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A Natural Sonification Mapping for Handwriting

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The sonification of handwriting has been shown effective in various learning tasks. In this paper, the authors investigate the sound design used for handwriting interaction based on a simple and cost-efficient prototype. The authentic interaction sound is compared with physically informed sonification designs that employ either natural or inverted mapping. In an experiment, participants copied text and drawings. The authors found simple measures of the structure-borne audio signal that showed how participants were affected in their movements, but only when drawing. In contrast, participants rated the sound features differently only for writing. The authentic interaction sound generally scored best, followed by a natural sonification mapping.

0 INTRODUCTION

Peripheral interaction [1] describes a new type of interaction that facilitates switching between the required level of attention, from peripheral to focused interaction, fostering learning processes through the continuous interplay between action and perception. The Human-Computer Interaction community, on the one hand, has gathered experience in designing peripheral systems, mostly using other modalities than sound. Sonification research, on the other hand, aims at exploiting hearing as additional information channel; specifically, sonic interaction design [2] adds sound to objects and their interactions. Adding auditory feedback to everyday interactions has been explored, for example, when driving a car more economically [3], when the sound produced by knocking on a door reveals whether or not someone is inside [4], or when opening a wardrobe door triggers an auditory weather report [5].

Bovermann et al. [6] introduced the method of auditory augmentation that combines sonification with peripheral displays. Their first prototype *WetterReim* was based on structure-borne sounds. The typing sound on a keyboard was recorded with a piezo microphone and played back in real time with added resonances. The typing sound perceptually grouped with the added resonances that were controlled by weather data. This system informed about the weather in a peripheral way, and it conveniently used a natural mapping.

The project presented in this paper ties in thematically with the *WetterReim* prototype but explores handwriting. From literature discussed in the following section, it is known that augmenting handwriting has beneficial effects in the context of learning, e.g., for school children with disabilities or adults with Parkinson's disease. But in these works, the actual sound design of the sonification was not investigated. Therefore, in the presented research, the authors tested and compared three types of interactive sonic feedback that will help to further develop systems of auditory augmentation of handwriting in the future.

This paper starts with an overview of the literature of biofeedback in the context of motor control and handwriting. Then, the prototype, experiment, and outcome are described, from analyzing both survey data and the recorded audio signals.

1 BACKGROUND

Dyer et al. [7] reviewed a number of relevant experiments in the field of auditory feedback in the context of motor skill learning. Their most relevant points of how such feedback can be effective are summed up: Firstly, the authors argue the need to choose well which data variables are presented, focusing on the fundamental kinematics of the task. This strategy opens room for better integrating intrinsic (for instance, proprioceptive) and extrinsic (for instance, auditory) feedback and henceforth diminishes the guidance effect, which is known to decline the performance when the extrinsic feedback is not available anymore. Since there are many ways to accomplish a motor task, with many parts of the body involved, it is a good idea to focus on the "end

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*To whom correspondence should be addressed, email: vogt@iem.at. Last updated: Feb. 19, 2024 effector”—in the case of handwriting, that would be the fingers holding the pen or the pen itself—and let the user explore their way to mastering their motor system.

Secondly, Dyer et al. argued convincingly in favor of a natural sound mapping, as originally demanded by Norman [8], i.e., to take advantage of physical analogies and existing cultural standards. Natural and ecological sound mappings have been repeatedly called for in sonification research, e.g., in [9, 10]. Third, and importantly, the mapping aesthetics must be carefully considered, and the authors state that, ideally, “sonified feedback can be designed to be pleasurable to listen to and intrinsically rewarding.” Besides the need to create an effective information display, this factor is equally relevant for a good sonification design, as has been, for instance, discussed in [11].

Sonification has long been known as a useful tool for guidance tasks, specifically when they involve hand movements [12]. More concretely, the field of handwriting sonification has been subject of extensive research. Initial studies explored feedback to overcome the writer’s cramp [13, 14] or evaluate the efficiency of a verification system for signatures [15], though the latter did not involve real-time feedback. Thoret et al. [16] investigated auditory perception of drawing movements and found that for simple, geometric shapes (that were not too similar), timbre movements in friction sounds enabled the participants to recognize and associate a drawn shape in most cases by merely listening. Interestingly, that was the case for both natural and synthesized friction sounds. This experiment showed that, even with handwriting being a very silent activity, there is still naturally occurring auditory feedback of the interaction that can be used further.

Rocchesso et al. [17] experimented with a stylus that is augmented by vibratory and/or acoustic feedback. They found a steering effect for these additional feedback modalities only in the case that no visual feedback was given. This study underlines that there is a tight coupling between the auditory modality and motor behavior and that a movement is able to be changed by manipulating its sound in real time.

The work of Danna et al. [18] systematically examined concurrent auditory feedback in the context of helping children with dysgraphia learn to write better. Nowadays, the use of graphic tablets makes it possible to explore and exploit the kinematic features of the writing movement as opposed to the static result, i.e., the writing trace. Danna et al. [19] first investigated which features are best suited for feedback. They found that poor handwriting in their use case is characterized by speed changes and a lack of fluency in the writing movement. From this, they derived objective variables for measuring writing movement, which will be revisited in SEC. 2.4.

Then, Danna et al. [20] mapped some of these kinematic variables to sound features in real time. In a learning experiment with adults, they found short-term benefits of conditions with auditory feedback, regarding the movement time and fluency of the writing, though at the cost of a lower spatial accuracy of the script. There were no specific long-term benefits of auditory feedback, but this might be due to the integration of the sound into a unified writing percept, as desired in Dyer at al.’s argument discussed above. The benefits of using auditory feedback for children with dysgraphia have shown positive effects in [21].

Danna et al.’s sonification design involved a natural mapping strategy, using the metaphor of the rubbing sound of chalk on a blackboard, linked to the instantaneous tangential velocity of writing. Furthermore, they added squeaking sounds for long stops in the writing movement and crackling noise for jerky handwriting. As briefly summarized above, the resulting sounds were effective, but at least some participants informally reported that they were not pleasant to listen to. Danna et al. did not focus on the aesthetics of the sound and argued that a musical sonification could circumvent low acceptance. Véron-Delor et al. [22] realized a musical sonification approach to improve motor control in Parkinson’s disease patients. They found the fluency of handwriting affected by musical sonification, but the same was true for non-interactive background music that was tested as a control condition.

Although factors such as engagement and motivation can certainly benefit from the use of music, musification has downsides as well, for instance, the individual musical taste and additional layers of meaning that are not appropriate to the task [10]. Specifically for handwriting, the rhythm of music may act as a rigid constraint for the writers, pushing the individual writing velocity. For instance, people have been shown that they cannot “standstill to the ‘beat”’ even when they try to [23]. While musification can certainly be useful in specific use cases, the present authors wanted to explore natural mappings as a more general design concept for sonifying handwriting and explore their effects and acceptance.

2 EXPLORING AUDITORY FEEDBACK FOR HANDWRITING AND DRAWING

The authors developed a basic prototype to explore real-time auditory feedback for handwriting and drawing. It is known that auditory feedback has benefits, e.g., for learning [20], but not which sounds are best suited. In an experiment, three different types of sound feedback were assessed. Which sounds are perceived as most natural, which ones are preferred by the test subjects? What is the difference between an authentic interaction sound and a natural sonification mapping? What if an arbitrary mapping is used instead of a natural one? Which mappings influence the writers in their movement?A demo video can be found at: https://phaidra.kug.ac.at/o:131343.

2.1 Apparatus

Instead of working with a graphic tablet, the authors intended to work with normal pen and paper, mounted on an ordinary clipboard. With this approach, they wanted to bypass user expectations, so test participants were not always aware if a sound was added to the authentic feedback sound. The authentic sound of a ballpoint pen on paper, mounted on the deliberately rough surface of a clipboard, is soft but clearly audible. It provides detailed information on the

(a) Apparatus with loudspeaker (b) Apparatus backside

Fig. 1. The clipboard apparatus used in the experiment. (a) Apparatus with loudspeaker and (b) apparatus backside.

kinematics of the writing without an advanced technical setup such as a graphic tablet used in previous experiments. The resulting sound is a rough noise with a varying spectrum that depends on the velocity and pressure of the pen. From the initial experiments of the setup, the brightness of the noisy sound was experienced to be its most salient feature—the quicker the movement, the higher pitched and brighter is the sound.

The prototype used in the experiment consisted of a clipboard mounted on two wooden wedges (see Fig. 1). A piezo element was taped to the bottom-facing surface of the clipboard, measuring the structure-borne sound of the cardboard, and connected to the audio input of an ultra-low–latency micro-controller of the type Bela Mini. It ran a PureData patch that processed the input and output of sounds at a sampling rate of 44.1 kHz.

In order to verify the relation between the writing movement and the audio signal of the apparatus, the authors conducted a separate experiment with an extended setup. They used a graphic tablet (Wacom Intuous M[1]) that was placed underneath the cardboard with a few millimeters of air in between. With this setup, position and pressure data are delivered from the tablet even when the pen does not directly touch the tablet. Thus, the position of the pen and its pressure were able to be sampled synchronously with the signal from the piezo microphone.

Four different conditions of drawing large circles were recorded: (a) slow/soft (i.e., low pressure), (b) quick/soft, (c) slow/tight (i.e., high pressure), and (d) quick/tight. First, the spectral centroid of these exemplified conditions (in between 100 Hz and 10 kHz) were analyzed, and the everyday listening experience, i.e., that the writing sound becomes higher pitched and brighter with higher writing velocity, was confirmed, although it was also found that higher pressure slightly lowers the frequency. For assuming a relatively constant mean pressure level of experienced writers as the test persons were, it was concluded that the writing velocity is the main factor changing the brightness of the sound.

Second, for each condition, velocity, pressure, and microphone SPL were compared for each drawing condition. To this end, velocity, pressure (original update rate from the tablet between 200 and 1,000 Hz), and SPL (original sampling rate of 44.1 kHz) were re-sampled to the same sampling rate of 441 Hz (including appropriate anti-aliasing filters) as used for the analysis of the main experiment. It could be seen that the SPL increases with the RMS values of both velocity and pressure, and a corresponding two-variable linear regression model achieved a coefficient of determination $R^2 = 0.97$. Moreover, the interactive pen of the tablet behaved similarly as a ballpoint pen on the cardboard: Comparing different normal pens to the interactive one, the spectrum was different, but the RMS level in decibels was relatively similar for the same writing style.

In conclusion, the authentic sound of this apparatus becomes brighter and higher pitched when writing quicker on the cardboard; it also becomes louder, and this is measured as SPL of the piezo microphone signal. The SPL is mapped to frequencies of the synthesis model, and therefore, the natural interaction sound is mimicked. Brightness is used for sonification, because it is the most salient feature; no matter which pen is used, the sound becomes brighter if writing velocity increases. However, because the actual sound may depend on the utilized pen, SPL is used as the input parameter of the sonification model and, thus, also as the main parameter for the analysis of the audio data.

2.2 Conditions of Auditory Feedback

Different conditions of auditory feedback were implemented. First, the authors amplified the input sound and played it back to create a basic feedback condition for the prototype. Furthermore, sonifications were implemented that abstract from the physical interaction sound, in an effort to achieve a natural mapping. The sound designs for the sonification follow in principle Müller-Tomfelde and Münch [24] who developed a sound model for writing in virtual environments, e.g., on electronic whiteboards. The present model was simpler, because whiteboards are also a different (and, arguably, a less pleasant) sound experience than pen on paper. The pen-on-cardboard noise was modeled as a white noise with harmonic bandpass filters, as detailed below.

For the polarity of the mapping, the authors chose two variants: the natural mapping is mimicked when high pen velocity creates high frequencies. In an inverted mapping, a high pen velocity leads to low frequencies. This “unnatural” mapping was meant to be a counter-example that was inspired by the early experiment of Walker et al. [25], which showed that in some cases, an arbitrary mapping can be more effective than the ones chosen by sonification designers. Similarly, the above cited work of Véron-Delor et al. [22] found that both the sophisticated musical sonification and background music had comparable effects.

Three different kinds of auditory feedback were implemented as experiment conditions:

> *Clean, amplified sound (C)*: The clean signal was amplified and played back, adding to the natural sound in a way that at least some participants did not realize a synthetic sound on top of the authentic one.
> *Natural pitch mapping (N)*: The sound was based on subtractive synthesis of white noise, filtered in five harmonic bands. The fundamental frequency of the

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[1] https://www.wacom.com/de-at/products/wacom-intuos.

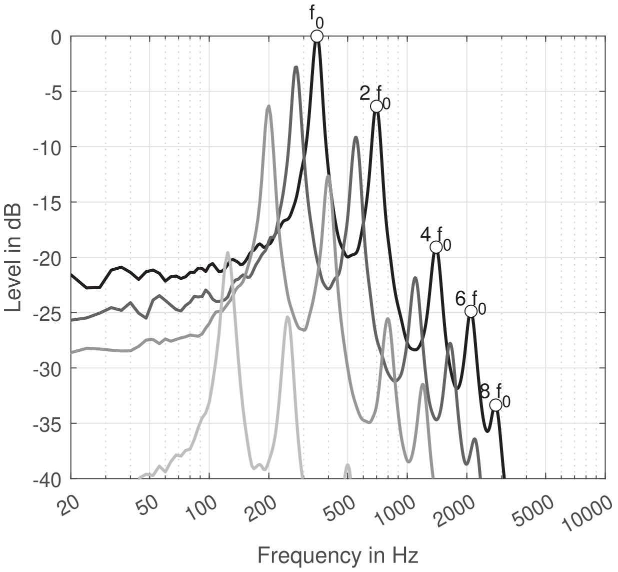
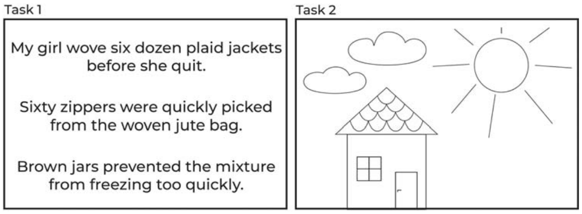


Fig. 2. Semitone-smoothed spectrum of the auditory feedback condition N for different RMS levels of the piezo microphone: 0 (black), –12 (dark gray), –24 (gray), and –36 dB (light gray).



My girl wove six dozen plaid jackets before she quit.

Sixty zippers were quickly picked from the woven jute bag.

Brown jars prevented the mixture from freezing too quickly.

(a) Writing task model (b) Drawing task model

Fig. 3. The task models that participants copied. (a) Writing task model and (b) drawing task model.

Table 1. The dimensions of the auditory feedback that were evaluated after each task. All questions were posed on a seven-point Likert scale.

Dimension (abbreviation)	Annotation of scale choices 1–7
Enjoyment (enj)	1, annoying–7, enjoyable
Distraction (dis)	1, helpful–7, distracting
Smoothness (smo)	1, strongly disagree–7, strongly agree
Authenticity (for the object/apparatus) (aut)	1, strongly disagree–7, strongly agree
Plausibility (for the writing/drawing task) (pla)	1, strongly disagree–7, strongly agree

first band moved between 100 and 350 Hz depending on the SPL of the piezo microphone.

Inverted pitch mapping (I): The signal was synthesized in the same manner as the above one; however, the SPL-to-frequency mapping was reversed. Consequently, the fundamental frequency went from 350 to 100 Hz, when the input signal went from soft to loud (i.e., corresponding to slow to quick writing). This can be considered an unnatural mapping.

In detail, conditions N and I were controlled by the 1,024-samples (23 ms) Hann-windowed RMS value $\hat{x}_{dB}$ of the piezo SPL that was high-pass filtered at 42 Hz to suppress hand movements and other low-frequency noise. To control the center frequencies of the bandpass filters, the RMS values in decibels $\hat{x}_{dB}$ were linearly mapped and clipped onto a value range of [0, 1], where $\hat{x}_{lin} = 0$ corresponded to –40 dB or less and $\hat{x}_{lin} = 1$ to 0 dB (full scale input from the piezo). For condition N, the center frequency of the lowest bandpass filter was calculated as $f_0 = 100\text{ Hz} + \hat{x}_{lin} \cdot 250\text{ Hz}$. In contrast, for condition I, the center frequency of the lowest bandpass filter was calculated as $f_0 = 350\text{ Hz} - \hat{x}_{lin} \cdot 250\text{ Hz}$. For both conditions, the other bandpass filters were set to harmonic center frequencies of $\{2, 4, 6, 8\} \cdot f_0$. All filters had a narrow-band Q-factor of 25 and their gains were decreasing for higher harmonics (see Fig. 2). Additionally, the playback level of the auditory feedback was also controlled by the RMS level of the piezo microphone by multiplying the output with $\hat{x}_{lin}$.

The overall loudness of all conditions was kept similar as subjectively based on trials of the authors. Moreover, the crosstalk attenuation of the auditory feedback into the piezo microphone, i.e., the difference between the RMS level of what arrived at the microphone when writing/drawing without any auditory feedback and just recording the corresponding auditory feedback without writing/drawing, was measured to be around 40 dB. Thus, the crosstalk was assumed to be negligible, and the recording of the piezo microphone can be interpreted as the sound of writing/drawing itself.

2.3 Experiment Procedure

After experimenting with the sound designs, the authors decided to use two different interactions: handwriting and drawing. Drawing was added because it was assumed that subtle differences would be less noticeable in handwriting due to the small and quick range of movements, and more effects in drawing, where longer, steady movements of the hand produced stronger sound differences, were expected. Participants were asked to copy three pangrams as a writing task and one simple illustration as a drawing task (see Fig. 3). The illustration was created to involve common shapes, such as circles, squares, or long and short lines. Each auditory feedback condition paired with one writing and one drawing task resulted in six tasks per participant in total. For variance, the three pangrams were in a different order for each task, and the illustration was once mirrored and once shifted in position. Still, all variants had exactly the same words to write and the same shapes to draw.

The survey design incorporated five questions that were assessed after each task, as listed in Table 1, and final questions at the end. The requested dimensions loosely follow Norman's design criteria [8], at least the ones that are applicable to an experimental prototype such as this apparatus (aesthetics, functionality, and usability, but excluding stability/safety and cost).

The authors asked for aesthetics in how annoying vs. enjoyable the sound was perceived. As users had no spe-

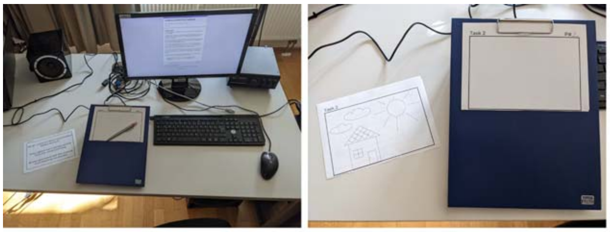

(a) Setup placement (b) Drawing model and template

Fig. 4. Experiment setup. (a) Setup placement and (b) drawing model and template.

cific task other than copying the text/ drawing, the only functionality of the sound was the smoothness of the auditory display. The authors argue that perceived smoothness is related to fluency, the most relevant kinematic feature of handwriting as found by Danna et al. [20]. Furthermore, the authors asked for distraction (how helpful vs. distracting the sound was perceived), which can be interpreted as usability factor. Finally, authenticity and plausibility are factors that evaluate the naturalness of the interaction. Authenticity was specified "for the object/apparatus," for which participants basically had the physical object as a reference at hand, i.e., pen and paper on a clipboard. This definition is derived from—but not identical to—Blauert's definition [26] that is given for the acoustic context and states that subjects cannot find a difference between a recorded sound and the real one. By contrast, plausibility was specified "for the writing/drawing task" so that participants had to compare the sound to their inner reference of handwriting, derived from plausibility as defined in [27].

All questions were evaluated using a seven-point Likert scale, either as unipolar or bipolar scale (bipolar in cases where two attributes made the dimension clearer, specifically enjoyment and distraction). After the experiment, seven general and demographic questions were asked. In addition to the qualitative data assessment, all input signals of the experiment were recorded for further quantitative analyses.

The experiment was conducted in three different quiet rooms. The clipboard apparatus was placed on a table, next to a computer that displayed the survey for the participants to fill out, see Fig. 4. The investigator led through the experiment and asked participants to sign the consent form. Participants were given the instruction to copy a text onto the paper of the clipboard, using their natural style of writing (usually, cursive writing, but block letters were accepted as well). Furthermore, they were asked not to put their idle hand on top of the clipboard, because any additional movement on the board causes structure-borne sounds that are not directly related to the writing. After copying each text or drawing, they answered the questions in the survey. The six tasks per participant were fully randomized.

Twenty-one people participated in this study. A mix of purposive and voluntary response sampling was used, drawn from the institute's staff, students, and private surroundings. Ten participants worked or studied in an audio-related field. Twelve participants were in the age range 21–29, followed by five between 30 and 39 years and four between 40 and 59 years; 13 were male, five female, and three non-binary or preferred not to say. Only two participants were left-handed. The experiment took around 20 min, thus learning effects and fatigue were minimized.

2.4 Analysis

The data from the survey and the audio data were both analyzed.

2.4.1 Analysis of the Survey Data

The survey data stemmed from quantized Likert scales. A Wilcoxon Signed-Rank Test was used to pairwise compare the different conditions, employing the Bonferroni correction. For calculating effect sizes (also for the audio data below), a non-parametric version for Cohen's d was used (i.e., employing the weighted median absolute deviation as alternative to the standard deviation to describe the statistical dispersion as proposed in [28]).

2.4.2 Analysis of the Audio Data

In order to test the influence of the auditory feedback on fluency in handwriting movement, the recorded audio data from the piezo element were analyzed. Audio analysis of handwriting is not commonly used, except in the rare application of reconstructing text from audio recordings of handwriting as eavesdropping via nearby mobile devices [29]. Closest to this application is the study of Danna et al. [30]. However, their analysis was based on kinematic data captured on a tablet. They used the measures of velocity (in meters per second), rate (as repetition of the same word, in hertz), trace length (in millimeters), dysfluency (as Signal-to-Noise velocity peak difference [19]), pen lift duration (in percent), and movement time (in seconds). Analyzing repeated writings of single words, they found differences between the participant groups only for the measures rate and movement time.

Unfortunately, the repetition rate could not be analyzed from the audio data, because repetitions of the same word were not recorded, and the writing time (as the total time of the whole writing/drawing task) did not reveal any effects of the sonification condition. For this reason, alternative audio-related measures were tried (calculated from the raw audio data, down-sampled by a factor of 100 from the original sampling rate of 44.1 kHz to achieve similar update rates as kinematic data from a tablet would provide): (i) the standard deviation (std; in decibels) of the recorded SPL as a measure of fluctuation and unevenness and (ii) the 75% quantile of the SPL (q75; in decibels) indicating particularly loud/intense writing. An informal pre-test by the authors confirmed an increase in std and q75 for intentionally dysfluent writing.

2.5 Results

2.5.1 Results of the Survey Data

Results for statistical analysis of the questionnaire data are shown in Fig. 5 and Table 2, comparing the three testing conditions (C, N, and I) separately for writing and draw-

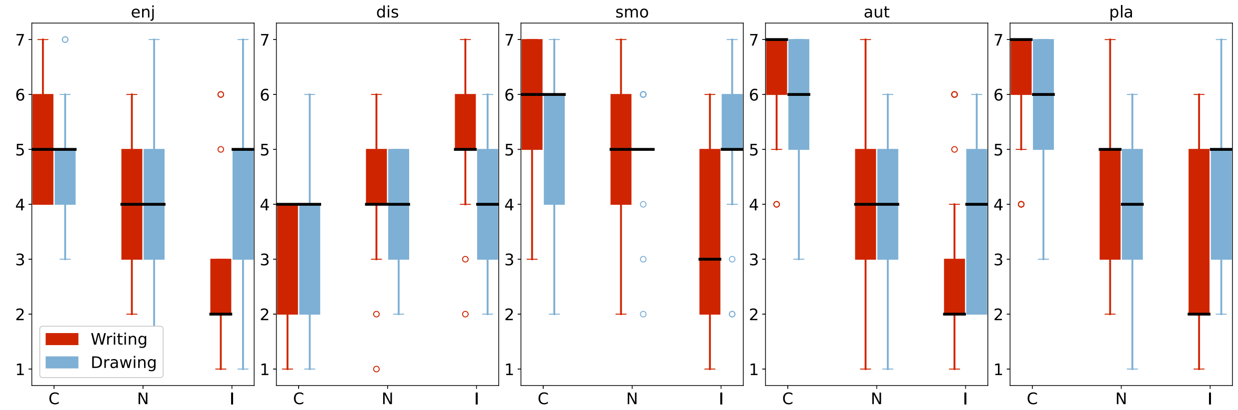


Fig. 5. Results for the basic aspects questioned in the survey (“enj” for enjoyment in pleasure, “dis” for distraction in functionality, “smo” for smoothness, “aut” for authenticity, and “pla” for plausibility). Each graph compares the three conditions (C, clean condition; N, natural mapping; and I, inverted mapping). This figure and the subsequent ones show boxplots with median, interquartile range (as box), minimum and maximum values (as bars), and outliers (as circles).

Table 2. Non-parametric Cohen’s d (effect sizes) comparing conditions of the questionnaire data for drawing (dr) and writing (wr) tasks. Large effects (**d** > **0.8**) have been found for most writing data. Bonferroni-corrected *p* values for Wilcoxon Signed-Rank Test (significant changes found for ***p*** ≤ **0.05**).

Aspect	cd.s	d (dr)	d (wr)	*p* (dr)	*p* (wr)
Enjoyment	C/N	0.67	0.67	0.50	**0.01**
	C/I	0.0	**2.02**	0.44	**0.00**
	N/I	–0.67	**1.35**	1.96	**0.01**
Distraction	C/N	0.0	0.0	0.34	**0.02**
	C/I	0.0	**–0.95**	1.34	**0.00**
	N/I	0.0	–0.67	1.36	**0.00**
Smoothness	C/N	**0.95**	0.67	1.58	**0.01**
	C/I	0.67	**1.28**	1.17	**0.00**
	N/I	0.0	**0.85**	2.27	**0.04**
Authenticity	C/N	**1.35**	**2.86**	**0.01**	**0.00**
	C/I	**1.35**	**4.77**	**0.00**	**0.00**
	N/I	0.00	**1.35**	2.42	**0.01**
Plausibility	C/N	**1.35**	**1.91**	**0.01**	**0.00**
	C/I	0.67	**4.77**	0.11	**0.00**
	N/I	–0.67	**2.02**	0.65	**0.05**

ing tasks. All aspects of the survey data show significant differences for writing when pairwise comparing between conditions C, N, and I (for $p \leq 0.05$). For drawing, on the contrary, only authenticity C/N and C/I and plausibility C/N show significant differences. Effect sizes are given in Table 2 as well. Large effects (d > 0.8) and medium effects (d > 0.4) have been found for all writing data but distraction C/N. For drawing, the significant differences show also large effect sizes.

Concerning the post-hoc questions at the end of the experiment, participants where asked if they usually enjoy writing respective to drawing. Twelve participants assessed writing more enjoyable than drawing, five equal, and four less; therefore, in general, drawing is less enjoyed by most participants.

Table 3. Non-parametric Cohen’s d (effect sizes) and *p* values of Wilcoxon Signed-Rank Tests comparing the conditions in the audio data: standard deviation (std) of the SPL in decibels and the 75% quantile (q75) of the SPL in decibels. Significant changes were found for **p** ≤ **0.05**.

Aspect	cd.s	d (dr)	d (wr)	*p* (dr)	*p* (wr)
std	C/N	–0.76	0.25	0.11	0.07
	C/I	–0.63	0.25	**0.04**	**0.01**
	N/I	0.15	–0.02	0.74	0.59
q75	C/N	**–1.09**	0.28	**0.04**	**0.03**
	C/I	**–0.96**	0.18	**0.01**	0.11
	N/I	0.21	–0.13	0.93	0.88

2.5.2 Results of the Audio Data

Results for the audio data are shown in Fig. 6. The analysis of the audio recordings revealed at least medium effect sizes for drawing when comparing the std measures of condition C to both conditions N and I, as reported in Table 3, while the std for C/N is not significant. Regarding the q75 measure, effect sizes of the same conditions are even larger and all significant (for drawing). In contrast, the comparisons of condition C to conditions N and I yield only small effect sizes in the case of writing for both std and q75.

Comparing drawing and writing pooled across all conditions showed 1.3 dB more q75 for writing with a small effect size of 0.39 ($p < 0.001$) and only less than 0.2 dB more std with a less than small effect size of 0.19 ($p = 0.18$).

3 DISCUSSION

The survey data show larger effects for writing and mostly behave as expected: condition C, the clean signal, in general behaves “best,” i.e., most enjoyed, smooth, authentic and plausible, and least distracting. Furthermore, the natural sonification mapping performs better than the inverted one. Discussing the individual aspects of the survey, the authors may find:

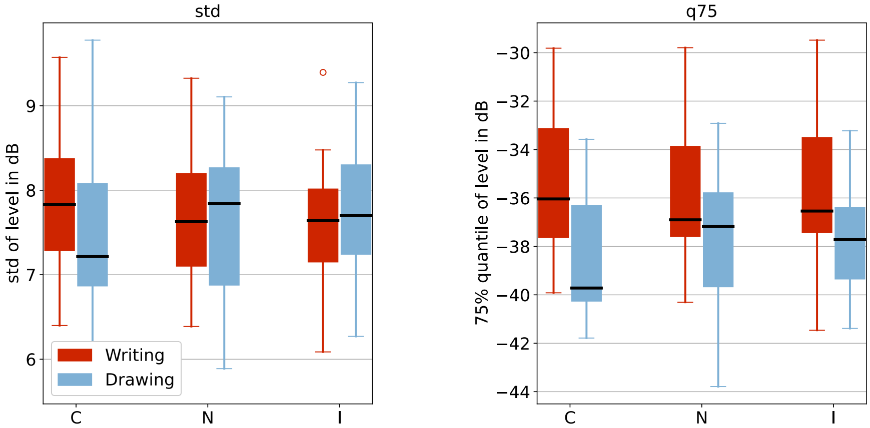


Fig. 6. Standard deviation (std) of the SPL in decibels and the 75% quantile (q75) of the SPL in decibels, for all conditions in writing and drawing tasks.

- Results for enjoyment and distraction look inverted: enjoyed conditions are less distracting and vice versa. The inverted mapping is least enjoyed and most distracting in writing.
- Analyzing the results for smoothness, it may be seen that all interaction sounds were at least partly perceived as smooth, with all medians lying in the upper half of the rating scale. Effects between conditions are less pronounced than for the other dimensions, though still large in writing tasks.
- Authenticity and plausibility behave rather similarly, and, as expected, condition C is rated as highly authentic and plausible. From informal remarks, the authors saw that participants at least sometimes were not sure if any sound was playing in condition C or if there was only the true, physical interaction sound. In writing, even the comparison between natural and inverted conditions show large effect sizes.

The results of the survey data, in general, show major differences between drawing and writing, as mostly writing tasks were found to be differently assessed.

The analysis of the audio data, on the other hand, revealed findings with simple acoustic measures. Participants were influenced to change their dynamics of drawing by the different interaction sounds. Specifically, the signal was louder (i.e., the writing faster or with more pressure) when the sonification was playing (conditions N and I). Also the std showed medium (nearly large) effects for drawing, so there was more fluctuation in these conditions, which can be interpreted as a more dysfluent drawing. Overall, it was found that participants were influenced by the sound when drawing but not when writing.

4 CONCLUSION

Auditory feedback for sonifying handwriting was explored in real time. It was interesting that large effects could be found from simple measures derived from the audio signal of the structure-borne sound, working with a deliberately basic and, therefore, also authentic setup. Three different sound designs were compared: the amplified, authentic interaction sound; a natural sonification design; and an inverted sonification design. The authentic sound was assessed best, with most differences found for writing, and led participants to draw more fluently than under both sonifications. All sounds in the experiment proved to be functional when assuming that this is reflected by the assessed smoothness, which also relates to the std measures found in the audio signal and to fluency identified as central in the work of Danna et al. The sound design of these sonifications was less enjoyed and more distracting than the authentic sound when drawing, although a natural mapping behaves better than the inverted one. After years of research in sonification, this finding is soothing.

In general, the assessment of authenticity vs. plausibility might have caused confusion, even though the authors tried to clarify the terms for the participants and received no informal feedback about possible misconceptions. It was expected that the sonification with natural and inverted mapping would be experienced as equally authentic (but large differences were found) and the interaction would be equally plausible under all conditions (also not the case). For future work, the terms need to be better introduced, possibly by a learning phase that is accompanied with examples of authentic interactions and plausible ones that can be experienced in virtual or augmented reality. Furthermore, it is a limitation of these results that a real “dry” condition, without any sound feedback, was not implemented. The motivation was that the impact of feedback sounds on movement has been thoroughly examined in previous works, while in this research, effects of different sound mappings were looked for.

Overall, it was surprising that the conscious assessment of sounds and the subconscious influence on the movement behave very differently, depending on the task, writing vs. drawing. It can only be speculated why. Writing is a highly trained, fully automatized process that, on the one hand, is more stable against external influences and, on the other hand, requires less cognitive load, so participants remarked more differences when writing. On the contrary, drawing was reported by participants to be less enjoyed than writing; it is assumed that they are also less experienced in drawing, which makes this task more open to influences and leaves less room of cognitive capacity to reflect the sound consciously. There was one comment stating that the sound was more dominating the movement when drawing than when writing. This individual feedback supports the interpretation that more experienced writers are less steerable in their movement, although they seemingly can tell better what they would prefer.

As main outcome of the experiment, evidence was found that the more natural the mapping between movement and sound is, the better. The authentic sound is best, but the natural sonification behaves better than the inverted one. This supports previous studies and the general demand in the sonification community toward natural and ecological mappings. The sonification was based on a simple model of subtractive synthesis in order to maintain highly controlled parameters. The authors believe that it is possible to create a better accepted sonification for handwriting that mimics the authentic sound more truly by a more elaborate sound design, although at the cost of having less controlled parameters. Such a future sound design can be both highly functional and pleasant, providing a more neutral and generally accepted alternative than a musically informed sonification of handwriting. The authors plan to utilize such natural sonification mappings in the context of learning and for auditory augmentation, conveying additional information by augmenting handwriting sound in real time.

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