technology is building applications that can function offline to dealing with the disconnected nature of mobility (Shrestha, Moore & Adelnour-Nocera, 2010) and without direct supervision or tutoring. For these reasons, such technologies must be built on explicit and consistent educational, social, and technological principles.

There is some empirical support for the fact that mobile technology may support both L1 and L2 learning, a relevant issue in many countries where the official language used as medium of instruction is not the mother idiom for the majority of the population. Since education in a known language, typically in mother tongue, has more chances of success compared to education in a new language (Williams & Cooke, 2002), and since multilingualism may be a positive feature for personal and societal development (see, e.g. Casale & Posel, 2011), any tool that may effectively and productively enhance language learning should be considered. Our brief review of MALL shows that mobile technology coupled with attention to cognitive factors and congruent pedagogical techniques may be a viable tool for language learning.

General Conclusions

Writing and learning technologies open a large amount of possibilities in research, from a cognitive point of view but also from a pedagogical one. On the one hand, as we have seen, technologies are analyzed in the educational field because of the great diffusion of new devices in school settings, but also in everyday life learning and in non-conventional institutions. For example, we can now learn by sitting on the couch with our smartphones. For these reasons, technological applications should be based upon an accurate pedagogical program. On the other hand, research should help to enlighten us about the potentials and the failures of technological introduction in education, but first we should know the basic cognitive processes involved in order to make any assumptions. An interdisciplinary research is advised to explain how our behavior is changing thanks to – or in spite of – technology diffusion.

There would be many different scientific issues about learning technologies and about writing technologies that could be discussed. However, to conclude this thesis, I want to reflect on one of the most important reasons why we should investigate cognitive and educational impacts of different writing modalities and of the dedicated devices: the question of literacy acquisition.

The diffusion of typing technologies, from personal computers to mobiles, has an impact on the acquisition of writing abilities and on language learning in general. A current issue regards the progressive abandoning of handwriting, and of graphomotor movements, in early education. Typing technologies alter the traditional acquisition of writing skills of children who are exposed to two different kinds of writing modalities. In detail, producing a text with a pen on a paper requires different visual and motor processes compared to writing on digital devices. It is plausible that the haptic affordances of different devices, digital or not, affect the way we learn to write. For this reason, sensorimotor behaviors and changes in writing due to digitalized environments should be taken into account when we conceptualize writing processes in any scientific field.

It is common ground that the acquisition of reading and spelling abilities requires the integration of phonological, morphological and orthographic knowledge during literacy learning ("triple word form theory": Berninger, Nagy, Carlisle, Thomson, Hoffer, Abbott et al., 2003; Berninger, Abbott, Nagy & Carlisle, 2010). Furthermore, according to the "self-teaching theory", visuo-orthographic and phonological information have to be linked in language learning (see among others Share, 1995, 1999, 2004; Nation, Angell & Castels, 2007). It seems that to become not only a good writer, but also a good reader it is fundamental to know the link between the written and the spoken forms of a word, hence, to have a stable orthographic knowledge base. However, if we consider orthographic knowledge on a broader level, we have to include the visual, haptic and tactile components of writing. Precisely, to acquire knowledge of the written form of words, perceptual and graphomotoric components are fundamental (Bosse, Chaves & Valdosi, 2014).

Concerning this issue, a recent line of research focused on the major influence of practices that include reading and writing trainings compared to the sole reading trainings on orthographic learning. Two studies found that an orthographic training was more efficient when children had to spell the item they read compared to a training that includes only reading (Ouellette, 2010) or only silently thinking about the item just read (Shahar-Yames & Share, 2008). Recently, Bosse, Chaves and Valdois (2014) compared the effect of handwriting trainings and spelling aloud trainings on production and on recognition tasks. Results showed that handwriting trainings improved orthographic learning in the production task. These authors suggested that the memorization of handwriting movements supports the memorization of orthographic information more than the articulatory movements alone. The main idea is that the graphomotor experimentation of a word provides an additional link between the written and the oral form of that word.

In line with this assumption, there is an open debate in the embodied theory field – as briefly discussed in Chapter 1 – that sustains how orthographic knowledge and letter representations may be composed by a complex neural network that includes motor-perceptual components that are acquired through the concomitant learning of reading and writing (Mangen & Velay, 2010). In applicative terms, some researchers in the cognitive neuroscience field showed that the experience of writing movements, in particular handwriting, can contribute to the memorization of the shape and/or to the orientation of characters, and so to their recognition. This assumption is supported by data showing motor area activations during letter perception in several studies (see among others Velay & Longcamp, 2012, for a review; Longcamp et al., 2003; Longcamp et al., 2005a; Jeames & Gauthier, 2006; Matuso et al., 2003). For example, in an fMRI study, Longcamp et al. (2003) showed that the visual presentation and the writing of letters activate the same area in the premotor cortex, whereas the presentation of pseudo-characters that have never been learned through writing do not activate that area. The same activation patterns were shown in both right- and left-handers in the corresponding regions of the opposite brain hemispheres (Longcamp et al., 2005a). This fact may suggest that the perception of characters is not strictly visual but involves specific motor regions, the same regions involved in handwriting, demonstrating a strong relation between manual writing and reading.

Regarding different peripheral processes of writing, some researchers compared handwriting to typing in order to examine whether the change of motor conditions during learning – as in passing from the pen to the keyboard – can have effects on letter representations and on the consequent recognition performances. In analyzing the distinction between handwriting and typing in pre-school children (Longcamp et al., 2005b; James & Engelhardt, 2012), and analyzing recognition performances in adults (Longcamp et al., 2006), it became more evident that the letters and the characters learned through typing are recognized less accurately than those learned through handwriting. Finally, in an fMRI study Longcamp et al. (2008) showed that zones of brain activation during letter recognition include motor patterns usually involved in handwriting but not in typing. These results can be attributed to the simultaneous learning of reading and handwriting and could imply that typing has a different impact on the cerebral representation of letters and on their memorization.

As reported in Paragraph 2.1 of the present thesis, a set of studies on expert typists showed that brain regions known to process orthography and phonology of single words are commonly activated during reading and typed spelling (Purcell, Napoliello & Eden, 2011). Furthermore, letter pairs that are easier to type are recognized faster than more difficult pairs (Van Den Bergh, Vrana & Eelen, 1990; Beilock & Holt, 2007; Yang, Gallo & Beilock, 2009). Finally, our study (Paragraph 2.1. Cerni, Velay, Alario, Vaugoyeau & Longcamp, submitted) showed that also words that are easier to type are recognized faster than more difficult words.

The comparison between the cited studies about the influence of handwriting and typing in orthographic recovery allows us to deduce that the different motor experience in writing is a key factor in shaping language processes and learning. A great experience in typing influences the way we process pairs of letters and words, whereas it seems that if we learned concomitantly to read and to handwrite, and we do not have a fine-grade experience in typing, handwriting is a better instrument to acquire letter and word features. Furthermore, studies in pre-literate children suggest that the graphomotor practice involved in handwriting, especially in the early phases of language learning, could improve memorization of orthographic information. If we think about the importance of hands and of the manipulation of objects during learning in general, the idea that graphomotor movements can help us in the memorization and identification of words and their components is not surprising.

These findings in cognitive psychology and neuropsychology can give an answer to the recent debate in education that proposes to abandon handwriting and to introduce massive typing training. Prior to drawing any conclusions we have to consider that the haptic experience of handwriting in learning seems fundamental, but we also have to consider that typing technologies are established in our society to such an extent that we are forced to plan educational programs that take into account digital reading and writing. Despite the fact that technological tools are only slowly being integrated in school settings, they are rarely used in educational programs and children rarely receive instruction on how they can take advantage of technology for learning. This way, technology is synonymous to amusement and play most of the time. Finally, one of the most important issues in typing and handwriting learning, and in future research, consists in the evaluation of individual differences in writing (Berninger, 2013). We have to consider the habits, the preferences and the cognitive skills of typically developing people and disabled people in writing to advise the best learning program with the best writing tools. This way, learning performances can benefit from trainings that use the favored writing modality.

To conclude, handwriting and typing are two fundamental writing modalities that affect the whole language process and the skills they are involved in cannot be ignored by education in any part of the world. For this reason, educational proposals and actual programs in language learning have to include different writing devices and to pay attention to specific and individual educational needs. What effectively happens in switching from one to the other writing modalities has to be investigated in more detail in future research. We do not know the influence of different technological tools for handwriting and typing and of the digitalization of educational materials in actual language learning methodologies. In my opinion, times are changing so fast that we should find not only answers to these issues, but we should also anticipate how different technological devices might lead to changes in our cognition. For example, the use of digital handwriting tools that provide benefits of both, multimedia and of graphomotor movements, may add advantages to handwriting acquisition and avoid to abandon this writing modality. If writing with a pen and with a keyboard should be integrated to foster a complete development of language abilities, it is fundamental to find a compromise between digitalization and "old" tools. I would suggest to think about touchscreen devices and tangible interfaces that are powerful at integrating tactile experience and learning materials to open new possibilities for children and adults in multisensory learning (see, e.g. Mayer & Sims, 1994; Lotto, Job & Rumiati, 1999). Another issue that we cannot ignore is the inevitable early exposure of children to technologies. Sometimes it seems that babies are better than adults in handling mobiles, and technological devices seem to be essential instruments for the social and educational life of younger people. What is happening with children's cognitive capabilities under these circumstances? How will the new modalities of text exploration change the first approach to reading and writing? In which way should we program our education considering the changes that are taking place? Giving an answer to these questions will be the assignment of future multidisciplinary research.

Supplementary Material

Table S1

Stimuli classification

	32 six letters words	*40 seven letters words*	*48 eight letters words*
Percentage of bimanual transitions	20% - 8 words (i.e. humour)	16% - 8 words (i.e. plumier)	14% - 8 words (i.e. pompiste)
	40% - 8 words (i.e. rayure)	33% - 8 words (i.e. mouflon)	28% - 8 words (i.e. pingouin)
	60% - 8 words (i.e. madame)	50% - 8 words (i.e. gourdin)	42% - 8 words (i.e. peuplier)
	80% - 8 words (i.e. rumeur)	66% - 8 words (i.e. typique)	57% - 8 words (i.e. infusion)
		83% - 8 words (i.e. plaisir)	71% - 8 words (i.e. jalousie)
			85% - 8 words (i.e. habituel)

Note: *Summary of the words used in the whole experiment with the number of letters and the ratio of bimanual transitions (expressed in % of the total number of transitions in a given word; for example the word "humour" has one transition from the right to the left hand between "u" and "r" out of 5 so its ratio is 20%).*

Table S2

Controlled variables

Transitions ratio	Consistency	Frequency	First letter	Nb syllables	Freq Bigrams	Nb phonemes	Old20	Pld20	Nb right letters	Nb left letters
					Means					
14	83.59	12.53	7	2.50	1332.96	6.50	2.63	2.31	4.38	3.63
16	8.04	26.98	5	1.88	1038.78	5.25	2.16	1.91	3.38	3.63
20	82.72	23.28	6	1.88	1212.65	4.38	1.93	1.71	3.00	3.00
28	8.63	11.20	3	2.75	1255.06	6.50	2.74	2.49	3.63	4.38
33	68.06	18.12	3	2.00	1418.41	5.00	2.15	1.81	3.50	3.50
40	86.69	45.49	6	1.88	1098.68	4.88	1.87	1.56	3.00	3.00
42	81.63	17.86	7	2.38	1422.50	6.63	2.45	2.26	4.00	4.00
50	82.24	48.88	6	2.25	1099.11	5.75	2.34	2.13	3.50	3.50
57	78.65	25.47	3	2.50	1609.06	6.13	2.53	2.04	3.88	4.13
60	82.53	55.87	6	2.13	1327.98	5.13	2.15	1.99	3.00	3.00
66	82.16	45.46	3	2.38	1327.14	5.88	2.20	2.05	3.50	3.50
71	8.02	2.24	7	2.63	1617.81	6.13	2.39	1.78	4.00	4.00
80	79.15	36.42	4	2.00	1178.20	4.38	1.91	1.72	3.00	3.00
83	85.00	4.58	8	2.25	1455.46	5.88	2.04	2.01	3.50	3.50
85	82.89	15.16	1	2.50	1912.56	5.88	2.05	1.68	3.88	4.13
F value	.25	.96	.84	1.8	6.8	.004	4.0	3.0	.03	.01
p value	ns	ns	ns	ns	p<.05	ns	p<.05	ns	ns	ns

Note: *the Table presented all the variables we control in the categories of transition ratio. We reported means per category and p value and F value per variables.*

Table S3

Mixed models: typing task

Typing task – IKIs mean

	β	SE	t value	p value
Nb. letters	-.016	.008	-1.9	= .05
Frequency	-.0004	.0001	-4.4	< .001
Bigrams Frequency	-.00006	.00001	-5.4	< .001
Old20	.06	.01	4.3	< .001
First letter	-.03	.01	2.8	< .01
Groups	**.2**	**.06**	**3.3**	**< .01**
Transitions	**-.002**	**.0003**	**-6.7**	**< .001**
Transitions * Group	**.003**	**.0002**	**16.6**	**< .001**

Typing task – Expert typists group

	β	SE	t value	p value
Frequency	-.0005,	.0001	-4.1	< .001
Bigrams Frequency	-.00008	.00001	-6.2	< .001
Old20	.07	.01	4.7	< .001
First letter	.04	.01	2.9	< .01
Transitions	**-.002**	**.0003**	**-5.7**	**< .001**

Typing task – Non-expert typists group

	β	SE	t value	p value
Frequency	-.0003	.0001	-2.9	< .01
Bigrams Frequency	-.00007	.00001	-5.5	< .001
Transitions	**.001**	**.0003**	**5.1**	**< .001**

Typing task – Reaction times

	β	SE	t value	p value
Nb. phonemes	-.02	.009	-2.3	< .05
Frequency	-.0004	.0001	-3.2	< .01
Bigrams Frequency	-.00005	.00001	-3.0	< .01
Old20	.05	.02	2.6	< .01
First letter	-.05	.02	-3.3	< .01
Groups	**.2**	**.04**	**5.5**	**< .001**
Transitions	**.0005**	**.0004**	**1.3**	**ns**
Transitions * Groups	**.0001**	**.0002**	**.5**	**ns**

Table S4

Mixed models: Lexical decision task

Lexical Decision Task

	β	SE	t value	p value
Trial rank	-.00007	.000008	-9.9	< .001
Frequency	-.004	.00009	-4.5	< .001
Nb. letters	.01	.007	2.3	< .05
Lexicality	**-.16**	**.03**	**-5.9**	**< .001**
Groups	**-.02**	**.05**	**-.4**	**> .05**
Transitions	**-.0004**	**.0003**	**-1.2**	**> .05**
Transitions * Groups	**.0006**	**.0003**	**2.45**	**< .05**
Lexicality * Transitions * Groups	**-.0007**	**.0004**	**-1.8**	**= .06**

Lexical Decision Task - Pseudowords

	β	SE	t value	p value
Trial rank	-.0001	.00001	-9.05	< .001
Nb. letters	.03	.007	3.7	< .001
Groups	-.02	.06	-.4	ns
Transitions	-.0003	.0003	-1.6	ns
Transitions * Groups	.0006	.0002	2.6	< .01

Lexical Decision Task - Words

	β	SE	t value	p value
Trial rank	-.00006	.00001	-5.4	< .001
Frequency	-.0007	.0001	-4.8	< .001
Old20	.07	.02	3.5	< .001
Groups	**.03**	**.05**	**.5**	**ns**
Transitions	**.0004**	**.0004**	**1.2**	**ns**
Transitions * Groups	**.00004**	**.0002**	**.2**	**ns**

Table S5

Controlled variables

Transitions ratio	Position of the probe	Hand for the probe	Transition with the probe
	Means		
14	4.25	4.00	4.00
16	3.00	3.00	5.00
20	3.00	4.00	4.00
28	4.50	3.00	2.00
33	3.13	7.00	2.00
40	3.50	1.00	5.00
42	2.88	3.00	6.00
50	3.88	7.00	2.00
57	3.25	4.00	4.00
60	3.38	6.00	4.00
66	3.75	3.00	3.00
71	3.75	4.00	8.00
80	2.38	4.00	2.00
83	3.25	5.00	6.00
85	4.50	2.00	1.00
F value	.01	.006	.01
p value	ns	ns	ns

Note: *These variables have to be added to Table S2.*

Table S6

Mixed models: Spelling Probe task

Spelling Probe

	β	SE	t value	p value
Trial rank	-.0003	.00002	-15.3	< .001
First letter	-.03	.01	-2.2	< .05
Nb. syllables	.03	.01	2.5	< .05
Yes/No Probe	**-.08**	**.02**	**-3.2**	**< .01**
Groups	**-.01**	**.06**	**-.2**	**ns**
Transitions	**-.0002**	**.0004**	**-.5**	**ns**
Transitions * Groups	**.00004**	**.0005**	**.1**	**ns**
Yes/No Probe * Transitions * Groups	**.0004**	**.0006**	**.6**	**ns**

Spelling Probe – No Responses

	β	SE	t value	p value
Trial rank	-.0002	.00002	-9.5	< .001
Groups	**-.02**	**.07**	**-.2**	**ns**
Transitions	**-.0002**	**.0004**	**-.5**	**ns**
Transitions * Groups	**.0001**	**.0004**	**.4**	**ns**

Spelling Probe – Yes Responses

	β	SE	t value	p value
Trial rank	-.0004	.00003	-12.5	< .001
Nb. phonemes	-.03	.01	-2.6	< .05
Nb. syllables	.05	.02	2.5	< .05
Probe Position	.04	.004	9.3	< .001
Groups	**-.05**	**.06**	**-.8**	**ns**
Transitions	**-.0005**	**.0004**	**-.2**	**ns**
Transitions * Groups	**.0004**	**.0005**	**.8**	**ns**

Table S7

Stimuli classification

	32 six letters words	*40 seven letters words*	*48 eight letters words*
Percentage of bimanual transitions	0% - 3 words (i.e. mulino)	0% - 3 words (i.e. polmoni)	0% - 2 words (i.e. opinioni)
	20% - 8 words (i.e. tempio)	16% - 8 words (i.e. polvere)	14% - 8 words (i.e. versioni)
	40% - 8 words (i.e. impero)	33% - 8 words (i.e. verdure)	28% - 8 words (i.e. finestre)
	60% - 8 words (i.e. veleno)	50% - 8 words (i.e. preside)	42% - 8 words (i.e. registro)
	80% - 8 words (i.e. sirene)	66% - 8 words (i.e. intuito)	57% - 8 words (i.e. idrogeno)
	100% - 2 words (i.e. torneo)	83% - 8 words (i.e. oriente)	71% - 8 words (i.e. proteine)
		100% - 3 words (i.e. profugo)	85% - 8 words (i.e. pensiero)
			100% - 3 words (i.e. elemento)

Note: *Experimental stimuli were rated based on their transition rate between the two hands during typing. For example, the word "polvere" (dust) has one transition from the right "L" key to the left "V" key, so it is rated as 16% - one transition/nb of interkeystrokes*100).*

Table S8

Controlled variables

		Transitions ratio Tot (0% - 100%)	F value	p value
Num right letters	Mean	3.79	2.29	ns
	SD	1.47		
Num left letters	Mean	3.32	2.70	ns
	SD	1.54		
First letter (right)	Mean	.51	.84	ns
	SD	.50		
Frequency	Mean	92.28	.34	ns
	SD	95.85		
Num characters	Mean	7.12	.14	ns
	SD	.81		
Num Phonemes	Mean	7.05	.07	ns
	SD	.80		
Num Syllables	Mean	3.09	2.96	ns
	SD	.48		
Orthographic Uniqueness point	Mean	4.61	.13	ns
	SD	3.53		
Phonological Uniqueness Point	Mean	5.63	.00	ns
	SD	2.92		
Num Homographs	Mean	.79	.40	ns
	SD	1.07		
NumHomophones	Mean	.83	.29	ns
	SD	1.11		
Orthographic Neighbours Mean Frequency	Mean	2.60	2.36	ns
	SD	1.47		
Phonological Neighbours Frequency	Mean	2.72	1.26	ns
	SD	1.49		
Orthographic Levenshtein Distance	Mean	2.08	.00	ns
	SD	.36		
Phonological Levenshtein Distance	Mean	2.21	.04	ns
	SD	.42		
Bigrams Frequency	Mean	121257.57	4.25	<.05
	SD	30976.75		
Biphone frequency	Mean	91151.29	.81	ns
	SD	29811.65		

Note: all the linguistic variables are controlled between transitions ratio categories considered as a continuous variable. In this table we reported the means and SD pooling transitions categories.

Table S9

Mixed models: Interkeystrokes Interval - “One-hand” Group

“One-hand” group – IKIs

	β	SE	t value	p value
Trial rank	-.0007	.0001	-6.27	<.001
Typing rate	-.009	.003	-2.91	<.05
Num right letters	.008	.003	2.42	<.05
Frequency	-.0001	.00005	-2.91	<.01
Num characters	-.09	.02	-4.75	<.001
Num phonemes	.08	.02	4.56	<.001
Orth. Neighbours Mean Frequency	-.007	.003	-2.33	<.05
OLD	.043	.018	2.35	<.05
Bigrams frequency	-.0000007	.0000002	-3.91	<.001
Tasks	**.8**	**.02**	**48.46**	**<.001**
Transition ratio	**-.002**	**.0002**	**-8.29**	**<.001**
Task * Transitions ratio	**.005**	**.0003**	**19.57**	**<.001**

Computer-typing task – “One-hand” group – IKIs

	β	SE	t value	p value
Typing rate	-.01	.002	-4.79	<.01
Num right letters	.01	.005	2.21	<.05
Frequency	-.0001	.00007	-1.99	<.05
Num characters	-.03	.01	-2.41	<.05
Orth. Neighbours Mean Frequency	-.009	.005	-1.99	<.05
OLD	.08	.03	2.88	<.01
Bigrams frequency	-.000001	.0000002	-4.42	<.001
Transitions ratio	**-.002**	**.0002**	**-7.87**	**<.001**

Mobile-typing task – “One-hand” group – IKIs

	β	SE	t value	p value
Trial rank	-.0009	.0001	-8.04	<.001
Frequency	-.0001	.00006	-2.15	<.05
Num characters	-.06	.02	-2.48	<.05
Num phonemes	.07	.02	-2.86	<.01
Transitions ratio	**.004**	**.0002**	**-17.01**	**<.001**

Table S10

Mixed models: Interkeystrokes Interval - “Two-hands” Group

“Two-hands” group – IKIs

	β	SE	t value	p value
Trial rank	-.0005	.00008	-6.38	<.001
Typing rate	-.007	.003	-2.68	<.05
Num right letters	-.01	.004	-3.89	<.001
First letter	.04	.01	3.93	<.001
Orth. Neighbours Mean Frequency	-.009	.003	-2.55	<.05
OLD	.04	.01	3.05	<.01
Bigrams frequency	-.0000009	.0000002	-5.67	<.001
Tasks	**.5**	**.01**	**41.44**	**<.001**
Transitions ratio	**-.001**	**.0002**	**-6.26**	**<.001**
Task * Transitions ratio	**.0007**	**.0002**	**3.45**	**<.001**

Computer-typing task – “Two-hands” group – IKIs

	β	SE	t value	p value
Typing rate	-.008	.002	-4.41	<.001
First letter	.03	.01	2.61	<.05
Orth.Neighbours Mean Frequency	-.01	.005	-2.77	<.01
OLD	.06	.0194100	3.01	<.01
Bigrams frequency	-.000001	.0000002	-5.19	<.001
Transitions ratio	**-.001**	**.0002**	**-4.96**	**<.001**

Mobile-typing task – “Two-hands” group – IKIs

	β	SE	t value	p value
Trial rank	-.0008	.00009	-7.96	<.001
Num right letters	-.02	.004	-4.81	<.001
First letter	.03	.01	-3.06	<.01
Bigrams frequency	-.0000008	.0000002	-4.87	<.001
Transitions ratio	**-.0005**	**.0002**	**-2.64**	**<.01**

Table S11

Mixed models: Reaction Time - “One-hand” Group and “Two-hands” Group

“One-hand” group – RT

	β	SE	t value	p value
Trial rank	-.0004	.00008	-4.66	<.001
First letter	-.06	.009	-6.62	<.001
Phon. Uniqueness Point	-.003	.001	-2.11	<.05
Phon. Neighbours Mean Frequency	-.006	.002	-2.16	<.05
Tasks	**.4**	**.01**	**37.21**	**<.001**
Transitions ratio	**-.0002**	**.0002**	**-1.06**	**ns**
Task * transitions ratio	**-.0000965**	**.0001938**	**-.49**	**ns**

“Two-hands” group – RT

	β	SE	t value	p value
Trial rank	-.0005	.00007	-7.67	<.001
Frequency	-.0001	.00004	-2.28	<.05
First letter	-.04	.008	-5.19	<.01
Tasks	**.3**	**.009**	**29.66**	**<.001**
Transitions ratio	**.00002**	**.0002**	**.12**	**ns**
Task * Transitions ratio	**-.000008**	**.0001**	**-.05**	**ns**

Table S12

Mixed models: Errors- “One-hand” Group and “Two-hands” Group

“One-hand” group – Errors				
	β	SE	z value	p value
Num right letters	.1	.06	2.44	<.05
Frequency	-.002	.0009	-2.16	<.05
Typing rate	-.03	.01	-2.35	<.05
Num carachters	.3	.1	2.60	<.01
Tasks	.7	.3	2.46	**<.05**
Transitions raio	.008	.004	2.04	**<.05**
Task * Transitions ratio	-.009	.005	-1.81	**=.06**

“Two-hands” group – Errors				
	β	SE	z value	p value
Tasks	.6	.2	3.09	**<.01**
Transitions ratio	.003	.003	1.01	**ns**
Task * Transitions ratio	-.005	.003	-1.43	**ns**

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