Handwriting versus Keyboard Writing: Effect on Word Recall

Anne Mangen[a], Liss G. Anda[b], Gunn H. Oxborough[a] & Kolbjørn Brønnick[b,c]

[a] National Centre for Reading Education and Research, University of Stavanger, Norway

[b] Regional centre for clinical research in psychosis, Division of Psychiatry, Stavanger University Hospital, Norway

[c] Network for medical sciences, University of Stavanger, Norway

Abstract: The objective of this study was to explore effects of writing modality on word recall and recognition. The following three writing modalities were used: handwriting with pen on paper; typewriting on a conventional laptop keyboard; and typewriting on an iPad touch keyboard. Thirty-six females aged 19-54 years participated in a fully counterbalanced within-subjects experimental design. Using a wordlist paradigm, participants were instructed to write down words (one list per writing modality) read out loud to them, in the three writing modalities. Memory for words written using handwriting, a conventional keyboard and a virtual iPad keyboard was assessed using oral free recall and recognition. The data was analyzed using non-parametric statistics. Results show that there was an omnibus effect of writing modality and follow-up analyses showed that, for the free recall measure, participants had significantly better free recall of words written in the handwriting condition, compared to both keyboard writing conditions. There was no effect of writing modality in the recognition condition. This indicates that, with respect to aspects of word recall, there may be certain cognitive benefits to handwriting which may not be fully retained in keyboard writing. Cognitive and educational implications of this finding are discussed.

Keywords: handwriting; keyboard writing; ergonomics of writing; word memory; embodied cognition; educational implications of digitization

journal of
WRITING RESEARCH

Mangen, A., Anda, L.G., Oxborough, G.H., & Brønnick, K. (2015). Handwriting versus keyboard writing: Effect on word recall. *Journal of Writing Research, 7*(2), 227-247. http://dx.doi.org/10.17239/jowr-2015.07.02.1

Contact: Anne Mangen, University of Stavanger, The National Centre for Reading Education and Research, NO-4036 Stavanger | Norway - anne.mangen@uis.no.

Copyright: Earli | This article is published under Creative Commons Attribution-Noncommercial-No Derivative Works 3.0 Unported license.

1. Introduction

1.1 Background and motivation

Writing is an intellectual achievement distinguishing humans from conspecifics (Preiss & Sternberg, 2005; van der Weel, 2011; Wolf, 2007). Since its invention in the 4th millennium BC, writing has been a mode of inscription, performed using some kind of object, tool or technology, and marking traces on a physical substrate. With Gutenberg's invention of the printing press around 1440, manual inscription was replaced by mechanical typewriting. Currently, more and more of our writing is done with digital rather than mechanical writing devices, and handwriting is increasingly marginalized. This trend is also evident in beginning writing instruction, as children are learning to write by typing on virtual touch-screen keyboards or conventional computer/laptop keyboards in parallel with traditional handwriting (see, e.g., Genlott & Grönlund, 2013; Trageton, 2003), and there is an increasing emphasis on ICT (i.e., information and communication technologies) in the curriculum. The implications of such a shift, on individual and cognitive as well as educational and societal levels, are largely unknown (Kiefer & Trumpp, 2012; Mangen, 2013; Mangen & Velay, 2010, 2014; Velay & Longcamp, 2013).

The marginalization of handwriting invites a number of reflections concerning practical and pedagogical as well as cognitive aspects of writing. We learn to write, says Margaret Wilson (2008, p. 382), in order to be able to put our thoughts down on paper: "For purposes of embodied cognition, this last example is perhaps most interesting not so much in terms of its archival functions […] but for its functions in serving as an external memory device during ongoing cognitive processing […]." Amplifying and supporting cognition by the use of symbols, writing is a cognitive technology par excellence (Frank, Everett, Fedorenko, & Gibson, 2008; Nickerson, 2005), "made possible by creative uses of the body." (Wilson, 2008, p. 382) In light of such reflections, it is worth asking if digital writing implements affect the ways in which writing supports and amplifies cognition: Does it affect how, and how well, we remember what we write down, if we write it by tapping keys on a keyboard rather than by writing by hand? And, when keyboard writing, does it make a difference for our memory if the keyboard we use is that of a laptop, or a virtual touch keyboard on an iPad? Anecdotal evidence (Chandler, 1992; Haas, 1996; Hensher, 2012; Keim, 2013; McCullough, 1996) suggests that handwriting engages the mind differently than writing on a keyboard. It has yet to be empirically established in what ways, and to what degree, such differences occur, and what the cognitive and educational implications may be.

Influenced by the "embodied cognition" research paradigm (Calvo & Gomila, 2008) and by studies in cognitive neuroscience comparing handwriting and keyboard writing (Longcamp et al., 2008; Longcamp, Boucard, Gilhodes, & Velay, 2006; Longcamp, Tanskanen, & Hari, 2006; Wamain, Tallet, Zanone, & Longcamp, 2012), the present experiment intends to measure the effect of writing modality (i.e., writing by hand and writing by [touch and mechanical] keyboard) on aspects of cognition, more specifically, on verbal episodic memory. We address the question whether it makes a difference for the memory of words if people have written them down by hand on paper, on a virtual touch keyboard, or a laptop keyboard.

1.2 The haptics of writing, and the ergonomic affordances of writing implements

The current digitization invites a reconsideration of the nature of writing as a cognitive and sensorimotor process. In particular, the transition from handwriting to keyboard writing entails changes pertaining to the haptics of writing (Mangen & Velay, 2010), that is, the combination of the (passive) sensation of touch with the active movement of our fingers and hands during writing. Handwriting differs from keyboard writing in a number of ways, from a physiological and ergonomic level through to cognitive and phenomenological dimensions. Typically, we type on computer/laptop or touch screen keyboards by using both hands (and, ideally, all ten fingers), whereas handwriting is one of the most lateralized of bodily processes and very few master it equally well with both hands. The beginning writer, in handwriting, also tends to use most of the available cognitive capacity to form the individual letters, at the expense of a focus on content. However, as the motor patterns involved in handwriting are automatized, cognitive capacity is free to process content (Feder & Majnemer, 2007). Moreover, the coordination of manual activity and visual attention typically differs in the two writing modalities. Skilled keyboard writers may keep their visual attention mostly on the screen on which the text appears, whereas less skilled touch typists may direct their gaze occasionally or mostly towards the keyboard (Johansson, Wengelin, Johansson, & Holmqvist, 2010). During handwriting, by contrast, we typically focus our attention very close to the tip of the pen from which the trace of text emerges. Hence, during handwriting, visual attention and sensorimotor action are temporally and spatially unified and contiguous (Mangen, 2013), whereas in keyboard writing, this unity is broken. In this sense, the act of inscription may be described as more abstract and physically detached with keyboard writing than with handwriting (Mangen, 2013).

Generally speaking, when writing with digital technologies, less precise and less discriminating manual movements are required than when handwriting with pen or pencil on paper (Mangen & Velay, 2014). Compared to keyboard writing, handwriting is a more motorically controlled and monitored translation and externalization of the writer's message. Such differences in motor control and coordination between handwriting and keyboard writing are perhaps most evident in the frequency of technical errors: in handwriting, we rarely form or apply an erroneous character (relative to the intended letter and, provided adequate grammatical skills, words), whereas technical errors occur frequently in keyboard writing. In many respects, the digitization of writing contributes to making the relationship between the embodied, sensorimotor input (viz., the writing process) and the audiovisual output (viz., the produced text) generated by the technology, more abstract and detached (Mangen & Velay, 2014).

Such differences in technological affordances notwithstanding, it is not easy to find studies actually comparing handwriting and keyboard writing with respect to cognitive outcomes and educational aspects. A cursory glance at the current state of writing research (e.g., Alamargot & Chanquoy, 2001, 2012; Berninger, 2012; MacArthur, Graham, & Fitzgerald, 2006; Torrance et al., 2012; Torrance, van Waes, & Galbraith, 2007; Van Waes, Leijten, & Neuwirth, 2006) yields the impression that writing is mainly, if not exclusively, a mental (i.e., cognitive) process dealing with linguistic representations at different levels. According to the most commonly referenced model in cognitively oriented writing research (Flower & Hayes, 1981), writing is a process primarily involving planning (i.e., developing the writing plan and setting goals), translating (i.e., converting the plan into text), and reviewing (i.e., text reading and editing). Recent empirical research has revealed that writing is also an activity involving visuospatial dimensions (Olive & Passerault, 2012), in that composing a text is a visuospatial activity resting to a large extent on the visuospatial processes of working memory.

When the act of writing is digitized, and we go from shaping signs, letters and words with pen-in-hand on the substrate of paper, to generating texts by tapping ready-mades on a variety of keyboards, it becomes apparent that writing is also a sensorimotor, tool-mediated activity entailing the dexterous use of writing implements (e.g., pens, pencils, keyboards, digital styluses) and writing surfaces (e.g., paper, cardboard, screens). These implements, as well as the writing surfaces, have distinct ergonomic – in particular, haptic – affordances which may influence cognitive aspects at different levels. Hence, the ergonomic aspects of writing merit closer scrutiny, and the embodied cognition paradigm may be particularly relevant for this purpose.

2. Theoretical framework

2.1 Embodied cognition

Viewed in light of the embodied cognition paradigm, it is reasonable to assume that replacing handwriting with keyboard writing may have implications on several levels, from basic perceptuo-motor processing to higher-level cognitive processes (Kiefer & Trumpp, 2012; Mangen, 2013; Mangen & Velay, 2010). The view that cognition takes place not only in a central system (Fodor, 1983) or a representation- or symbol-processing unit (Clark, 1997, 2008), but fundamentally in the perceptual and motor systems, has gained traction and is a prominent perspective in cognitive science (Calvo & Gomila, 2008). More precisely, embodied cognition implies that processes of perception (visual, audio, tactile), motor action, and cognition are more closely and reciprocally connected than has typically been acknowledged (cf., e.g., Gibbs, 2005;

Shapiro, 2010; Wilson, 2002). Theories of embodiment have received increasing empirical support from behavioral and neuroscientific studies (for an overview, see Kiefer & Barsalou, 2011), suggesting that cognitive processes are fundamentally based on a reinstatement of external (perception) and internal (proprioception, emotion and introspection) as well as bodily actions that produce simulations of previous experiences (Kiefer & Trumpp, 2012).

A number of theoretical contributions from adjacent fields can be subsumed under the heading of embodied cognition. For the present purposes, the most relevant cluster consists of motor theories of perception. Initially developed for the perception of spoken language by Liberman et al. (Liberman & Mattingly, 1985), motor theories of perception indicate that we mentally simulate movement and actions even though we only see (or only hear, or only touch) them. Research data from cognitive neuroscience and neurophysiology (Fogassi & Gallese, 2004; Jensenius, 2008; Olivier & Velay, 2009) show how motor areas in the brain (e.g., premotor and parietal area; Broca's area) are activated when subjects are watching someone else performing an action, and when they are watching images of tools requiring certain actions (e.g., a hammer, a pair of scissors, a pen) (Chao & Martin, 2000), even when no action or movement is required from the subjects themselves. Motor theories of perception hence support the view that human cognition is "sandwiched" between perception as input from the world to the mind, and action as output from the mind to the external environment - also called an "action-perception loop", and demonstrating underlying motor-perceptual links.

Object perception is perhaps the domain in which the greatest number of examples of functional links between action and perception have been documented, and in which the notion of embodied cognition is most obvious (Velay & Longcamp, 2013). Although alphabetic characters are not physical objects, motor-perceptual links can be assumed to contribute to their representation, since they are associated with highly specific handwriting movements. These movements entail producing a graphic form as close as possible to the corresponding visual model. Handwriting movements are thus associated with consistent spatial information about a letter. In addition, they are governed by very strict spatial and temporal rules, which Goodnow and Levine (1973) described as the "grammar of action" (Velay & Longcamp, 2013).

The particular relevance of such mental simulations of movement to the present experiment pertains to the trace of movement intrinsic to anything written by hand. Calling handwritten script an "imprint of action," Longcamp et al. (2006) point to the rather striking fact that we are usually able to recognize handwriting accurately despite the extreme variability from one writer to another: "Several psychophysical studies have demonstrated a striking ability of the perceptual system to reliably extract production-related information from the graphic trace […]." (Longcamp, Tanskanen, et al., 2006, p. 681) This is evidence to suggest that we apply knowledge about the implicit motor rules involved in writing by hand, during the perception of the handwritten traces.

To summarize, the shaping of letters and words involved in handwriting involve distinct kinesthetic processes that differ markedly from the kinesthesia involved in tapping keys on a keyboard. In light of this fact, a continued marginalization of handwriting can be expected to have considerable cognitive, educational and cultural implications, on an individual as well as on a societal level.

2.2 Handwriting and keyboard writing; relationship to word memory

As evidenced by research on writing and drawing in neuroscience and, more specifically, graphonomics, writing is a process requiring the integration of visual, proprioceptive (i.e., haptic/kinesthetic), and tactile information (Fogassi & Gallese, 2004). The acquisition of handwriting skills involves a perceptual component (learning the shape of the letter) and a graphomotor component (learning the trajectory producing the letter's shape) (Van Galen, 1991). Sensory modalities involved in handwriting (viz., vision and proprioception) are so intimately entwined that clear neural network activation pattern similarities have been revealed between perceiving, reading, and writing letters in different languages and writing systems, e.g., comparing logosyllabic systems (e.g., Chinese), Japanese ideograms, and alphabet systems (Kato et al., 1999; Longcamp, Anton, Roth, & Velay, 2003, 2005; Van Galen, 1991). Brain imaging techniques have shown how neural networks can be differentially activated from processing different writing systems: logosyllabic writing systems seem to activate very distinctive parts of the frontal and temporal areas of the brain, particularly regions involved in what is called motor perception (Chen, Fu, Iversen, Smith, & Matthews, 2002).

The motor component, in particular, seems to play a fundamental role during handwriting (Longcamp, Tanskanen, et al., 2006; Velay & Longcamp, 2013). Experimental data in neuroscience provide further support for this claim. There is evidence that writing movements are involved in letter memorization. For instance, repeated writing by hand is an aid that is commonly used in school to help Japanese children memorize kanji characters (Naka & Naoi, 1995). In the same vein, Japanese adults report that they often write with their finger in the air to identify and mentally retrieve the meaning of complex characters. This is, moreover, a well-known phenomenon in Japan, commonly referred to as "kuusho" (Cibulka, 2013; Sasaki, 1987). It has also been reported that learning by handwriting facilitates subjects' memorization of graphic forms (Naka & Naoi, 1995).

On a day to day basis, we write for a number of different purposes, and in a variety of situations. One of the main purposes of writing is mnemonic – that is, we write in order to remember something (e.g., shopping lists; note taking during reading or lectures; post-it notes). Considering this role of writing, the effect of writing modality on memory is a topic warranting systematic empirical scrutiny. The present study was designed to measure the effect of writing modality (i.e., writing by hand with pen on paper, writing with a laptop keyboard, or writing with a virtual touch-screen keyboard) on verbal memory for material written by the subjects themselves.

When writing shopping lists, taking notes during meetings and lectures, and note taking when study reading, people increasingly use mobile, handheld digital touch-screen technologies such as tablets and smart phones rather than conventional computers and laptops. Touch-screen (or virtual) keyboards differ from conventional computer and laptop keyboards, in particular with respect to the tactile and haptic feedback. More specifically, a computer keyboard provides a more sensorially salient tactile and haptic feedback than a touch-screen keyboard, where such information is reduced to the (optional) slight vibration enabled by force feedback and where, furthermore, there are no tactilely felt borders (or edges) between individual keys. For this reason, and in order to enhance the ecological validity of the study, we decided on three writing modalities in a within-subjects design, viz., handwriting with ballpoint pen on paper, keyboard writing with a laptop computer, and keyboard writing with an iPad touch keyboard.

A number of studies, notably in neuroscience, have investigated the effect of writing modality (handwriting and keyboard writing) on aspects of retention, recognition and recall. In two behavioral studies, Longcamp et al. compared memory for letters learned by handwriting and by keyboard writing, one in children (Longcamp, Zerbato-Poudou, & Velay, 2005) and one in adults (Longcamp, Boucard, et al., 2006). In both studies, participants who had learned to write by hand showed better subsequent memory and visual recognition than those in the keyboard writing condition. Longcamp et al. replicated these studies in a neuroimaging study (Longcamp et al., 2008), in which fMRI data showed that processing the orientation of handwritten and typed characters did not rely on the same brain areas. More specifically, the brain activation of participants in the handwriting condition was more pronounced in several regions known to be involved in the imagery, observation, and execution of actions, more precisely the left Broca's area and bilateral inferior parietal lobules (Longcamp et al., 2008). These findings suggest that the sensorimotor movements entailed in writing by hand may contribute to the subsequent memorization of the shape and/or orientation of characters (Longcamp, Tanskanen, et al., 2006; Mangen & Velay, 2010).

These findings all relate to memorization of single letters or characters. Arguably, memory for single letters may be said to have limited ecological relevance for many everyday purposes of writing related to functional memory or learning outcomes. To our knowledge, only one study, Smoker et al. (2009), has extended this line of research to examining potential associations between writing modalities and memory at the word level. Smoker et al. (2009) report findings from a small study comparing recall and recognition of words, depending on whether they had been written down by hand or typed on a computer keyboard. In their experiment, sixty-one adults participated in a between-subjects experiment measuring the effect of writing modality on word recognition and recall. The two writing modalities were handwriting with pen on paper, and the keyboard condition was a conventional computer keyboard. Participants in both conditions were presented, visually, the same words (taken from the sixth grade Florida Comprehensive Assessment Test (FCAT), on a printout in the handwriting condition, and on the left hand side in the computer condition. They were instructed to copy the words by writing them down next to the words listed, either on the paper or on the computer. There was no time constraint, and time on task was recorded. After being presented the stimuli, a distractor task was administered. Once the distractor task was completed, participants were asked to recall, within the span of five minutes, as many words as they could remember by writing them down onto a blank sheet of paper. Upon completion of the recall task, participants were asked to complete a recognition task containing a mix of stimuli words and new words from the same FCAT vocabulary. The recognition task was also limited to five minutes.

Results from the Smoker et al. (2009) study showed that memory on the recall task approached significance in favor of the handwritten words, and the effect of writing modality was significant in the recognition task. On the basis of these findings, Smoker et al. (2009) conclude that the results support the hypothesis that due to additional kinesthetic information provided by handwriting, subjects tend to remember words better when they have written them by hand than when they have written them by keyboard.

The present experiment is in part a replication of Smoker et al.'s (2009) study, but as a completely counterbalanced within-subjects design. We address the question of whether people remember words written as parts of lists better when they are written by hand than when they are typed using a virtual touch keyboard, or a mechanical laptop keyboard. More specifically, the present experiment was designed to test the following two hypotheses:

H1: Our first hypothesis was that we would observe superior free recall of words written by hand as compared to on a physical laptop keyboard and a virtual keyboard on an Apple iPad.

H2: We also expected that results on the word recognition measure would differ as a function of writing modality, more specifically, that participants would recognize more words that they had written by hand, compared with words they had written on the computer or iPad keyboard.

3. Method

3.1 Ethics statement

The project was approved by the Norwegian Social Science Data Services (NSD), and all participants gave informed written consent in accordance with the requirements of the NSD prior to participating in the study.

3.2 Participants and design

The present study was a within-subjects experimental design with three different writing conditions for each participant. Thirty-six female college students or staff at a middle-sized Norwegian university participated. Participants were required to have Norwegian as their first language. All reported to have normal sight and hearing as well as no literacy impairments. Three subjects reported being left-handed and 13 described themselves as being "touch-typists". A power analysis showed that the power to detect a medium effect-size (f = 0.25) was 0.9, given 36 subjects in a repeated measures design with three conditions.

In Table 1, we show descriptive statistics for age, education, typing speed (words per minute) on a conventional keyboard, years of experience with keyboard and years of experience with using touch-screens:

Table 1. Demographics, writing experience and writing skill

	Mean (SD)	Max, min	Median
Age	25.22 (7.98)	54, 18	22
Education	15.81 (2.70)	22, 12	15
Years of experience with keyboards	12.97 (6.19)	35, 4	12
Years of experience with touchscreens	0.89 (1.04)	3, 0	1
Age when started with keyboard writing	12.25 (5.32)	23, 3	12
Keyboard words per minute	61.00 (21.12)	118, 26	59

3.3 Instruments

Word lists

In order to measure the effect of writing modality on a central cognitive outcome, we used a word list paradigm. Word list learning is a well-established paradigm in cognitive psychology, commonly used to measure episodic verbal memory (Tulving, 2002), a form of verbal, consciously accessible memory for elements related to events (Mayes & Roberts, 2001). Such memory is conceptualized as a multi-component process, involving stages such as the encoding, or learning of new information, the retention (storage) of what was encoded and, finally, the retrieval or recognition of what was being encoded and stored (Mayes & Roberts, 2001). Asking subjects to freely recall the contents of a previously learned/encoded and stored word-list involves retrieval processes that put higher demands on attentional resources than if subjects are shown previously learned words vs. new words and being asked if it was old/new (Naveh-Benjamin, Craik, Guez, & Dori, 1998). Further, differences in strategy use during encoding can differently affect retrieval vs. recognition (Tulving & Thomson, 1973). Thus, in order to investigate the role of retrieval processes on memory as related to list-learning during different forms of writing, this study included measures of both word recognition and free recall.

Three word lists were used for the listening-writing task. Each list consisted of 28 semantically related words, falling into three discernible semantic sub-categories. Main themes for the lists were (1) action verbs (sample item: "paint"), (2) animals (sample item: "dog") and (3) food (sample item: "avocado"). Each word list contained the same number of one-, two- and three-syllable or longer words. Word lists were recorded digitally and edited with a 6 sec. pause between each word (sound offset to onset), leaving each list to last approximately 3 minutes. Each recognition checklist consisted of all 28 target words as well as 28 distractor words approximately matched for length and complexity. The order of each checklist was randomized.

Technical equipment

A Dell laptop was used to play auditory recordings of the three different word-lists, using a pair of KOSS SB/45 headphones.

A first generation iPad running IOS 4 and its standard notepad software with the default font type and size was used to provide a touch technology keyboard. A Dell laptop with a full-size keyboard was used for the physical keyboard condition, with participants writing in the Windows XP Notepad application with the window maximized and using the standard Lucida Console 10 point font. For the handwriting condition, a blue-ink regular ball pen was used alongside an A4 notepad.

A digital video camera with internal microphone mounted on a stationary tripod was used to record each session to allow for examination of recall sessions.

Procedures

In the experiment, subjects were required to use handwriting, a physical laptop keyboard and an iPad virtual touch keyboard, each to write down a different word list. At the beginning of the session, participants were provided with a pair of headphones. They were informed that they were going to listen to a series of words that would be read aloud to them. They were informed that they were to write down each word, one by one, immediately after hearing the word. This same procedure was repeated for all three conditions. Participants were told that they would be asked to recall as many words as possible having finished writing down all the words in a particular list. There was no instruction on whether or not to organize the written words to enhance memory and recall, but upon request, participants were informed that they were free to, e.g., create line breaks for each new word or organize words into columns or clusters while writing.

A pre-recorded list of words was then played back through headphones and participants were required to write down the words using the designated writing device. Having written down all the words from the list currently being read to the participant, the word list produced by the participant was put aside, and participants were immediately asked to recall as many words as possible. Each listening-writing session was followed by a recognition test in which a lab assistant read out a list of target and distractor words, the participants being asked to indicate whether or not each word had been present in their written-down list. The order of both writing technologies and word lists were fully counterbalanced across subjects.

In the physical keyboard and handwriting conditions, participants were asked to seat themselves comfortably in front of the laptop and notepad. For the iPad condition, participants were handed the tablet, and could choose to either keep it on their lap or to put it on the desk in front of them. Participants were asked to orally recite all words they could remember in the free recall condition. Unlimited time was given for participants to recall words, and they were asked to notify the experimenter when they thought no more words could be recalled. The words recalled, as well as the order in which these words were recalled, were recorded, alongside any intrusions (words not in the list).

In the recognition condition, the experimenter read out loud to the participant the list of targets and distractors for that particular condition, asking the participant to indicate with a 'yes' or 'no' whether they thought each word was included among those they had written down. On finishing this task, the subject repeated the whole procedure for the two remaining writing technology conditions.

Finally, following the completion of all three conditions, participants were asked to complete a speed typing test (found at http://norwegian-speedtest.10-fast-fingers.com) to measure keyboard writing speed and to assess whether they were touch typists. They were also asked to indicate their keyboard writing experience by stating the number of years they had been using keyboards and touch-screen technology.

Analysis

In order to assess recognition memory performance, we calculated d' (d-prime) which is based on a signal-detection approach for estimating discrimination performance where the proportion of recognition hits is balanced according to the proportion of false positives (Macmillan & Creelman, 2005).

The one-sample Kolmogorov-Smirnov test was applied to assess whether the data was normally-distributed. Several variables showed a statistically significant departure from normality according to the Kolmogorov-Smirnov test: The d' measure of recognition in handwriting condition, was negatively skewed (p=.001; skewness: -1.02), word-recall in the keyboard condition showed a flattened distribution (p=.026; kurtosis: -0.723) and the data from the Pad condition was right-skewed (p=.001; skewness: 0.721). Hence, non-parametric statistics were used throughout.

Omnibus analyses of differences between ranks in the groups for free recall and recognition were analyzed with Friedman's related samples analysis of variance. Planned follow-ups were conducted using paired comparisons with the related samples Wilcoxon test. Effect-sizes (r) were calculated as described in Rosenthal (Rosenthal, 1991) by dividing the z-scores with the square root of N. Non-parametric Spearman rank-order correlations between memory performance, typing speed, experience with keyboard use and touch-screen technology were also conducted. Finally, differences in memory performance as related to being a touch-typist, were assessed using the non-parametric Mann-Whitney U test. Data analysis was carried out using SPSS 22.

4. Results

In Table 2 , we show descriptive statistics for free recall and recognition in the three different writing modalities:

Table 2: Performance

	Free recall		Recognition (d′)	
	Mean (*sd*)	Median	Mean (*sd*)	Median
Handwriting	15.33 (*4.67*)	15.0	2.91 (*0.56*)	3.04
Keyboard	13.89 (*3.64*)	13.0	2.78 (*0.51*)	2.79
iPad	13.64 (*4.54*)	12.5	2.67 (*0.78*)	2.72

sd: standard deviation;

d′: d-prime

The only statistically significant omnibus group-difference was found for free recall, $p<.049$. The follow-up analyses showed that free recall was better in the handwriting condition than in both the keyboard ($p = .024$, $r = .37$) and the iPad ($p = .050$, $r = .32$) condition. Both of these effect-sizes (r) are considered medium (Cohen, 1988). There were no other statistically significant findings, nor any trends towards significance.

To investigate whether keyboard or touch technology skill/experience was related to the free recall effect, we used non-parametric (Spearman) rank-order correlation analyses between free recall for word-lists written on keyboard or iPad with the respective relevant variables. We found that recall for lists written on the iPad touch screen was positively correlated with years of experience with touch-screens (rho = .329, $p = .050$). There was no relationship between recall for lists written on the conventional keyboard and years of experience with keyboards (rho = -.070, $p = .686$), with keyboard writing speed (rho = -.049, $p = .785$), or with age when first learning keyboard writing (rho = .115, $p = .504$). Nor was there any difference of recall for words written on the keyboard for touch-typists ($N = 13$) vs non-touch typists ($N = 23$) (Mann-Whitney $U = 138$, $p = .721$).

5. Discussion

The results show that handwriting is associated with better free recall of written material as compared to material written using conventional keyboards on PCs and virtual keyboards such as those on iPads. This is in support of hypothesis 1 (H1) of the study. We did not find support for our second hypothesis (H2) related to recognition memory, in that there was no difference between writing modalities with respect to word recognition. Thus, our results are incompatible with a simple notion that keyboard writing *per se* (whether on a virtual or a conventional keyboard) attenuates or disrupts memory for what is written. However, with respect to aspects of word recall, our findings indicate that there may be certain cognitive benefits to handwriting which may not be fully retained in keyboard writing. The partly exploratory nature of the present study precludes a confident explanation of the observed pattern; however, and building on relevant empirical and theoretical research on similar aspects of writing, below are some speculations intending to shed at least partial light on our findings. As such, they may also serve as a framework for future studies.

Firstly, our findings only partly replicate those of Smoker et al. (2009) in showing that writing modality affects episodic memory, but in the Smoker study, the effects of modality were significant only for the recognition measure, and only bordering on significance for the recall measure. Moreover, in the present study, the follow-up analyses indicated that the iPad-related memory recall performance was related to years of experience with touch-screens, but there was no effect of skill or experience with conventional keyboards regarding recall for word lists written on such keyboards. The positive correlation between lists written on the iPad touch keyboard and years of experience with touch keyboards is an indication that participants' degree of automaticity may have played a role, but only in the touch keyboard input mode. In our study, all participants had quite extensive (minimum four years) experience with writing on conventional (laptop) keyboards, while several reported having less than one year of experience with virtual keyboards. The limited proficiency in using virtual keyboards may, in other words, have contributed to this result. Additionally, the fact that there was an effect of experience in the touch screen keyboard but not in the conventional keyboard condition, may perhaps be related to cognitive load in that proficiency in touch keyboard writing may have allowed participants to rehearse (orally; silently) previous words. In contrast to conventional keyboards, on a touch keyboard spatial distribution of keys and their boundaries are merely virtual and, hence, provide no tactile feedback which can support discrimination between keys. In addition, touch keyboards often provide force feedback (in the form of vibration). In terms of cognitive load, it may be the case that familiarization and experience with a virtual keyboard providing force feedback may play a greater role in contributing to automaticity of skill and correspondingly reduced cognitive load, than automaticity with conventional, physical, keyboards.

However, caution is warranted when interpreting these results; more empirical research comparing effects of different kinds of keyboards on cognitive outcomes will help to better understand the potential impact of haptic and tactile affordances of different keyboards, on sensorimotor and cognitive processes during writing. Addressing more precisely the mechanisms involved, future studies in writing should try to disentangle the specific associations between cognitive processing, perhaps in particular cognitive load, sensorimotor affordances of input mode (i.e., writing modality), and aspects of cognitive outcomes.

Although our results do not provide support for H2, there are several possible reasons why we found that participants had better free recall for the words they had written by hand on paper, than for the words they had typed on a laptop or on an iPad keyboard. One potential explanation pertains to the different kinds of sensorimotor/graphomotor processes involved in writing by hand versus writing on a keyboard. In handwriting, the writer has to graphomotorically form each letter from scratch – i.e., produce a graphic shape resembling as much as possible the standard shape of the specific letter. The graphomotor processes in the handwriting condition in our experiment may have facilitated a richer encoding of the words into long-term memory, resulting in better retrieval as evidenced in the free recall measure. This finding is partly consistent with Smoker et al. (Smoker et al., 2009), who found participants in the handwriting condition performed better than people in the keyboard writing condition. However, whereas in the present study, the difference between writing modalities in favor of handwriting was more pronounced for the free recall measure and there was no significant difference for the recognition measure, the results of Smoker et al. (2009) showed an inverse pattern: using one-way ANOVA to test if memory was better for handwriting versus typing resulted in the finding that memory on the recall task approached significance for handwritten words whereas it was significant in the recognition task (see their table 1 for details). Together, these results may be taken as indications that the embodied nature of handwriting may contribute to improve certain aspects of memory. The kinesthesia entailed in the sensorimotor process of shaping the words by hand may underlie, and contribute to, a more solid memory trace, in turn positively affecting recall. This does not, however, explain why, in the present experiment, there was no difference between handwriting and keyboard writing for the recognition measure.

Another possible explanation for the superior free recall of words written by hand on paper may be related to visual feedback or, more precisely, the ways in which writing by hand and writing by keyboard differently relate and combine sensorimotor input (viz., the [physical] act of writing) and the visual feedback resulting from this input. When writing by hand on paper (or any other material substrate), the target of visual attention typically coincides both temporally and spatially with the locus of inscription, i.e., the tip of the pen on the substrate. Hence, during handwriting, there is a spatiotemporal contiguity between sensory and motor action and (audio)visual output – the "imprint of action" (Longcamp, Tanskanen, et al., 2006). Such a unity of haptic, tactile and audiovisual information in space and time may plausibly contribute to an enriched cognitive processing, subsequently enhancing aspects of memory and recall. When writing on a keyboard, and depending on the automaticity or skill of typing, writers may oscillate between focusing their visual attention on the keyboard (and, hence, receiving visual input from the characters on the keys) and the screen. If they are proficient keyboard writers, visual attention is predominantly on the screen, that is, at a location which is spatiotemporally distinct from the "motor area" (i.e., the keyboard). Hence, one can argue that (skilled) keyboard writers receive visual feedback about their haptic and tactile input which is different in kind as well as degree from that provided when writing by hand. While this may have an effect on certain cognitive measures, resulting in a less solid mental representation of letters and (possibly) words, it could also be argued that dissociations between the motor area (keyboard) and the visual manifestation of the sensorimotor input (the screen) could lead to a stronger mental representation due to there being less spatial information competition. Either way, these speculations fall short of explaining why the benefit of handwriting was found only in performance on the free recall measure but not the word recognition measure.

Another visual aspect may be worth mentioning. The visual attention of keyboard writers is split between looking at the emerging text and looking at the keyboard on which they write. From a visual-spatial perspective, a keyboard separates the "motor area" (or input area) where the letters are being produced (the keyboard) from the visual presentation area of the letters (the screen; or output area). A keyboard thereby provides less real-time sensory and visual information about the writer's own writing process, a fact which may result in less robust mental representations of the words. One consequence of such a separation may be that the writer engages less with the written text and consequently is provided with an attenuated visual memory of the word, than in the handwriting condition, where the subject may fixate near the point where the physical writing takes place.

However, people differ in how much they look at the keyboard when writing. Some are expert typists who spend very little time looking at the keyboard during writing, whereas others allocate most of their visual attention to the keyboard rather than to the text, due to lack of touch type training, or they perform frequent oscillations between looking at the keyboard and looking at the screen. In our experiment, we investigated this indirectly, and found no relationship between being a self-reported "touch typist" and free recall. This weakens the plausibility of visual feedback as an explanation for our findings. Future research could help clarify this issue by utilizing eye movement recording in order to determine the effect of visual feedback on retention and recall.

A final aspect to be considered is the fact that participants in the current experiment were adults, and experienced writers in both modalities. Moreover, most of them learned how to write by handwriting, and not by keyboard writing. Today, this situation is changing and in some schools, beginning writing instruction occurs digitally in addition to, or instead of, writing by hand. Equally, an increasing amount of children's out-of-school writing is performed with keyboards rather than putting pencils to paper. The question begs itself whether, in a study like the present one, having participants who were "keyboard-first" writers would have yielded different results. Although research on this topic is still sparse, particularly with respect to longitudinal studies of children whose language and writing system resembles that of the present study (i.e., Norwegian), some relevant observations can be found in research with Chinese children. In China, children now increasingly learn to use electronic devices based on the pinyin, and not the logographic, written Chinese. Pinyin associates the phonemes and English characters without relating to the visuographic characteristics of logographic Chinese. Tan et al. (2013) hypothesized that this might negatively affect Chinese children's reading abilities. Testing character reading ability and pinyin use in primary school children in three Chinese cities, the authors found that the overall incident rate of severe reading difficulty seemed much higher than previously reported, and also that children's reading scores were significantly negatively correlated with their use of the pinyin input method. These results are indications that Chinese children's reading performance significantly decreases with the use of digital writing tools in combination with the pinyin input method: "Pinyin typing appears to be harmful in itself; it interferes with Chinese reading acquisition, which is characterized by fine-grained analysis of visuographic properties of characters. Handwriting, however, enhances children's reading ability." (Tan et al., 2013, p. 1122) One can assume that using a keyboard instead of handwriting may have a greater effect on Chinese children's character recognition ability than that of children learning an alphabetic language due to the fact that the former requires more sophisticated and elaborate visuo-spatial mapping and more repetitions than the more straightforward correspondence of the latter. An intriguing question is whether replacing handwriting with keyboard writing for children whose language system is alphabetic rather than logographic will yield the same results.

6. Conclusion, limitations, and future perspectives

There are several limitations in the present study. The lack of differences in the recognition condition could be due to a ceiling effect. This ceiling effect was most pronounced in the handwriting condition as shown by a negative skewness of -1.02, and this may have masked real differences in recognition across the different modalities. The ceiling-effect implies reduced statistical power to detect real differences, as the ceiling effect will mask such differences and reduce the effect-size; the use of non-parametric statistics will further reduce the statistical power. Another limitation is that the study only manipulated the encoding conditions regarding modality. Hence, we did not explore the encoding specificity principle regarding compatibility between the encoding and retrieval conditions, but rather assessed all memory performance by oral report, which was not used during encoding (i.e. no oral recital of the stimuli). Thus, the study does not explore situations where recall or recognition is mediated by different modalities as related to encoding. Visual feedback, i.e., memorizing the words by looking at the growing list of words written down, may have influenced our findings. One may assume that the participant in the two keyboard writing conditions would have had more time available to visually memorize their lists, than when writing in the handwriting condition (where the writing process takes longer, hence leaving less time for visual memorization of written words). We did not control for "time on task"; hence, this is an issue to be investigated in future research. Further, the participants in the current experiment were adults who were experienced writers in both modalities. Our findings are therefore not necessarily applicable to children and beginning writers, neither for handwriting nor for keyboard writing. Equally, we do not know how this experiment would have turned out in a group who first learned to write using a keyboard rather than writing by hand. Another possible problem in our study is that we did not control for spatial organization when subjects wrote down the lists, and the different modalities offer different affordances in this regard. However, only one subject grouped words spatially according to semantics when writing. All others wrote one word on each line. Finally, since all recall procedures were performed immediately following the encoding of the material, there may be effects of working memory at the time of recall.

The ongoing digitization of the process of writing mandates acknowledging the importance of the changing affordances of the writing devices, as well as of the substrates on which the writing occur (e.g., paper vs. screens). Writing is a (visuo-)cognitive and linguistic act, but it is also a tool-mediated skill requiring dexterous finger and hand movements, in intricate interrelations with attention, perception and cognition. The process of writing by hand by means of writing implements such as a ballpoint pen and paper is sensorimotorically and kinesthetically different from the process of writing by tapping keys on a keyboard. The findings of the current experiment point to the importance of considering the role of the sensorimotor and kinesthetic processes involved in writing, as these differ substantially during handwriting and keyboard writing. Our finding that subjects had better free recall of the words that they had written by hand, compared to both the iPad touch keyboard and the laptop keyboard conditions, can be read as an indication of the importance of considering the embodied nature of writing and how different technologies might differently affect cognitive outcomes.

In order to assess the impact of digital technologies on cognitive aspects of writing, more empirical investigations are warranted. Our findings reveal the importance of considering the impact of material and ergonomic features of the writing technologies and, in particular, the relations between sensorimotor execution, psychological processes and cognitive outcome of writing in different modalities. There is nothing in the study reported here to indicate whether such differences are transitory and that the better performance found in the handwriting condition in this study is due to the fact that participants have grown up learning to write by using pen and paper rather than keyboards. More empirical studies, in particular longitudinal research involving children and young adults, are required to shed light on whether and to what extent this is a generational issue, or whether something more fundamental and less time-bound and generation-specific is at stake.

Acknowledgments

The authors thank Anne Håland, University of Stavanger, for valuable input during the preparatory phase of this study, and feedback and suggestions from anonymous reviewers contributing to improving the quality of the article.

References

Alamargot, D., & Chanquoy, L. (2001). *Through the models of writing*. Dordrecht: Kluwer. http://dx.doi.org/10.1007/978-94-010-0804-4

Alamargot, D., & Chanquoy, L. (2012). Through the models of writing: Ten years after and visions for the future. In V. Berninger (Ed.), *Past, present, and future contributions of cognitive writing research to cognitive psychology* (pp. 567-572). New York: Psychology Press.

Berninger, V. (Ed.). (2012). *Past, present, and future contributions of cognitive writing research to cognitive psychology*. New York: Psychology Press.

Calvo, P., & Gomila, A. (Eds.). (2008). *Handbook of cognitive science: An embodied approach*. Amsterdam: Elsevier.

Chandler, D. (1992). The phenomenology of writing by hand. *Digital creativity, 3*(2 & 3), 65-74. http://dx.doi.org/10.1080/14626269209408310

Chao, L. L., & Martin, A. (2000). Representation of manipulable man-made objects in the dorsal stream. *NeuroImage, 12*, 478-484. http://dx.doi.org/10.1006/nimg.2000.0635

Chen, Y., Fu, S., Iversen, S. D., Smith, S. M., & Matthews, P. M. (2002). Testing for dual brain processing routes in reading: a direct contrast of Chinese character and pinyin reading using fMRI. *Journal of Cognitive Neuroscience, 14*(7), 1088-1098. http://dx.doi.org/10.1162/089892902320474535

Cibulka, P. (2013). The writing hand: Some interactional workings of writing gestures in Japanese conversation. *Gesture, 13*(2). http://dx.doi.org/10.1075/gest.13.2.03cib

Clark, A. (1997). *Being there: Putting brain, body, and world together again*. Cambridge, Mass.: MIT Press.

Clark, A. (2008). *Supersizing the mind: Embodiment, action, and cognitive extension*. Oxford: Oxford University Press. http://dx.doi.org/10.1093/acprof:oso/9780195333213.001.0001

Cohen, J. (1988). *Statistical power analysis for the behavioral sciencies*: Routledge.

Feder, K. P., & Majnemer, A. (2007). Handwriting development, competency, and intervention. *Developmental Medicine & Child Neurology, 49*(4), 312-317. http://dx.doi.org/10.1111/j.1469-8749.2007.00312.x

Flower, L., & Hayes, J. R. (1981). A cognitive process theory of writing. *College composition and communication, 32*(4), 365-387. http://dx.doi.org/10.2307/356600

Fodor, J. A. (1983). *The modularity of mind: An essay on faculty psychology*. Cambridge, Mass.: MIT Press.

Fogassi, L., & Gallese, V. (2004). Action as a binding key to multisensory integration. In G. A. Calvert, C. Spence & B. E. Stein (Eds.), *The handbook of multisensory processes* (pp. 425-441). Cambridge, Mass.: MIT Press.

Frank, M. C., Everett, D. L., Fedorenko, E., & Gibson, E. (2008). Number as a cognitive technology: Evidence from Pirahã language and cognition. *Cognition, 108*(3), 819-824. http://dx.doi.org/10.1016/j.cognition.2008.04.007

Genlott, A. A., & Grönlund, Å. (2013). Improving literacy skills through learning reading by writing: The iWTR method presented and tested. *Computers & Education, 67*(0), 98-104. doi: http://dx.doi.org/10.1016/j.compedu.2013.03.007

Gibbs, R. W. (2005). *Embodiment and cognitive science*. Cambridge: Cambridge University Press. http://dx.doi.org/10.1017/CBO9780511805844

Goodnow, J. J., & Levine, R. A. (1973). "The grammar of action": Sequence and syntax in children's copying. *Cognitive Psychology, 4*(1), 82-98. http://dx.doi.org/10.1016/0010-0285(73)90005-4

Haas, C. (1996). *Writing technology: Studies on the materiality of literacy*. Mahwah, N.J.: L. Erlbaum Associates.

Hensher, P. (2012). *The missing ink: The lost art of handwriting*: Pan Macmillan.

Jensenius, A. R. (2008). *Action - sound: developing methods and tools to study music-related body movement.* (No. 324), University of Oslo, Oslo.

Johansson, R., Wengelin, Å., Johansson, V., & Holmqvist, K. (2010). Looking at the keyboard or the monitor: relationship with text production processes. *Reading and Writing, 23*(7), 835-851. http://dx.doi.org/10.1007/s11145-009-9189-3

Kato, C., Isoda, H., Takehara, Y., Matsuo, K., Moriya, T., & Nakai, T. (1999). Involvement of motor cortices in retrieval of kanji studied by functional MRI. *Neuroreport, 10*(6), 1335-1339. http://dx.doi.org/10.1097/00001756-199904260-00033

Keim, B. (2013). The science of handwriting. *Scientific American Mind,* 54-59. http://dx.doi.org/10.1038/scientificamericanmind0913-54

Kiefer, M., & Barsalou, L. W. (2011). Grounding the human conceptual system in perception, action, and internal states. In W. Prinz, M. Beisert & A. WHerwig (Eds.), *Tutorials in action science*. Cambridge: MIT Press.

Kiefer, M., & Trumpp, N. M. (2012). Embodiment theory and education: The foundations of cognition in perception and action. *Trends in Neuroscience and Education, 1*(1), 15-20. http://dx.doi.org/10.1016/j.tine.2012.07.002

Liberman, A. M., & Mattingly, I. G. (1985). The motor theory of speech perception revised. *Cognition, 21*(1), 1-36. http://dx.doi.org/10.1016/0010-0277(85)90021-6

Longcamp, M., Anton, J.-L., Roth, M., & Velay, J.-L. (2003). Visual presentation of single letters activates a premotor area involved in writing. *NeuroImage, 19*(4), 1492-1500. http://dx.doi.org/10.1016/S1053-8119(03)00088-0

Longcamp, M., Anton, J.-L., Roth, M., & Velay, J.-L. (2005). Premotor activations in response to visually presented single letters depend on the hand used to write: a study on left-handers. *Neuropsychologia, 43*(12), 1801-1809. http://dx.doi.org/10.1016/j.neuropsychologia. 2005.01.020

Longcamp, M., Boucard, C., Gilhodes, J.-C., Anton, J.-L., Roth, M., Nazarian, B., & Velay, J.-L. (2008). Learning through hand- or typewriting influences visual recognition of new graphic shapes: Behavioral and functional imaging evidence. *Journal of Cognitive Neuroscience, 20*(5), 802-815. http://dx.doi.org/10.1162/jocn.2008.20504

Longcamp, M., Boucard, C., Gilhodes, J.-C., & Velay, J.-L. (2006). Remembering the orientation of newly learned characters depends on the associated writing knowledge: A comparison between handwriting and typing. *Human Movement Science, 25*(4-5), 646-656. http://dx.doi.org/10.1016/j.humov.2006.07.007

Longcamp, M., Tanskanen, T., & Hari, R. (2006). The imprint of action: Motor cortex involvement in visual perception of handwritten letters. *NeuroImage, 33*(2), 681-688. http://dx.doi.org/10.1016/j.neuroimage.2006.06.042

Longcamp, M., Zerbato-Poudou, M.-T., & Velay, J.-L. (2005). The influence of writing practice on letter recognition in preschool children: A comparison between handwriting and typing. *Acta Psychologica, 119*(1), 67-79. http://dx.doi.org/10.1016/j.actpsy.2004.10.019

MacArthur, C. A., Graham, S., & Fitzgerald, J. (Eds.). (2006). *Handbook of writing research*. New York: Guilford Press.

Macmillan, N. A., & Creelman, C. D. (2005). *Detection theory : a user's guide*

Mangen, A. (2013). "… scripta manent"? The disappearing trace and the abstraction of inscription in digital writing. In K. E. a. F. Pytash, Richard E. (Ed.), *Exploring technology for writing and writing instruction* (pp. 100-114). Hershey, PA: IGI Global.

Mangen, A., & Velay, J.-L. (2010). Digitizing literacy: Reflections on the haptics of writing. In M. H. Zadeh (Ed.), *Advances in Haptics* (pp. 385-402). Vienna: IN-TECH web.

Mangen, A., & Velay, J.-L. (2014). Cognitive implications of digital media. In M.-L. Ryan, L. Emerson & B. Robertson (Eds.), *The Johns Hopkins Guide to digital humanities* (pp. 72-78). Baltimore, MD: Johns Hopkins University Press.

Mayes, A. R., & Roberts, N. (2001). Theories of episodic memory. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 356*(1413), 1395-1408. http://dx.doi.org/10.1098/rstb.2001.0941

McCullough, M. (1996). *Abstracting Craft: The Practiced Digital Hand*. Cambridge, Mass.: The MIT Press.

Naka, M., & Naoi, H. (1995). The effect of repeated writing on memory. *Memory & cognition, 23*(2), 201-212. http://dx.doi.org/10.3758/BF03197222

Naveh-Benjamin, M., Craik, F. I., Guez, J., & Dori, H. (1998). Effects of divided attention on encoding and retrieval processes in human memory: further support for an asymmetry. *J Exp Psychol Learn Mem Cogn, 24*(5), 1091-1104. http://dx.doi.org/10.1037/0278-7393.24.5.1091

Nickerson, R. S. (2005). Technology and Cognition Amplification. In R. J. Sternberg & D. Preiss (Eds.), *Intelligence and Technology: The Impact of Tools on the Nature and Development of Human Abilities* (pp. 3-27). Mahwah, New Jersey: Lawrence Erlbaum Ass.

Olive, T., & Passerault, J.-M. (2012). The visuospatial dimension of writing. *Written Communication, 29*(3), 326-344. http://dx.doi.org/10.1177/0741088312451111

Olivier, G., & Velay, J.-L. (2009). Visual objects can potentiate a grasping neural simulation which interferes with manual response execution. *Acta Psychologica, 130*, 147-152. http://dx.doi.org/10.1016/j.actpsy.2008.11.004

Preiss, D., & Sternberg, R. J. (2005). *Intelligence and technology: the impact of tools on the nature and development of human abilities*. Mahwah, N.J.: Lawrence Erlbaum Associates.

Rosenthal, R. (1991). *Meta-analytic procedures for social research*. Newbury Park, Calif.: Sage. http://dx.doi.org/10.4135/9781412984997

Sasaki, M. (1987). Why do Japanese write characters in space? *International Journal of Behavioral Development, 10*(2), 135-149. http://dx.doi.org/10.1177/016502548701000201

Shapiro, L. A. (2010). *Embodied cognition*. New York: Routledge.

Smoker, T. J., Murphy, C. E., & Rockwell, A. K. (2009). *Comparing memory for handwriting versus typing.* Paper presented at the Human Factors and Ergonomics Society Annual Meeting. http://dx.doi.org/10.1177/154193120905302218

Tan, L. H., Xu, M., Chang, C. Q., & Siok, W. T. (2013). China's language input system in the digital age affects children's reading development. *PNAS: Proceedings of the National Academy of Sciences, 110*(3), 1119-1123. http://dx.doi.org/10.1073/pnas.1213586110

Torrance, M., Alamargot, D., Castello, M., Ganier, F., Kruse, O., Mangen, A., . . . Van Waes, L. (Eds.). (2012). *Learning to Write Effectively: Current Trends in European Research*. Bingley, UK: Emerald Group Publishing Limited.

Torrance, M., van Waes, L., & Galbraith, D. (Eds.). (2007). *Writing and Cognition: Research and Applications*. Amsterdam: Elsevier.

Trageton, A. (2003). *Å skrive seg til lesing: IKT i småskolen*. Oslo: Universitetsforl.

Tulving, E. (2002). Episodic memory: From mind to brain. *Annual review of psychology, 53*(1), 1-25. http://dx.doi.org/10.1146/annurev.psych.53.100901.135114

Tulving, E., & Thomson, D. M. (1973). Encoding specificity and retrieval processes in episodic memory. *Psychological review, 80*(5), 352. http://dx.doi.org/10.1037/h0020071

van der Weel, A. (2011). *Changing Our Textual Minds: Towards a Digital Order of Knowledge*. Manchester: Manchester University Press.

Van Galen, G. P. (1991). Handwriting: Issues for a psychomotor theory. *Human movement science, 10*(2), 165-191. http://dx.doi.org/10.1016/0167-9457(91)90003-G

Van Waes, L., Leijten, M., & Neuwirth, C. (Eds.). (2006). *Writing and digital media*. Amsterdam: Elsevier.

Velay, J.-L., & Longcamp, M. (2013). Motor skills and written language perception: Contribution of writing knowledge to visual recognition of graphic shapes. In Y. Coello & A. Bartolo (Eds.), *Language and action in cognitive neuroscience* (pp. 161-176). New York: Psychology Press.

Wamain, Y., Tallet, J., Zanone, P.-G., & Longcamp, M. (2012). Brain responses to handwritten and printed letters differentially depend on the activation state of the primary motor cortex. *NeuroImage, 63*(3), 1766-1773. http://dx.doi.org/10.1016/j.neuroimage.2012.07.020

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review, 9*(4), 625-636. http://dx.doi.org/10.3758/BF03196322

Wilson, M. (2008). How did we get from there to here? An evolutionary perspective on embodied cognition. In P. Calvo & A. Gomila (Eds.), *Handbook of cognitive science: an embodied* *approach* (pp. 375-393). Amsterdam: Elsevier. http://dx.doi.org/10.1016/B978-0-08-046616-3.00019-0

Wolf, M. (2007). *Proust and the squid: The story and science of the reading brain*. New York: HarperCollins.