Handwriting Movement Sonification for the Rehabilitation of Dysgraphia

Danna J[1,2], Velay JL[1], Paz-Villagrán V[1], Capel A[3], Pétroz C[3], Gondre C[4], Thoret E[4], Aramaki, M[4], Ystad, S[4], Kronland-Martinet R[4]

[1] Laboratoire de Neurosciences Cognitives, UMR 7291, CNRS – Aix-Marseille Université
[2] Brain & Language Research Institute, LPL, CNRS – Aix-Marseille Université
[3] Département d'Orthophonie, Faculté de Médecine, Aix-Marseille Université
[4] Laboratoire de Mécanique et d'Acoustique, UPR 7051, CNRS
jeremy.danna@univ-amu.fr

Abstract. Sounds can be used to inform about the correctness of an ongoing movement, without directly interfering with the visual and proprioceptive feedback. Furthermore, the dynamic features of sounds make them particularly appropriate means of accessing the spatiotemporal characteristics of movements. Finally, because of their playful characteristics, sounds are potentially effective for motivating children in particular need of such assistance. Based on these theoretical considerations, the present work investigated the relevance of applying an online auditory feedback to spatiotemporal characteristics of handwriting for the rehabilitation of handwriting learning disabilities.

Keywords: Motor control, Sounds, Real-time feedback, Dysgraphia

1 Introduction

The motor learning of handwriting is both long and demanding. Several hundred hours of practice are necessary to learn how to control this fine gesture. The ability to control graphic movements clearly impacts on the quality of writing. Unfortunately, between 10% and 34% of children fail in handwriting learning and display handwriting difficulties [1, 2]. These children are considered as poor writer or with a dysgraphia. Here, we adopt the classic definition of dysgraphia, namely, a learning disability that concerns the mechanical handwriting skill, unrelated to reading or spelling abilities [1].

The majority of children are diagnosed with dysgraphia due to their illegible writing that impacts on their academic success. In other words, handwriting is evaluated mainly on the basis of an analysis of the handwriting product, i.e., the static trace on the paper, rather than the handwriting process, namely the movement that produces the trace. The main problem is that some children with dysgraphia succeed in writing a word correctly, whereas the movement they make to produce it is not fluent. Because the most frequent complaint in children with dysgraphia concerns their legibility, these children are neither easy to diagnose nor easy to rehabilitate.

In classic protocols for dysgraphia rehabilitation, the therapist corrects the child's movements using the produced trace. In *Motor control* terms, they use supplementary feedback based on the knowledge of results (KR) [3]. Supplementary feedback can also inform us about the writing movement, in other words, about the knowledge of performance (KP). Contrary to KR which is inevitably provided after the performance, KP can be provided either after or during the performance. We chose the latter option and supplied children with dysgraphia with real-time supplementary feedback during the execution of handwriting movement in order to improve their rehabilitation.

Although the use of supplementary feedback to improve handwriting movements is not a novel idea [4], the development of new technologies in the field of *Graphonomics* and *Human-Computer Interaction* (e.g. graphic tablets or haptic devices) has improved this technique by providing the writer with real-time computer-assisted feedback. Various categorizations are possible, depending on when they are received (during or after the performance), their contents (e.g. spatial, kinematic, dynamic, or based on muscular activity) and their modality (visual, proprioceptive or auditory).

1.1 Real-time Feedback in Handwriting

Which sensory modality can be used for providing the writer with real-time feedback? An initial approach could be to give supplementary visual feedback. This method has been little used because of three main limitations. Firstly, adding visual information would increase task difficulty, especially for beginners who use vision a lot to control their movements. For instance, Weil and Amundson [5] reported that, for beginners, lined paper may add visual confusion and thus jeopardize legibility. Secondly, the time required for processing the visual information would be too long, thus making it incompatible with online handwriting correction [6]. Indeed, reaction times to visual stimuli, measured with EMG responses in arm muscles, are known to be around 125 ms [7]. This exceeds the 100 ms necessary to write a sub-stroke [8] and, thus, the supplementary real-time visual feedback would tend to maintain handwriting both slow and dysfluent [9]. Finally, supplementary visual cues might change the nature of the task, replacing writing by copying which does not require the same cognitive processes [10].

A second idea was to supply supplementary proprioceptive feedback. Proprioception is likely more effective than vision for accessing spatiotemporal information regarding handwriting movements. The main problem of applying supplementary proprioceptive feedback is that it, inevitably, affects the action of the writer. For this reason, studies in this field have used the term *"haptic guidance"* [11, 12]. Palluel-Germain et al. [11] evaluated the effect of a visuo-haptic training protocol on copying task for 5-to-6 year-old children. They found that children who learnt with the visuo-haptic device produced more fluent handwriting movements. In the same team, Bluteau and colleagues [12] refined haptic guidance in a graphic task for adults, by comparing two modes of correction: A first based on the distance between the position of the stylus and the nearest position of the ideal required trajectory. A second based on errors in the force profile, corresponding to the difference between the produced force and the ideal required force. The authors revealed a positive effect of haptic guidance based on force profile only. They concluded that the visual modality is mainly responsible for providing spatial information and that the haptic modality provides the kinematic information, probably encoded in the force coordinates.

Beyond the technical constraints related to its complex implementation and the costly tools required, the two main drawbacks are, firstly, haptic guidance can render the writer passive, and, secondly, it requires a model of the ideal trajectory that the writer needs to reproduce and from which the comparison can be made. However, the well-known fundamental laws of handwriting are 1: no two people write exactly alike and 2: no one person writes the same word twice in exactly the same way [13]. The variability and the individuality of dysgraphic handwriting question the validity of methods based on model reproduction for rehabilitation. Furthermore, as already explained, copying and tracing tasks do not require the same cognitive processes [10].

1.2 To Auditory Feedback for Handwriting Rehabilitation

Applying auditory feedback to help the writer to improve his or her movements is a more original approach, if we consider handwriting as a silent activity. Thanks to the availability of auditory modality, sounds can be used to give real-time information about the correctness of the ongoing movement, without interfering directly with visual or proprioceptive feedback. Congruent multisensory (audiovisual) integration resulting from movement sonification is known to improve the perception and performance of motor skills [14]. Furthermore, the dynamic features of sounds make them particularly relevant for informing the writer about the spatiotemporal characteristics of his or her movements. Finally, because of their playful characteristics, sounds are potentially effective for motivating children in need of such assistance.

To our knowledge, no study has evaluated the effect of supplementary auditory feedback in children with dysgraphia. In adults, a first attempt was made in order to test a method of signature recognition [15]. The authors gave forgers the possibility of using auditory information to imitate signatures. Sounds were provided while the forger was viewing the trajectory of the signature to be imitated. Two different sounds were produced, one when the pen was moving upwards and another when it was moving downward. However, the effect of the sounds was not analyzed and results concerning the effectiveness of this technique in improving signature imitation were not conclusive.

More recently, auditory feedback was mainly explored mainly as a means of compensating disabilities in other sensorimotor deficits. For example, Baur and colleagues [16] used auditory feedback relating to grip force in the treatment of writer's cramp. A sound was presented, the frequency of which changed with the variation in grip force. Results revealed a significant reduction of writing pressure and an improvement in performance. Plimmer and colleagues [17] proposed a multimodal system based on auditory and haptic feedback for signature learning in blind children. A first sound varied as a function of the x and y position of the stylus and a second supplied haptic feedback corresponding to the force produced. The authors concluded that the multisensory feedback was indeed effective in helping the blind children in this study learn how to produce a signature. They did not, however, include a precise analysis of the kinematic variables.

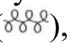
The aim of the present study was to evaluate the effect of real-time auditory feedback in a rehabilitation protocol for dysgraphia. We hypothesized that if the variable to be sonified and the sounds used for its sonification were appropriately selected, children with dysgraphia would be able to improve their handwriting movements "by ear".

In a previous experiment, to check the variable/sound association, adult participants had to listen to and score the sonified handwriting of different writers [18]. The writers were children with dysgraphia and proficient child and adult writers. The writers' handwriting was recorded and transformed into sound files before the experiment. The assumption was that, if these associations were relevant, the listeners would be able to recognize dysgraphic handwriting "by ear" only i.e., without seeing it. The results of this experiment revealed that listeners scored poor handwriting significantly less than skilled handwriting, thus validating the variable/sound associations. The goal of the present study was to investigate the same method of sonification as a real-time feedback in the rehabilitation of dysgraphic handwriting.

2 Experiment

2.1 Method

Seven children with dysgraphia (all boys, mean age 8.1 years) diagnosed by means of the *Concise Evaluation Scale for Children's Handwriting* (*Brave Handwriting Kinder* – BHK) test [19, 20], and following a handwriting rehabilitation program, participated in the experiment. Prior to the experiment, parents signed an informed consent form. The experiment was conducted in agreement with the Aix-Marseille University guidelines and the ethical standards laid down in the declaration of Helsinki. Data were collected directly in the therapist's office by the authors.

The experiment comprised a classic "pre-test/ training/ post-test" protocol. The pre- and post-tests were run at the beginning and end of each training session. They were completely identical and consisted in tracing six alternating downward and upward loops (), and in writing the French sentence '*la nuit, la lune est belle*' ('in the night, the moon is beautiful') in cursive letters. Training consisted in producing various strokes, elliptic and circular shapes, and loops in synchrony with the real-time auditory feedback.

Based on a previous study [18], three variables were selected for real-time sonification: the instantaneous pressure exerted by the pen on the paper, the instantaneous tangential velocity and the supernumerary velocity peaks, which inform specifically of movement fluency. Tangential velocity and pressure were supplied by a graphic tablet. The supernumerary velocity peaks were determined from a specific variable, the Signal-to-Noise velocity peak difference (SNvpd) [21]. SNvpd is computed by subtracting the number of velocity peaks when velocity is filtered with a cutoff frequency of 5 Hz from the number of velocity peaks when velocity is filtered with a cutoff frequency cut of 10 Hz.

The instantaneous tangential velocity was sonified by a synthesized rubbing sound on a metallic plate [22, 23]. This model simulates the physical sound source resulting from successive impacts of a pencil on the asperities of a given surface. The surface roughness was modeled by a white noise reflecting the height of the surface asperities. This noise was low pass filtered with a cut off frequency mapped to the tangential velocity of the writer. Supernumerary velocity peaks were sonified using an impact sound. Finally, the instantaneous pen vertical pressure was associated to the sound volume. During the pen was in contact with the tablet, the sound volume varied lightly as a function of pen pressure. During pen lifts, no sound was emitted.

Within- and between-session evolution was evaluated by comparing in the pre- and post-test performance for each session (short-term effect) and by comparing the sessions 2, 3 and 4 pre-test with the first pre-test (long-term effect). Performances in loop production were determined on the basis of two kinematic variables, 1- Movement Time (MT), and 2- the SNvpd [21]. The sentence writing performances were determined on the basis of the same kinematic variables. In addition, sentence legibility was estimated by six items extracted from the BHK test (items 3, 5, 6, 9, 11 and 13). Note that one of the children did not succeed in sentence writing: sentence writing analyses were carried out for six children only.

Repeated measures ANOVAs (followed by Fisher's LSD post-hoc test with Bonferroni's correction) were performed on each of the variables.

A second BHK test was administrated to all children two months after the fourth training session. The speed and legibility scores obtained in the first and second BHK tests were compared by means of a non-parametric test (Wilcoxon test).

2.2 Results

Loops. Analysis of MT in the pre- and post-tests of the four sessions revealed a long-term effect ($F(3,18) = 6.37$, $p < .01$), a short-term effect ($F(1, 6) = 22.71$, $p < .01$), and a significant interaction ($F(3, 18) = 3.25$, $p < .05$). Post-hoc analysis showed that MT significantly decreased between the first pre-test and the pre-test of the three other sessions (see Table 2, $p < .0001$). Analysis of SNvpd revealed a long-term effect ($F(3, 18) = 8.55$, $p < .001$), a short-term effect ($F(1, 6) = 20.67$, $p < .01$), and an interaction ($F(3, 18) = 4.31$, $p < .05$). Post-hoc tests confirmed that movement fluency improved between the first pre-test and the pre-test of the three other sessions (Table 1, $p < .0001$).

Table 1. Loops production. Mean (standard deviation) of Movement Time (MT) and movement fluency (SNvpd) in the pre- (PRE) and post-tests (PST) of the four sessions (S).

Loops	S1-PRE	S1-PST	S2-PRE	S2-PST	S3-PRE	S3-PST	S4-PRE	S4-PST
MT (s)	11.4 (5.8)	6.2 (2.7)	6.1 (1.3)	4.2 (1.1)	5.9 (2.1)	3.4 (0.7)	6.9 (3.6)	3.2 (0.5)
SNvpd	16.0 (6.9)	16.4 (8.9)	9.5 (5.0)	11.1 (5.1)	7.0 (2.3)	6.5 (3.9)	7.7 (4.4)	6.8 (2.9)

Sentence. Comparison of pre- and post-tests of the four sessions revealed a significant within-session decrease in MT ($F(1, 5) = 9.24$, $p < .05$). Post-hoc test showed that MT the decrease was significant only between the first pre-test and the pre-tests of the third and fourth sessions only ($p < .05$ and $p < .01$, respectively). Movement fluency showed a within-session improvement (short term effect, $F(1, 5) = 7.65$, $p < .05$). In addition, post-hoc tests revealed that movement fluency improved between the first pre-test and the pre-tests of the three other sessions (long term effect, $p < .01$, $p < .001$, and $p < .0001$, respectively). Finally, analysis of sentence legibility did not show any significant between- and/or within-session variation (p > 0.26, see Table 2).

Table 2. Sentence writing. Mean (standard deviation) of Movement Time (MT), movement fluency (SNvpd), and legibility in the pre- (PRE) and post-tests (PST) of the four sessions (S).

Sentence	S1-PRE	S1-PST	S2-PRE	S2-PST	S3-PRE	S3-PST	S4-PRE	S4-PST
MT (s)	31.9 (13.7)	25.1 (12.3)	27.1 (13.5)	22.6 (11.4)	22.4 (10.2)	23.0 (9.0)	22.6 (6.4)	18.4 (4.1)
SNvpd	51 (39.9)	34.3 (25)	32.5 (19.1)	26 (17.8)	24.0 (12.6)	23.7 (12.1)	24.7 (13.1)	19.8 (6.8)
Legibility	6.0 (1.8)	7.3 (1.9)	6.7 (1.9)	6.2 (1.8)	5.8 (3.6)	7.5 (2.9)	7.8 (3.2)	7.0 (3.6)

BHK. Comparisons of the two BHK tests confirmed that both handwriting legibility and speed were greater after the four weeks of rehabilitation than before (see Table 3, $p < .05$).

Table 3. Mean scores, ± standard deviation (median) of legibility and speed for the two BHK tests. Note that the lower the score of legibility, the better the handwriting legibility and that the speed score corresponds to the number of letters produced in 5 minutes.

BHK scores	Before the experiment	After the experiment
Legibility	25.5 ± 11.0 (21.5)	15.2 ± 4.4 (13)
Speed	140.5 ± 58.3 (147)	203.0 ± 91.4 (205)

3 Conclusion

The development of new technologies in the field of *Graphonomics* and *Human-Computer Interaction* has improved techniques, providing the writer with real-time computer-assisted feedback. The kind of supplementary feedback can vary as a function of their informational contents and the sensory medium used. Each sensory modality is especially adapted to give information about a specific physical dimension, and, on this basis, we emphasized the appropriateness of the auditory modality for providing online supplementary feedback about handwriting movements for dysgraphia rehabilitation purposes.

The improvement of performance both within and across sessions confirmed a positive effect of the sonification procedure: children with dysgraphia were able to improve their handwriting movements after their rehabilitation with sounds. Sentence writing results showed that real-time auditory feedback helped children with dysgraphia to write faster and more fluently without reducing legibility of their writing. These results are promising even in light of the fact that legibility did not increase within the four weeks of rehabilitation. It is well known that when children manage to write more fluently and with less effort, they save their attentional and cognitive resources for what is primordial in handwriting: the syntactic and semantic content of the written production. We can suppose that, with a longer period of rehabilitation with sonified handwriting, legibility may improve also. Indeed, a comparison of the two BHK tests, one before and one after the experiment, confirmed that handwriting legibility increased for all children. However, due to the long delay between the two tests (three months), it is hard to disentangle handwriting improvements related to the development of children from those related to the specific effect of the rehabilitation.

Of course, these results should be completed with an additional control in which another group of children with dysgraphia perform the same protocol but without auditory feedback, this would allow us to confirm the specific effect of adding sounds.

An important issue that needs to be addressed is the emotional and aesthetic aspects of auditory feedback. With this in mind, we envisage using an adaptation of the Questionnaire for User Interface Satisfaction [24] for children. The goal, here, would be to individualize the sounds used as a feedback to optimize the motivation of children with dysgraphia, who are very often reluctant to write.

Finally, we need to pay particular attention to ensure that learners do not become dependent upon the supplementary feedback, a phenomenon described by ‘the guidance hypothesis of information feedback’ [25]. Although these authors demonstrated that, in a motor learning task, learners are less dependent on auditory than visual augmented feedback, our aim is to facilitate the improvements of children’s handwriting movement and legibility without the permanent assistance of auditory feedback (and not to enable them to produce good sounds but bad shapes).

In conclusion, auditory feedback may be applied as an interesting means of providing information on kinematic characteristics of handwriting movements. Sounds may be used to complete the proprioceptive and visual feedback naturally used by the writer, thereby giving access to “hidden” dynamic variables which are not taken into account sufficiently by children with dysgraphia. We believe that sounds may be used as a palliative way to access information about kinematics of handwriting movements and, maybe, to assist movement rehabilitation in general.

Acknowledgements. This research was supported by ANR (METASON CONTINT 2010: ANR-10-CORD-0003) and CNRS (Mission interdisciplinarité, projet DEFI-SENS).

References

1. Hamstra-Bletz, L., Blöte, A.W.: A Longitudinal Study on Dysgraphic Handwriting in Primary School. J. Learn. Disabil. 26, 689--699 (1993)
2. Smits-Engelsman, B.C.M., Niemeijer, A.S., van Galen, G.P.: Fine Motor Deficiencies in Children Diagnosed as DCD based on Poor Grapho-motor Ability. Hum. Movement Sci. 20, 161--182 (2001)
3. Schmidt, R.A., Lee, T.D.: Motor Control and Learning. A Behavioral Emphasis. Human Kinetics, Champaign, IL (2005)
4. Reavley, W.: The Use of Biofeedback in the Treatment of Writer's Cramp. J. Behav. Ther. Exp. Psy. 6, 335--338 (1975)
5. Weil, M.J., Amundson, S.J.: Relationship between Visuomotor and Handwriting Skills of Children in Kindergarten. Am. J. Occup. Ther.48, 982--988 (1994)
6. Teulings, H.L., Schomaker, L.: Invariant Properties between Stroke Features in Handwriting. Acta Psychol. 82, 69--88 (1993)
7. Luschei, E., Saslow, C., Glicksein, M.: Muscle Potentials in Reaction Time. Exp. Neurol. 18, 429--442 (1967)
8. Smyth, M.M., Silvers, G.: Functions of Vision in the Control of Handwriting. Acta Psychol. 65, 47--64 (1987)
9. Portier, S.J., van Galen, G.P.: Immediate vs. Postponed visual Feedback in practicing a handwriting task. Hum. Movement Sci. 11, 563--592 (1992)
10. Gonzalez C., Anderson, J., Culmer, P., Burke, M.R., Mon-Williams, M., Wilkie, R.M.: Is Tracing or Copying Better when Learning to Reproduce a Pattern? Exp. Brain Res. 208(3), 459--465 (2011)
11. Palluel-Germain, R., Bara, F., Hillairet de Boisferon, A., Hennion, B., Gouagout, P., Gentaz, E.: A Visuo-Haptic Device –Telemaque – Increases the Kindergarten Children's Handwriting Acquisition. In: Proceedings of the Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp. 72--77. IEEE Computer Society, Washington (2007)
12. Bluteau, J., Coquillard, S., Payan, Y., Gentaz, E.: Haptic Guidance Improves the Visuo-Manual Tracking of Trajectories. Plos One 3(3): e1775 (2008)
13. Morris, R.N.: Forensic Handwriting Identification. Academic Press, London (2000)
14. Effenberg, A.O.: Movement Sonification: Effects on Perception and Action. IEEE Mulimedia 12, 53—59 (2005)
15. Plamondon, R.: The Design of On-line Signature Verification System: From Theory to Practice. Int. J. Pattern Recogn. 8, 795--811 (1994)
16. Baur, B., Fürholzer, W., Marquart, C., Hermsdörfer, J.: Auditory Grip Force Feedback in the Treatment of Writer's Cramp. J. Hand Ther. 22, 163--171 (2009)
17. Plimmer, B., Reid, P., Blagojevic, R., Crossan, A., Brewster, S.: Signing on the Tactile Line: A Multimodal System for Teaching Handwriting to Blind Children. ACM T. Comput.-Hum. Int. 18, 3, Article 17 (2011)
18. Danna, J., Paz-Villagran, V., Gondre, C., Aramaki, M., Kronland-Martinet, R., Ystad, S., Velay, J.-L.: Handwriting sonification for the diagnosis of dysgraphia. In: Nakagawa, M., Liwicki, M., Zhu, B. (eds.) Recent Progress in Graphonomics: Learn from the Past – Proceedings of the 16th Conference of the International Graphonomics Society pp. 123--126. Tokyo University of Agriculture and Technology Press, Tokyo, Japan (2013)
19. Hamstra-Bletz, L., DeBie, J., den Brinker, B.: Concise Evaluation Scale for Children's Handwriting. Swets & Zeitlinger, Lisse, Netherlands (1987)
20. Charles, M., Soppelsa, R. & Albaret J.-M.: BHK - Échelle d'Evaluation Rapide de l'Ecriture chez l'Enfant. Editions et Applications Psychologiques, Paris (2003)

21. Danna, J., Paz-Villagrán, V., Velay, J.-L.: Signal-to-Noise Velocity Peak Difference: a New Method for Evaluating the Handwriting Movement Fluency in Children with Dysgraphia. Res. Dev. Disabil. (in revision)
22. Aramaki, M., Besson, M., Kronland-Martinet, R., Ystad, S.: Controlling the Perceived Material in an Impact Sound Synthesizer. IEEE T. Audio Speech, 19(2), 301--314 (2011)
23. Van den Doel, K., Kry, P.G., Pai, D.K.: Foleyautomatic: Physically-Based Sound Effects for Interactive Simulation and Animation. In: Proc. SIGGRAPH '01, pp. 537--544. ACM Press, New York, USA (2001)
24. Chin, J., Diehl, V., Norman, K.: Development of an Instrument Measuring User Satisfaction of the Human-Computer Interface. In: Proc. ACM CHI '88, ACM Press, New York, USA (1988)
25. Ronsse, R., Puttemans, V., Coxon, J.P., Goble, D.J., Wagemans, J., Wenderoth, N., Swinnen, S.P.: Motor Learning with Augmented Feedback: Modality Dependent Behavioral and Neural Consequences. Cereb. Cortex 21, 1283--1294 (2011)