

# Technical Correspondence

## Handwriting Movement Sonification: Why and How?

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**Abstract**—Sonifying handwriting, i.e., transforming some characteristics of handwriting movement into sounds, aims to improve handwriting perception, evaluation, and control. The educative or clinical interest is to make hidden variables of handwriting, which are not accessible through a visual inspection of the trace, perceptible and useful for novice or poor writers. From a theoretical point of view, handwriting sonification might be a powerful tool for assessing multisensory integration in motor control and learning. In a brief introduction, the main studies on handwriting sonification are reported and the interest of handwriting movement sonification is justified. Then, the project of sonification is described, with a specific focus on select variables of handwriting movement and associated sounds. The experimental validations of this sonification strategy are presented, followed by a conclusion and a few theoretical perspectives.

**Index Terms**—Auditory displays, augmented reality, motor control, multisensory processing.

### I. INTRODUCTION

From the reader's point of view, handwriting problems are limited to illegibility: unreadable handwriting may affect academic success and social integration. From the writer's point of view, handwriting difficulties result from a deficiency in the motor control of "handwriting." Interestingly, these two aspects are not systematically associated: handwriting may be legible but produced slowly, at the cost of great effort. Up to now, teachers, clinicians, and therapists have evaluated the graphomotor skills from the written trace rather than from the movements that generate that trace (e.g., the brave handwriting kinder—BHK [1] or the tremor rating scale [2]).

Digitized handwriting on graphic tablets is allowing us to analyze, beyond the written trace, several "hidden" variables which inform about the movement generating the trace. Velocity fluctuations, pen lifts, or pressure are some examples of variables that may inform about movement quality. Finally, beyond analysis, interacting in real time with the writing movement is becoming possible.

With this aim, we propose transforming some of these hidden variables of handwriting movements into auditory information in order to enhance handwriting perception, control, and learning. This method, called sonification, aims at using nonspeech audio to convey information [3]–[6]. In a recent review on sensory feedback in handwriting, the relevance of auditory modality for perceiving supplementary feedback in real time was emphasized [7]. A first argument is that, as with most

human movements, handwriting is mainly controlled by vision and proprioception; hence, audition is fully available for the provision of supplementary information during motor execution. Furthermore, the ear can better perceive fine dynamic or temporal cues than the eye [8]. Therefore, sounds are particularly relevant in providing information about a dynamic process such as human movement. Finally, applying supplementary auditory information may change attentional and motivational processes and, from this point of view, it is worth taking into account the esthetic nature of the sounds as it is an important motivational factor [9].

From a more theoretical point of view, why may sonification facilitate handwriting control and learning? Generally, when we learn movements that make sounds (in music for example), the auditory perception and the other sensory perceptions (visual and proprioceptive) are bound to create a unified percept [10]. Once this percept is created, the internalized sounds associated with the movement would be re-enacted even if they are not physically supplied [11]. This hypothesis is supported by the presence of multimodal neurons that code for both movements and their associated sounds within the left premotor cortex [12].

According to the "internal model" theory [13], applying concurrent auditory feedback would be particularly useful at an early stage of handwriting learning: The use of multiple streams of sensory information would enhance the estimation of the motor commands required to achieve the desired percepts during handwriting. However, in the final stage, applying supplementary feedback to handwriting movement would avoid a reduction in the use of feedback. Such an effect would not be compatible with the high-temporal constraints relative to fast and fluent handwriting. Furthermore, frequent supplementary feedback could make the writer dependent upon it and thus degrade learning [14].

### II. BRIEF REVIEW ON HANDWRITING SONIFICATION

Until the last decade, very few attempts had been made to sonify handwriting, probably because of technical limitations. Real-time auditory feedback in handwriting has mainly been applied in the clinical field, to treat patients with neurological deficiencies [15], [16]. The first idea was to help patients with writer's cramp by transforming electromyography (EMG) activity involved during handwriting into sounds in order to better control muscles contractions that were not appropriate [15]. Nevertheless, the numerous and fairly inaccessible muscles involved in handwriting restrict the potential of this technique. The second idea, which was to transform the hand grip force into sounds, seemed more encouraging [16].

In 1992, in an interesting attempt in the field of Forensics, sounds were applied to help "forgers" to imitate signatures, the actual goal being to evaluate the efficiency of a signature verification system [17]. Different sounds were produced according to the pen's displacement in the original signature in such a way that they provided the imitators with a representation of the duration and direction (upward or downward)

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of each stroke to be reproduced. However, this approach, though quite interesting did not really bring auditory feedback into play because the forgers did not hear their own sonified movement.

Over the last decade, three other attempts have been proposed [18]–[20]. In the first attempt, auditory feedback drawn from sonification of the spatial coordinates of adults’ handwriting was compared to music during a learning task [18]. The authors concluded that the supplementary feedback had no effect on the learners’ performance but simply a significant effect on their motivation. In the second attempt, the spatial characteristics of children’s handwriting were sonified and evaluated [19]. A total of 15 children, divided into three different groups, were required to write three characters (a, k, and m). The sonification strategy was more detailed than in the previous study: it consisted of mapping the pen abscissa to the spectral composition (brightness) of the sound, its ordinate to the sound frequency, and its vertical pressure to the sound amplitude (volume). The authors reported no change in spatial accuracy as assessed by a shape-matching algorithm, but some performance enhancements as assessed by a dynamic time warping algorithm, corresponding to a point-to-point spatial comparison in which both spatial and temporal information is available. The results of this study were promising, although five children per group is clearly too small a size for definite conclusions.

In these two attempts, the sonification strategy was based on translating spatial variables into sounds. However, such a sonification strategy for handwriting learning and rehabilitation is questionable. According to the “modality appropriateness” hypothesis, it is known that audition is less accurate than vision for the treatment of spatial information [21]. Consequently, this method would be more promising when compensating for a visual deficit [22]. In our opinion, providing sighted persons with additional spatial information during writing would not really be efficient because it would push them to focus their attention on the spatial accuracy of their writing and they would, therefore, tend to write more slowly.

In 2014, Chang and Yu [20] evaluated a very interesting computer-assisted program of handwriting rehabilitation with the help of 42 children with dysgraphia (also distributed into three different groups: a computer-assisted, a sensorimotor, and a control group). For the experimental (computer-assisted) group, the method consisted of applying auditory and visual feedback informing on legibility, pauses during writing, stroke velocity, and pen pressure. More precisely, auditory and visual feedback on pen pressure immediately followed the end of each stroke, whereas stroke speed and legibility were given once the entire character had been written. The authors observed more significant improvements in the experimental group than in the other two groups in both handwriting legibility and fluency. This approach sounds promising but some essential information about the auditory feedback was missing: the association between the acoustical parameters and each kinematic and dynamic variable were not reported by the authors. Therefore, the auditory feedback could either result from a movement sonification strategy, or correspond only to an auditory signal informing about the mean performance, as suggested by the authors. Moreover, the feedback was always distributed just after and not during the movement. For both these reasons, their approach was completely different from the sonification strategy we are presenting here.

### III. TOWARD A SONIFICATION STRATEGY ON HANDWRITING KINEMATICS

The experimental setup and validation steps of handwriting sonification are summarized in Fig. 1. In the first step, handwriting was recorded with a graphic tablet and the variables most relevant to sonification were identified. Then in the second step, relevant synthetic sounds associated with these variables were generated. The third step

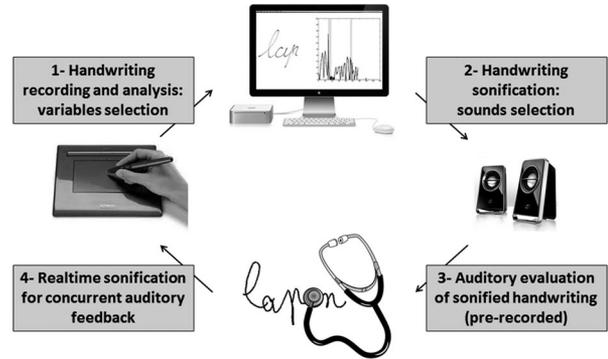


Fig. 1. Illustration of the experimental setup and validation steps.

consisted of validating the sonification strategy. For that, we hypothesized that it should be possible to recognize the sonified handwriting of children with dysgraphia solely “by ear,” without seeing it. At this step, the sonification was not in real-time. Finally, in the fourth step, real-time sonification was assessed. The potential of concurrent auditory feedback to facilitate the control and learning of handwriting movements was evaluated.

#### A. Step 1: What are the Variables Relevant to Sonification?

The effectiveness of handwriting sonification depends on the mapping between the variables of handwriting movement and the sounds. In the present case, the two main constraints were: 1) to determine the most relevant variables and 2) to check whether it was possible to associate sounds with these variables to produce auditory information that, in turn, could enable the recognition of a graphical movement and could inform about handwriting correctness. Danna *et al.* [23], in a meta-analysis, reported the variables most frequently studied in the characterization of graphic movement disorders. They concluded that poor handwriting movement was mainly characterized by speed changes and a lack of movement fluency. Two variables for characterizing movement dysfluency were then proposed: the signal-to-noise velocity peaks difference (SNv<sub>pd</sub>) [23] and the stops [24].

The SNv<sub>pd</sub> was built from two variables: the signal-to-noise amplitude ratio (SNA ratio) and the number of velocity peaks. The SNA ratio differentiates the amplitude frequency spectra between two frequency bands, one (0–5 Hz) characterizing controlled movement, and the other (5–10 Hz) reflecting noncontrolled fluctuations resulting from noise in the motor system [25], [26]. Therefore, the SNv<sub>pd</sub> was computed by subtracting the number of velocity peaks when the velocity is filtered with a cutoff frequency of 5 Hz, from the number of velocity peaks when the velocity is filtered with a cutoff frequency of 10 Hz in order to identify only the abnormal velocity peaks (see [23] for more details).

The stops in handwriting movement were defined as periods during which, although the pen is still in contact with the paper, its position does not change for at least 40 ms [24]. Children with handwriting difficulties waste time because of stops that are too frequent and long-lasting.

To conclude, the velocity profile seems to be particularly relevant for capturing some information about movement quality and hence for sonification strategy: abnormal velocity fluctuations and a very low instantaneous velocity (corresponding to stops) both inform about the lack of movement fluency.

#### B. Step 2: Which Sounds Should be Associated With the Selected Variables?

There are several possible strategies for movement sonification (for a review, see [27]). In this project, two strategies were adopted.

The first strategy consisted of applying a mapping between movements and sounds with the rationale of using synthetic sounds that evoke a natural action, thanks to perceptually relevant acoustic morphologies [5], [28]–[31]. Indeed, if we listen the sound produced by the pen moving on a rough paper, we can hear a slight friction sound. This sound contains timbre variations directly related to the handwriting movement. Thoret *et al.* [5] have compared a real handwriting friction sound to a synthetic friction sound whose timbre was associated with the pen's velocity and they concluded that such a sonification adequately informs about what was being drawn. Therefore, sounds produced by handwriting could contribute to building a “multimodal sensorimotor representation of handwriting” [32]. Based on this assumption, we mapped the timbre of a synthetic friction sound to the pen's velocity. Furthermore, we enslaved linearly the sound amplitude to the pen's pressure on the paper, so that the higher the pressure, the higher the volume. Consequently, no sound was emitted during pen lifts.

The second strategy was quite different. The aim was to apply an “auditory alarm” informing about movement dysfluency by means of very short sounds associated with abnormal velocity peaks. This index of movement fluency is artificial because velocity peaks are naturally inaudible. A crackling sound was emitted when the handwriting was dysfluent, i.e., for each abnormal velocity peak. The less fluent the movement, the more the crackling sounds (for an illustration, see [33, supplementary video]).

### C. Handwriting Evaluation

If the sonification strategy was appropriate, judging the correctness of the handwriting should be possible solely “by ear,” without seeing it. This hypothesis was tested and validated as follows [32]. First, samples of the French word “*lapin*” (rabbit) written by adults without dysgraphia, children without dysgraphia, and children with dysgraphia were digitized. From these recordings, movement velocity, movement dysfluency, and pen pressure were sonified with the previously described strategy. To avoid excessive differences in volume between the audio samples, the pressure values were normalized between 0 and 1 for each trial. Then, these audio samples were presented to 48 naïve adult listeners who had to guess the handwriting correctness by marking them between 0 and 20. The higher the score, the higher the perceived quality. During the whole experiment, the listeners were never informed that they were evaluating sonified handwriting arising from three different groups.

The experiment was divided into two conditions, called “implicit” and “explicit.” Under the implicit condition, the listeners made their evaluation without any cue as to the meaning of what they were listening to. They only knew that the audio files corresponded to sonified handwriting. This condition allowed the authors to assess whether the sonification strategy was intuitive for the listeners. Then, at the end of this implicit condition, additional information about the meaning of the sounds and the evaluation criteria were given to the listeners. The first piece of information concerned the continuous sound that was associated with handwriting velocity: the faster the movement, the higher the level of handwriting correctness. The second concerned the silences associated with pen lifts: the fewer the pen lifts, the higher the handwriting correctness. Finally, the third piece of information concerned the very short crackling sounds associated with movement dysfluency: the fewer the crackling sounds, the higher the handwriting correctness.

Under the implicit condition, a cluster analysis revealed that 32 out of 48 listeners marked the dysgraphic handwriting significantly lower than that of writers without dysgraphia (mean score about 7/20 for the dysgraphic handwriting, 11.6/20 for the proficient child handwriting,

and 12.2/20 for the proficient adult handwriting). Under the explicit condition, the three writers' groups were marked differently by all listeners (about 5.5/20 for the dysgraphic handwriting, 10.7/20 for the proficient child handwriting, and 13.9/20 for the proficient adult handwriting).

These results highlight the clinical interest of handwriting sonification in the diagnosis of dysgraphia: it could allow a therapist to complement the visual inspection of the trace with an auditory verification of the handwriting movement. It should be noted that, as the movement analysis can be postponed and translated into visual scores, sonification might be more useful for movement learning and rehabilitation.

### D. Effect of Real-Time Sonification for Helping in Graphomotor Learning

After validating the sonification strategy with the evaluation task, the same strategy as real-time auditory feedback for helping the writer to better perceive their movement was applied. Based on the previous study about handwriting evaluation [32], similar variables were selected for real-time sonification: the instantaneous pen pressure, the instantaneous velocity, and the abnormal velocity peaks, which inform on movement dysfluency. Instantaneous pressure was directly supplied by the graphic tablet and required no delay for sonification. Instantaneous velocity was calculated by dividing the distance between the two successive coordinates of the pen tip by the time between these two recorded points. This simple calculation implied a short time delay (depending to the frequency acquisition of the graphic tablet, 5 ms in the present case). Concerning the sonification of abnormal velocity peaks, the SNvpd could not be computed in real-time, due to the high number of coordinates required to filter the velocity with a cutoff frequency at 5 Hz. Consequently, a velocity peak was considered as an abnormal peak when the time between it and the previous peak was less than 40 ms and when the velocity difference between it and the previous peak was less than  $1.0 \text{ cm}\cdot\text{s}^{-1}$ . These thresholds were determined empirically and validated from the high correlation between the number of velocity peaks computed with this real-time method and those computed with the SNvpd. The mean time delay between the recording of the movement and the sonification was about 35 ms.

In order to validate the real-time sonification, a first experiment was conducted to test the effect of movement sonification on handwriting learning [33]. For ethical reasons (it was not quite sure whether sonification would have a positive effect on handwriting learning), this study was conducted in adults, in whom any possible detrimental effect would have less impact than in children. However, in order to place the adults in a situation comparable to that of a child who has not mastered handwriting, the participants were required to learn to write four new characters using their nondominant hand.

This study used a repeated measures pretest/training/post-test design. Two post-tests were conducted: one few minutes after the training sessions and another the following day. During training sessions, half of the characters were learned with real-time sonification. A total of 32 adult participants were divided into two groups. The first group first began by learning the characters first without, then with the auditory feedback whereas the second group learned the characters in the reverse order.

In the short term, the characters learned with auditory feedback were written faster and more fluently, but less accurately, than those learned without for the first group. For the second group, which had learned the characters first with then without the auditory feedback, there were no differential effects of sonification. The conclusion was that the effect of auditory feedback was transferred to characters learned without supplementary feedback. In the long term, all the participants

still wrote more quickly and fluently than before training but without a decrease in their spatial accuracy.

These results validated the efficacy of sonification for helping adults to write new characters. This positive effect remains to be validated for children who would use feedback differently than adults [34].

### E. Effect of Real-Time Sonification for Helping in Handwriting Rehabilitation

To go a step further, the same sonification strategy was tested in a rehabilitation protocol with children suffering from dysgraphia [35]. A total of seven children (mean age approximately 8 years), diagnosed with dysgraphia by means of the French adaptation of the BHK test [1], participated in this pilot study. All the children followed a handwriting rehabilitation program with a therapist. Only children with difficulties which concerned “the mechanical writing skill” [36], unrelated to any other learning abilities, were included in the study. Children with dyslexia or with more general motor difficulties were not included. The protocol was a classical pretest/training/post-test design lasting four weeks, with one session per week. The pre- and post-tests were run at the beginning and end of each session. They consisted of tracing graphic shapes and in writing a short sentence in cursive letters. The training consisted of producing various shapes (ellipses, circles, and loops) with the real-time auditory feedback. The training with the sonification tool lasted about 20 min. As a whole, each session lasted 30 min. The improvement in performance between the pre- and the post-test of each session and between the pretest of the first and the last sessions confirmed the clinical interest of sonification for the rehabilitation of dysgraphia. Following real-time auditory feedback training, children with dysgraphia were able to write the sentence more quickly and fluently without reducing their legibility.

These results are promising despite the absence of a positive effect on legibility after the four weeks of rehabilitation. Of course, we cannot determine how specific the effect of sonification was, because of the lack of a control group who would have performed the same protocol but without auditory feedback.

## IV. CONCLUSION AND PERSPECTIVES

The two previous experiments highlight the potential of the auditory modality for providing online supplementary feedback to improve the control and learning of handwriting. Nevertheless, an important issue that needs to be addressed is the aesthetic aspects of auditory feedback. Both therapists and children reported that the sounds accompanying handwriting were not always pleasant. They would have preferred more musical sounds. However, replacing friction sounds by music would lead us to a very different theoretical approach than the one we had previously adopted. As a matter of fact, beyond the emotional aspects, music contributes something more than simple sounds: music carries an intrinsic rhythm which can play the role of an external cue that guides movements, thanks to a natural and spontaneous tendency in humans to synchronize action with rhythm. Rhythm perception has been envisaged as a “backdoor” into the motor system, which may facilitate movement rehabilitation [37], [38]. A growing number of studies have reported significant effects of rhythm perception on the motor behavior of patients with neurological disorders related to pathology [39] or after a stroke [40].

We tried to associate a preselected music to movement but the results were not convincing because the music was too often distorted and very unpleasant. To avoid that, we only associated music to movement when the movement velocity was above a preselected threshold. To present and describe this method of musical sonification, a

video is available as supplemental material to this paper available at <http://ieeexplore.ieee.org>. This video shows a prototypical performance improvement in the production of loops. Abrupt changes of auditory feedback can be perceived, from squeaking sounds to music as the speed of the production improves. Note that with music, the movement tends to be synchronized to the musical rhythm. The partial association of preselected music to handwriting movement leads to a mixed strategy of sonification: When the movement velocity was above the threshold, the writer only heard external cues (e.g., the rhythm) contained in the music. However, when the movement velocity was below the threshold, the writer heard their sonified movement containing internal cues only. This mixed strategy would allow the writer to focus their attention more on their movement when it is considered as incorrect (too slow in this case). This method would reduce the internal focus of attention with expertise, another factor that would improve motor learning [41]. A comparison between this new mixed strategy and the previous sonification strategy for handwriting learning is currently being conducted.

From a more theoretical point of view, how can sonification help poor writers to better control handwriting movements? One hypothesis would be that poor writers have proprioceptive integration deficiencies. If they do not correctly process proprioceptive information, they would be unable to automatize their movements which would still remain dependent on visual control [42]. Movement sonification would then play the role of “sensory prosthesis”: poor writers would “hear to feel” their movements in order to improve their control. To try to validate this hypothesis, the effect of handwriting movement sonification was tested in two proprioceptively-deafferented patients [43]. These patients can write (they had learned to write before they lost proprioception) but their movements are entirely and permanently under visual control. The experimental task was close to the previous one [33]: The two deafferented subjects and a matched (age and gender) group of 16 participants had to learn four new characters with their dominant hand. The four characters were written in two training sessions, one without real-time auditory feedback (A) and one with the auditory feedback (B), according to a specific within-subject ABBA protocol. Two post-tests were conducted: one just after the training sessions and another 2 h later. The performance before and after learning with and without the supplementary auditory feedback was compared. It was moreover compared to that of healthy control participants.

Three main findings were obtained in this study:

- 1) the characters learned with sonification were reproduced more quickly and more fluently than the characters learned without.
- 2) Deafferented subjects were able to learn the characters only when they were trained with sonification, whereas control subjects were also able to learn without sonification.
- 3) Two hours after the training with sounds, the performances of the deafferented subjects came back to the pretest level, whereas the improvement was still present in the controls.

These results support the hypothesis that sounds supply auditory information about movement kinematics and compensate for proprioceptive processing deficits.

Proprioceptive integration deficits have also been observed in patients with Parkinson’s disease (PD) [44]. Therefore, sonifying movements in PD patients might enhance their motor control. However, it remains to be seen whether patients with PD are able to process this supplementary auditory information. Promising results provided by a recent study on the use of auditory guidance confirm the potential of movement sonification for these patients [37]. Beyond its various clinical applications, movement sonification might, in the future, be a powerful tool for a multisensory approach to human motor control and learning.

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