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SoundScript – Supporting the Acquisition of Character Writing by Multisensory Integration

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Abstract: This work is introducing a new movement sonification method called ´SoundScript´ to support the acquisition of character writing by children. SoundScript creates ´sound traces´ from the writing trace in real-time during the process of handwriting. The structural correlation of both – optic and acoustic – traces leads to an integrated audio-visual perception of writing with the expected stimulation of multisensory integration sites of the CNS. Data of a pilot study are introduced indicating that the writing kinematics is reproduced more adequately if additional sound traces are available during writing. In the future SoundScript shall be applied to verify if the establishment of internal character representations can be accelerated, if the conciseness of the specific shape of the particular characters can be made stronger and if thereby the efficiency of the handwriting learning process can be enhanced.

Keywords: Handwriting acquisition, motor learning, movement sonification, multisensory integration, real-time auditory feedback.

THEORETICAL BACKGROUND

For a successful participation in society the ability to communicate in writing is particularly important. Therefore, the majority of the Primary School period is allocated to literacy acquisition – a fundamental cultural technique. Nowadays, the knowledge in society is growing exponentially. At the same time, school children have increasingly less time to devote to improving their abilities and knowledge. If the process of writing acquisition could be improved, spared time could be assigned to learn other fundamental skills.

Of further concern are the high proportions of children experiencing difficulties in the field of literacy, with dysgraphia and dyslexia as two of the most frequent ones. Recent research is indicating that reading and spelling disorders are depending on different kinds of limitations of the working memory [1]. Dysgraphia – a learning disability that involves difficulties in acquiring and processing language, manifested by a deficiency in writing – can be considered as a common cause for difficulties in school and later for a professional career. Dysgraphia is obviously correlating with limitations of the "phonological loop"-function of the working memory. In contrast dyslexia covers difficulties in reading and spelling, correlating with deficits of central executive functions of the working memory [1]. Nevertheless both difficulties frequently correlate with one another [2]. However, before complete sentences can be built, the ability of writing single characters in a legible way is essential. Only if this skill is successfully mastered, the child may allocate attention mainly to the semantic level and the complex task of orthography.

Multisensory approaches like using additional proprioceptive feedback via visuo-haptic devices are relatively new approaches. These had been deployed in 1998 on Japanese [3-7] and 2002 on Chinese [8] handwriting, but still contain some limitations. A crucial requirement to haptic guidance is a model trajectory which implies limited tolerance for individual variations in handwriting. This way little latitude is granted to develop an individual handwriting style. This approach stands in contrast to current school concepts, for example in Germany, in which the evaluation of calligraphy no longer plays a role. Especially at the beginning of the learning process it might be important that the child can establish an independent feeling for the writing. This can barely happen if it is forced by means of strength on a given ´ideal´ trajectory. Feedback could be designed as a supporting instrument which the child can take up for himself. There should also be the possibility to accept feedback only in parts. Moreover, force feedback involves the risk of dragging the writer passively by the model default instead of reproducing the characters independently and guided by the already established representation. A remaining question is how the child will write in the future without having this feedback available – the benefit might decrease, as addressed by the 'guidance hypothesis' [9].

The idea that children may respond in a positive way to modern technology, such as tablets, is not new. In the past, there have been other devices used to study the impact of supportive information as an additional modality, for example visuo-haptic arrays for handwriting of children, particularly for children who are still younger than school age [10]. As Palluel-Germain *et al.* (2007, 72) suggest, "fluency was analysed by kinematic parameters: average velocity, number of velocity peaks, and number of breaks during the production of six cursive letters (a, b, f, i, l, s). The results showed that the fluency of handwriting production for all letters was higher after the experimental training with the visuo-haptic

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device than after the control training: The movements were faster, exhibited less velocity peaks and children lifted the pen less often during the letter production. These results showed that the ´Phantom´ device may help kindergarten children to increase their proactive strategy to control handwriting movements". The authors illustrate that proactive control of movements develops over time and practice based on an internal representation of the motor act in contrast to the non-automatic retroactive motor control based on sensory feedback. The above mentioned ´Phantom´ is a device that adds haptic information as a further modality and delivers children haptic feedback about their deviation of the character model trajectory immediately. This immediate error-feedback in form of a force-feedback arm allows children, according to the authors of the study, greater fluency and better retention of characters – even early in education and before they have received formal writing training.

Historically, research on acoustic feedback focused on sensorimotor deficits such as mogigraphia, a dystonic neurological affection [11]. Early work was published in the seventies by Reavley in 1975 [12] and by Bindman and Tibbetts in 1977 [13]. So far only few data exist with regard to acoustic feedback: No specifications are made about the used devices, the data analysis, the participants or the exact kind of the acoustic feedback. Furthermore, no pre- and posttest results were made public, so that the issued results cannot be evaluated. The published results vary strongly: O´Neill [14] reports in 1996 a complete recovery from writer´s cramp after only one week of auditory treatment whilst Bindman and Tibbetts [13] observed the maintenance of the symptoms even after months of treatment. Without further details about the used method a classification of the studies is nearly impossible, even if the studies contain a similar structure. Muscle contractions are measured as a function of the muscle activity with EMG and the resulting signal is converted into an acoustic signal. With this auditory bio-feedback a physiological parameter is linked to an acoustic signal, used as an error-feedback in case of too much pressure being applied to the pen by the writer.

Only little initial research was performed yet concerning sonification as a feedback-system in the process of handwriting acquisition. An intervention study has just been published in 2013 by Danna *et al.* [15]. During the pre- and posttest shortly before and after the training, six alternating downward and upward loops were traced and the French sentence "la nuit, la lune est belle" (at night, the moon is beautiful) was written. Training sessions consisted of the production of various strokes, loops, elliptic and circular shapes. After the training the participating children with dysgraphia wrote faster and more fluently as a result of the study. However, the legibility of the handwriting did not increase.

In learning studies a retention measurement to prove the temporal stability of the learning success should be realized about two to three weeks after the last training. Danna *et al.* did the retention measure two month after the last training, which is quite a long period for children in the kindergarten age due to the competing influence of natural development factors. The authors explain their positive study results with the application of an additional – acoustic – modality and primarily with additional audio-motor couplings. But it has to be remarked that no comparative data of a control group are presented to enable an assessment of the reported learning effect. Subsequently an alternative approach of using real-time movement sonification supportingly on the acquisition of character handwriting will be introduced – configured in a different way to address mechanisms of multisensory integration explicitly.

REAL-TIME MOVEMENT SONIFICATION

Real-time movement sonification is used by our research group since about 15 years in different fields of application, such as sports [16, 17], motor rehabilitation [18] or basal everyday movements [19, 20]. Here, we are adapting real-time movement sonification to the field of handwriting. Thereby sonification cannot be considered as a new technique. Many different sonification applications and techniques exist, some already established for a long time and widely used across various fields. For example, different devices such as the Geiger counter to measure ionizing radiation, variometers to inform the pilot of sailplanes about the rate of descent or climb, sonar as navigation technique or certain devices used by engineers in some fields of machine diagnostics [21] are in widespread use.

To characterize the key elements of real-time sonification on handwriting we will use subsequently the term 'SoundScript'. This method complements the writing traces of the handwriting with typical sound traces. Spatial feature classes of the handwriting are assigned systematically to acoustic feature classes. Repeated writing with SoundScript might create an additional movement-acoustic reference system in the perceptual system of the participant, which allows a more stable retention of information and a more concise distinguishing of the audio-visual character patterns – compared to unimodal patterns. Through the additional activation of audio-motor and multisensory-motor cerebral functions during the writing process the formation of adequate representation of the different characters is expected to get enhanced, like shown on swimming movements by Schmitz *et al.* [20]. With reference to our own previous work as to the work of Dubus & Bresin [22] and Küssner *et al.* [23] we have decided to realize the following mapping procedure: The vertical position (1) of the sound pen on the surface of the tablet has been mapped to the frequency (pitch) of the sound. The pressure (2) of the tip of the sound pen has been mapped to the amplitude (volume) of the sound. And the horizontal position of the sound pen (3) has been mapped to the spectral composition (brightness) of the sound. Our previous own research had already indicated the given efficiency of frequency-mapping (1) as well as amplitude-mapping (2) and brightness mapping (3) [16-18, 20]. An electronically generated sound is used based on a saxophone timbre which is chosen despite of its adequate sustain duration and based on sound aesthetic considerations.

The additional integration of non-verbal auditory and multisensory functions in the character writing acquisition leads to additional movement-acoustic information during the writing process with no need of expanding the practise time: While the character writing is practiced the SoundScript method generates additional 'sound traces', which correlate structurally extensively with the familiar visual writing trace. Thus, the effect of the writing movement becomes audio-visually perceivable and a multisensory effect strengthening of the writing movement is expected. Multisensory integration can occur in principle when the contributing factors derive from the same temporal and spatial location. Typically, effects of multisensory action support the perception in terms of a concise, more differentiated processing and a more stable memorization of the given information, as it has scientifically been proven in different behavioural domains: in the fields of linguistic perception [24], while making music [25], in neurological rehabilitation [18] and also on motor perception and control [16] as well as on learning of sport movements [17].

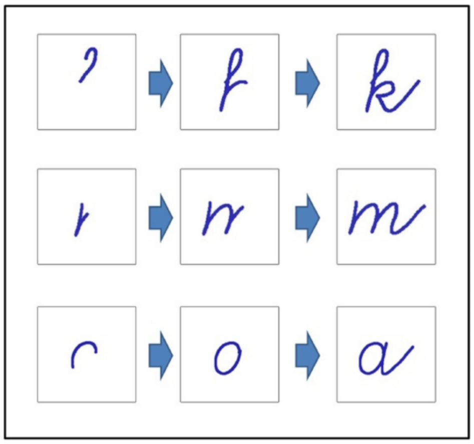


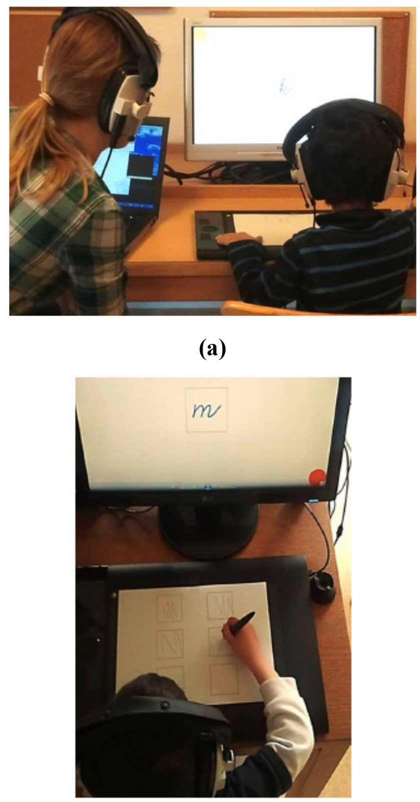
Fig. (1). Dynamic presentation of the character models used as instruction modes.

In the course of the character writing training, the acoustic component of the handwriting trace is realized during the character instruction as well as during the writing process as real-time feedback. All single characters of te instruction phase are presented dynamically on the tablet screen (see Fig. **1**): The temporal course of the writing can directly be observed and simultaneously be heard. Accordingly, the handwriting of the characters generates structural-analogous sound traces beside the optical written trace. Since these writing acoustics is perceived in real-time, the integration of visual and auditory effects of the writing movement in the perception system of the participants is elicited. In this context, real-time stands for a latency of less than 100 ms [26]. The perceptual system processes spatial congruent audio-visual information with minimal temporal differences as originating from the same event and thus integrating it in multisensory integration sites of the central nervous system (CNS) – down to the level of single neurons, or, more precisely, multisensory convergence neurons [27].

This additional involvement of audio-motor and multisensory integrative functions of the CNS in the writing acquisition process offers the following potential effects on learners with and without reading and writing weakness:

- A higher efficiency on the acquisition of the perceptuo-motor representation of characters resulting in an enhancement and acceleration of the learning process.
- A stronger conciseness of the respective character shape, resulting in a more reliable differentiation of figural similar characters (d, b; p, q *etc.*).
- A temporarily more stable learning result.
- An effective and individually adaptable support of low-achieving children with less frustration related to the acquisition of the cultural technic 'handwriting'.

Identical repetitions of movement patterns and stroke orders result in identical repetitions of the corresponding sound pattern. The cognitive system´s ability to identify structural correspondences in the perceptual streams of different modalities and to the detection of inter- and intramodal invariants is a central neurobiological mechanism for learning, or like Shams and Seitz (2008, 412) [28] state "...it nonetheless seems that the multisensory benefit to learning is an overarching phenomenon.". Under multisensory learning conditions the discrimination of different rhythms was more subtle and reliable on 5-month old infants for instance and the retrieval of information was enhanced. The effectiveness of this mechanism apparently increases if multimodal – but structurally convergent – perceptual streams emerge [20], with the result of a more precise movement execution [27] and improved learning [18, 28].



(a)

(b)

Fig. (2). (**a** & **b**) Illustration of the pilot application of the method on a digitizing tablet (Wacom Intuos 4L).

It should have become clear that SoundScript is not used as some kind of error-feedback tool to inform about the level of correctness of a movement that is currently executed. In this sense, SoundScript will not provide feedback that the child has created something incorrectly (illustrated in Fig. **2a** and **2b**); instead, the system translates whatever character is written into sound. This sound can be compared to the sound that a specific character should make – in terms of a character sound model. With consecutive handwriting practice a multimodal representation will emerge containing certain auditory properties of each character. Recalling the special sound pattern of a character will deliver figural information for writing this character again. This kind of information is expected to support the child at the transition from a retroactive to a more proactive writing style.

This implies that children are able to memorize significant features of the instruction, which requires certain working memory resources. Children should further be able to identify differences between instructed and reproduced characters. Such a comparison between remembered and produced sound should be facilitated by the homogenous presentation of presented and reproduced characters, which does not require an internal translation between auditory instructed information and the sensory consequences of the own action.

The acquisition of character handwriting is mainly determined by motor-sensory and memory processes. The contribution of our workgroup, located in the field of human movement science, is based on a current theory on motor control and learning, the 'internal model' theory [3, 4]: "Skilled motor behavior requires both inverse and forward internal models. Motor learning can be viewed as the acquisition of forward and inverse internal models appropriate for different tasks and environments. We need to acquire an inverse model in order to estimate accurately the motor commands required to achieve a desired sensory response:" (Wolpert *et al.* 2001, 488, [3]). Transmitted to the acquisition of character handwriting the desired sensory response can be understood as the sensing of the writing movement in terms of tactile, kinesthetic and visual percepts during the writing process and the visually perceivable result, the written character.

It had been Wolpert *et al.* (2011) [4] themselves with reference to Ernst & Bülthoff (2004) [5] highlighting exemplarily the relevance of multisensory integration for such acquisition processes: "...multiple streams of sensory information, within and across modalities (for example, visual and tactile inputs), can be optimally combined to achieve estimates that reduce the effects of noise... . Interestingly, this integration process can take into account the properties of external objects, such as tools, so that the visuo–haptic integration is optimal even when the tactile input comes through a hand-held tool... . (2011, 2). Thereby a direct link to the internal model theory is disclosed for the real-time sound trace produced by a sound pen as a hand-held tool when writing characters: The emerging scriptsound is directly specified by the motion of the pen tip, so the sound trace is an analogous effect of the executed inverse model. But if the writing child is imagining a whole soundpattern of a certain character, this soundpattern might be used as an auditory forward model.

So, what can concludingly be expected about both potential functions of the SoundScript method when using it for a period of about three weeks? At the beginning of using SoundScript the generated sound traces are primarily usable to develop new inverse models for the characters. But with ongoing writing practice, if character writing is becoming more stable and characters are becoming more invariant, also variance of produced sound traces is getting smaller resulting in a corresponding soundpattern that is getting more and more typical and concise. Thereby it will be easier to be retrieved – an auditory character representation is emerging within the CNS. If this auditory character representation is retrieved it will work as a forward model. But could additional real-time acoustic feedback really improve the development of usually visually guided character representations of children in the pre- and school-age and thus support the acquisition of character writing?

Visual information yields accurate perception of spatial attributes, but less accuracy with respect to temporal attributes of movements. These types of information can be well provided by the auditory modality through sound. The SoundScript method therefore might primarily provide additional information about the temporal structure of a movement – but with a direct reference to spatial features.

Previous research [6] emphasizes how important it is to develop stability within the temporal structure of a movement. The authors suggest to apply methods that address the rhythm of movements and help subjects to stabilize their own temporal movement control. In such way skill acquisition should be supported. By observing the audiovisual instruction of characters in advance to its reproduction, children can perceive how this character can be efficiently produced, and they can subsequently try to reproduce it in an adequate way. This is also a general advantage of a dynamic, compared to a static stimulus.

In addition to that, the correspondence of instruction and feedback modality should address a further learning mechanism: According to Shadmer *et al.* [29] sensorimotor learning is driven by a prediction error. This prediction error is understood as the difference between sensory consequences of the own action and the predicted sensory consequences. That means, learning does not necessarily require a comparison of feedback with instruction but can unfold by a comparison of feedback and expected feedback. The internal simulation of the sensory consequences of an action might also benefit from the homogenous relationship of instruction and feedback.

Summing up, instruction and movement congruent feedback, as realized in the SoundScript method, should enable children to apply two different learning strategies: They might directly compare the sensory information provided by instruction and feedback and/or use these information to enhance the feedforward modelling of the own action.

ASSESSING THE QUALITY OF CHARACTER WRITING

But how can the learning effect in the course of the training be assessed? In the following section two algorithms are introduced for quantifying the similarity of the instructed character pattern compared to the written character by the participant.

Recognizing handwritten characters is still a challenging task in Computer Vision. Especially recognizing characters written by children. Each child has its own style of writing a character leading to large variations. Besides inter-individual variability there is also intra-individual variability, addressing the differences between individual repetitions of the same character. Therefore, a quality rating system has to be robust against individual time characteristics. In this work we propose to use Dynamic Time Warping as a pre-processing step and Shape Matching to interpret the gathered coordinates as shapes. These algorithms were already applied in this context successfully [30].

Dynamic Time Warping (DTW) was introduced by Bellman and Kalaba and has been applied to several fields of applications like video or audio processing to measure the similarity of two temporal sequences. The main idea of the DTW-algorithm is to map values between two temporal sequences to each other. Therefore it is suitable to determine similarity metrics of time series of different lengths [31]. This algorithm can be considered as very effective and efficient in order to drastically reduce effects of distortion and shifting in the measured times [31]. It can be assumed, that each child will need an individual characteristic time to write characters of the alphabet and therefore produce an unambiguous time series. Doing so, the time series of a certain input will be compressed or stretched in comparison to other time series. As a result, similar elements of both rows to be compared can be revealed. The results are suited for the documentation and analysis of the participants writing achievement over time with the similarity to the model character as a reference.

In the following, a brief technical explanation is given. First, the algorithm applies a distance between any two values of the signals using a weighting function, such as the euclidean distance for each parameter of each tuple. The output is referred to as a cost function. In the next step the algorithm seeks the lowest cost from the start to the end of both signals over the stretched matrix of pairwise current cost of all points of both signals. The actual path, referred to as a warping, is determined by backtracking the first pass of the algorithm. The backtracking allows a precise representation of each point of the shorter signal to one or more points of the longer signal. Thus the approximate time distortion is represented. Further information and a detailed review are presented by Senin [31].

Shape Matching or shape registration generally describes a method to measure the similarity of point correspondences and is used in various Computer Vision applications such as image segmentation or image retrieval. In contrast to the DTW, the Shape-Matching-algorithm– in this work – detects similarities between forms and sets aside differences in the dynamic with the generation of these forms. Any shape – and thus the characters within this study – is digitized and can therefore be partitioned into vectors of screen pixels. The partition, recognition, and comparison of these vectors of screen pixels are subject of Shape-Matching-algorithms. The algorithms that compute the input information are subject to a wide ranged research topic within computer science and mathematics and do not represent a determined and not-to-be-changed term nor function. The complexity of these algorithms is not to find exact accordance of input and predefined shape after interpretation and computing – this would be a straight mathematical issue. In these terms, a shape is only defined as an equivalence class within a group of transformations [32]. This is not sufficient [33] in order to fulfill the means of the SoundScript pilot study. The Shape-Matching-algorithm points to cover up the similarity of shapes and its components and must be understood as fundamental for electronic recognition of handwritten inputs [34].

Both, the Shape-Matching- and the DTW-algorithm must not necessarily be understood as being conditional. While the Shape Matching points to the interpretation and computing of graphical inputs with the aim of covering up similarities in object and character recognition, the DTW is of more abstract character and stands for a technique of time series alignment and was initially developed for the recognition of speech inputs [35]. In combination, the algorithms of shape matching and DTW build the fundament for the data evaluation of the SoundScript method.

EXPERIMENTAL PILOT-STUDY

15 kindergartners participated in the study. They were 5.0 ±0.6 years of age and had no overt neurological, psychic or developmental disorders. The children themselves verbally expressed their consent, and their parents gave their written consent to participation. The experimental procedure was pre-approved by the local ethics committee of the Leibniz University Hannover.

A female adult wrote three characters of different complexity (a, k, m) on a paper placed on a digitizing tablet (Wacom Intuos L, spatial resolution of <1mm, synchronized with the screen at a rate of 60 Hz). The digitizer also worked as common ballpoint pen, thus visual feedback of performance could be provided. The simplified standard lettering, developed from the Latin source writing, was chosen as writing style, because it has been established in several West German Federal Lands in order to simplify the learning process of how to write. Tablet data were submitted and stored by the sonification software Pure Data (PD). The recording of the characters contained the complete spatial-temporal profile of the original production process and was used for visual presentation (Fig. **3**) and sonification by the same software. For sonification, the before mentioned mapping was applied. Pitch and brightness modulations were limited to a square of 6 cm side length, which had been pre-printed on the paper.

Fig. (3). Model characters used in the experimental study. The characters were written into a square of 6 cm side length. These dimensions also defined the space for sound modulation.

The characters served as model for the children. During the pre- and the post-test, each character was presented once as static image without sound. Children were instructed first to watch the presentation and then to repeat the character three times within the squares as accurately as possible without lifting the pen. During training, the characters were presented dynamically (*i.e.* in the same time-course as during the original production). All three characters (a, k, m) were presented five times each in random order, and the children were instructed to reproduce each character twice directly

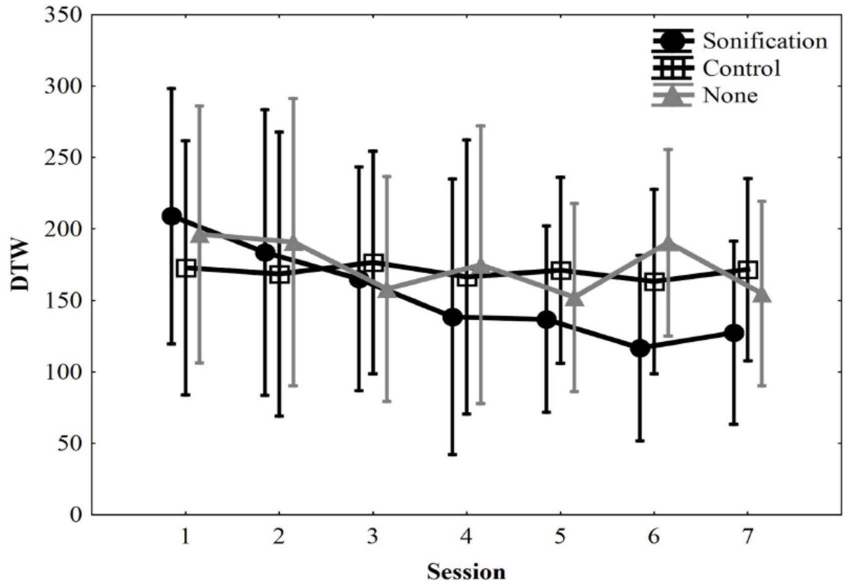


Fig. (4). Results of the Dynamic Time Warp (DTW) algorithm. Means and 95%-confidence intervals of subjects that heard a sonification (black line, balls), a control sound (black line, squares) or no sound (grey line, triangles).

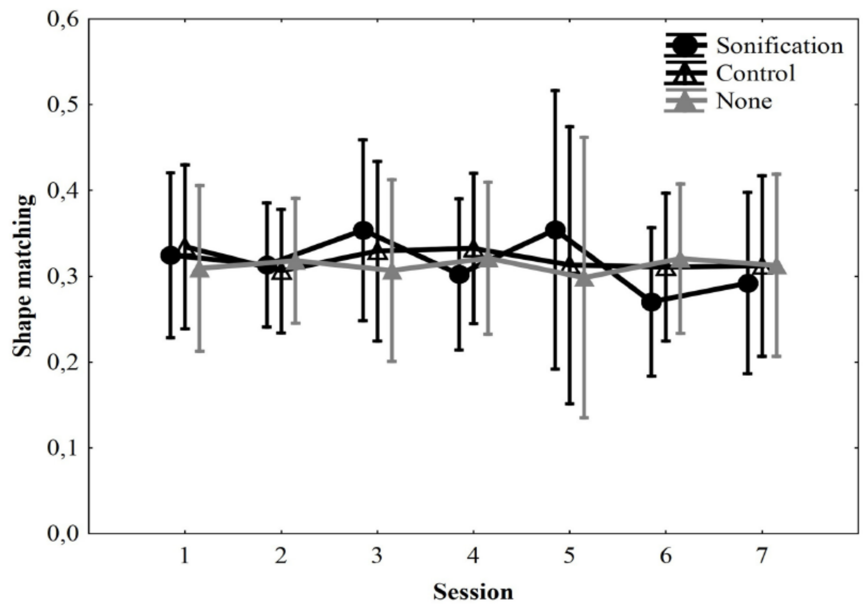


Fig. (5). Results of the shape matching algorithm. Means and 95%-confidence intervals of subjects that heard a sonification (black line, balls), a control sound (black line, triangles) or no sound (grey line, triangles).

after its presentation before the next character was presented. Each child trained five times for about 30 minutes. Training sessions were interleaved with breaks of two to three days.

The children were pseudo-randomly assigned to one of three groups. The children had not learned to write before and therefore, these groups could not be parallelized on the basis of the individual writing skills. As an alternative, grapho-motor skills were screened by a standardized grapho-motor test battery [36] and used for parallelization. All groups watched the dynamic writing trace. Group *Sonification* further heard the sonification. Group *Sound* heard the basic frequency of the same sound, but the sound was not modified during the movement. Group *Control* did not hear any other sound than the pen tip was evocating on the paper.

Data were analyzed by a DTW- and a Shape-Matching-algorithm implemented in Matlab. The outcome was submitted to three-way ANCOVAs with the between factor Group, the within-factors Character and Session and the covariate Grapho-motor Skills. Data were presented and statistically analyzed with the software Statistica 12.

RESULTS

Childrens' performance during the pre- and the post-test (1, 7) as well as the five training sessions (2-6) is illustrated in Figs. (**4** and **5**). Regarding the DTW-algorithm, performance changed differently between groups over time. This is confirmed by a significant interaction Session*Group ($F(12,66)=2.44$, $p<0.05$, $\eta_p^2=0.31$, Greenhouse-Geisser corrected). In a Tukey-post-hoc-test performance changes were statistically significant for group *Sonification* only*:* Pre-test performance differed significantly from performance in training sessions two to five (at least $p<0.05$), as well as from performance in the post-test ($p<0.01$). No differences between sessions were significant for group *Sound* nor group *Control*. The covariate Grapho-motor Skills did not significantly predict performance, but prediction of the interaction Character*Session bordered significance ($p=0.06$, Greenhouse-Geisser corrected).

The results of the shape-matching-algorithm are illustrated in Fig. (**5**). Groups performed quite similar, and seemingly, performance did not change over time. Accordingly, ANCOVA yielded no significant result.

CONCLUSION AND OUTLOOK

SoundScript aims at an enhancement of the handwriting acquisition by creating an additional sound trace via real-time movement sonification. By ensuring structural equivalence of the acoustic writing trace with the visual writing trace and with proportions of the hand- and arm-writing-movements, perceptual streams in different modalities will be provoked that should be integrated in different sites of multisensory integration within the CNS [37]. The involvement of such additional neuronal functions during the acquisition of handwriting is addressed to support the learning process of character handwriting of preschool- and school-children, especially of low-achievers and children with dysgraphia and dyslexia.

The pilot study provided first evidence that hand-writing sonification supported the learning of three new characters in kindergartners. That was not the case for children that heard a static sound instead or just the natural sound of the pen on the paper (not amplified) – a contrast against current findings for simple rhythmical movements like breathing, which had been affected more tightly by ecological sounds [38]. Increase of performance for the *Sonification* group was indicated by the similarity computations with the DTW-algorithm but not with the Shape-Matching-algorithm. Since the latter considers only spatial and not temporal features of the character production, but the DTW-algorithm spatio-temporal features, this finding indicates that the sonification might primarily support the acquisition of the temporal structure of the writing movement. But by the results of the chosen Shape Matching computations it is not disproved that the sonification also supports the acquisition of the spatial structure of the writing movement. With our data this aspect is only supported by the results achieved with DTW till now, and the legibility of written characters had not been proved additionally by experts. But there exists supporting evidence on adult handwriting delivered by Longstaff and Heath [39] that dynamic variability is related to spatial inconsistencies at least in adult handwriting. Nevertheless this relation should be proven with a larger sample and a longer training period in the future.

Methods that support the acquisition of the temporal profile of a movement, are recommended for skill acquisition [6]. The SoundScript method therefore might be a useful tool for the acquisition of writing. It still remains unclear, if children with dysgraphia will benefit in an adequate way when using the SoundScript method, because dysgraphia is correlating obviously with limitations of the phonological loop-function of the working memory. It has further to be examined, if these limitations are also critical for recall of the sound pattern of the particular characters. But despite the structural equivalence between the visual and the auditory effect of the writing trace this certain limitation might be covered proportionately via multisensory integrative mechanisms.

The article has primarily described a method developed for practical applications by supporting the initial acquisition of a culture technique. Added value to theory is given by providing empirical evidence that artificially generated movement information can enhance the learning of fine motor skills. But presented empirical data are indicating only in a first step the efficiency of a kinematic and dynamic real-time movement sonification on the initial handwriting acquisition of children – with or without special limitations in the sensory-motor systems or the memory system. Further research is needed to find out, which type of acoustically transformed movement information supports the acquisition best and how individual limitations can be compensated efficiently.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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