TOWARDS INTERACTIVE SONIFICATION IN MONITORING OF DYNAMIC PROCESSES

Niklas Rönnberg

Linköping University,
Division for Media and Information Technology
Linköping, Sweden
niklas.ronnberg@liu.se

ABSTRACT

The modern control room is predominantly made up of visual displays, which might make monitoring different processes a cumbersome and visually cognitively demanding task. Sonification could be used to support the monitoring task. However, it is not clear how the most beneficial sonification should be designed. In this pilot study an experimental setup was developed to explore perception of different sonification approaches. A user experiment was performed to assess perception of the sonification when and where simulated data deviated most from the normal level. It was found that all sonification conditions were generally useful, regardless of the participant's musical experience, shown both in terms of objective and subjective measurements. Stereo panning of the sound was also generally experienced as helpful, but the use of different pitch might not have been experienced to contribute as much for solving the task. The findings in this pilot study will be further used to create new research ideas about sonification for monitoring of dynamic processes.

Figure 1: *One example of a modern control room for monitoring of dynamic processes, consisting primarily of displays and visual information. Photo courtesy ABB.*

Figure 2: *One example of a modern remote tower control room, for monitoring and controlling the air traffic at and around an airport, built-up by multiple displays. Photo courtesy LFV.*

1. INTRODUCTION

As the foreman arrived at the power plant, the factory or the ironworks in the morning and entered the factory floor, the sound, the sonic ambience or the soundscape of the work place would tell about the night shift, about machines in need of repair or maintenance, about the overall performance and the general status of the plant. For a closer insight individual meters and indicators could be read. As time changed more and more of the surveillance and monitoring were moved to quiet and air-conditioned control rooms (see examples in Figure 1 and 2). These monitoring environments provide more information and one person can easily monitor multiple dynamic processes simultaneously. As a consequence, not only in process control but in monitoring in general, the amount of visual information has increased while auditory information has decreased. The sonic ambience, the peripheral monitoring through the soundscape, has been lost.

If too much information is presented in the visual modality, there is a risk of cognitive overload (see for example discussions in [1, 2, 3, 4]). The consequences might be that information is neglected and ignored, or completely missed (see, for example, discussions in [5, 6, 7]). Not only that, visualization also presents challenges for the visual perception, such as simultaneous brightness contrast [8]. Simultaneous brightness is when a colored area with a set luminance is perceived as brighter when it is surrounded by darker hues compared with when it is surrounded with brighter hues. Another challenge is the Mach band phenomenon [9], which occurs at boundaries between different hues, and a solid hue is perceived as a gradient where it is brighter at the border to a darker hue and darker at the border to a brighter hue. Such challenges might negatively effect the perception of a visualization, where constructs like density levels or amount in data might be encoded as intensity levels. Perceiving differences in intensity levels could be essential for understanding and interpreting visualization correctly, consequently flaws in the visual perception will affect the perception of visual representations negatively. Therefore, it seems justified to argue that sound should be reintroduced in process control and monitoring of dynamic processes.

The challenges with visualization and cognitive load in the visual modality, could be addressed by the use of sonification. Sonification focuses primarily on turning data into sound and could be considered as a complementary modality to the visual modality [10, 11, 12]. Sonification has the ability to provide additional input and further information [13, 14], and the combining of visual and the auditory modalities should be able to present more effective and efficient multimodal visual representations [15]. Also, by adding sound as an additional modality visual cognitive load can be reduced [16]. Sonification can successfully be used in process control and process monitoring [17]. Auditory icons, caricatures of naturally occurring sounds [18], can be used in multiprocessing and collaborative systems for diagnosing problems, monitoring a set of processes as well as individual processes, and providing a shared reference point for collaboration [19].

For sonification to be useful for data exploration, dynamic human interaction is necessary (see discussion in [20, 21]). Therefore, in a monitoring control situation, interactivity is essential for exploration of historical data and for making comparisons between past and present states possible.

Even though some research suggests that natural real-world sounds might be better in a soundscape for monitoring and control [22, 23, 24], sounds can also be designed deliberately with a music-theoretical and aesthetic approach to create a nice sounding sonic ambience. The aim of such a sonic ambience could be to provide a peripheral awareness of the overall status of one or several processes. The use of musical sounds provides design opportunities that are to some degree lacking in sonification approaches based on arbitrary or natural sounds, including musical qualities such as timbre, harmony and tempo. The reason for using a musical approach is somewhat similar to the sonification approach to Barra et al. 2001 and 2002 [25, 26] who used musical sounds or an aesthetic approach to sounds bordering between music and background noise as compared to simple alarm sounds, reasoning that aesthetically designed sounds might minimize fatigue and annoyance in long-term monitoring. Musical structures and compositions have an ability to convey a multitude of information to listeners quickly and intuitively [27], suggesting that the use of musical sounds should be well suited for sonification for monitoring control systems. Music (and a musical approach to sonification) can convey meaning, information, and emotions (see for example discussions in [28, 27]), and sonification with musical sounds also seems to be able to support visual perception [29].

By using sonification for peripheral monitoring it should be possible to provide a sonic ambience that could indicate changes in one or multiple levels of change from the normal status-quo level of a machine, or an operator, or an entire process. Such a soundscape would then provide status information peripherally, creating an awareness of overall system conditions (see an example in Rönnberg et al. 2016 [30]). The notion of peripheral sonification is not new, but the choice of musical sonification of an overwhelmingly visual task introduces some opportunities to broaden the understanding of the concept of peripheral sonification. For instance, continuous soundscapes could provide a base for new and interesting research questions compared with short repetitive approaches or strictly musical treatments [31, 32].

1.1. Aims and objectives

This project is a pilot study, an exploration and analysis of sonification design options. The aim of this research is to develop an experimental setup for sonification of multi-variate time-varying data for a future monitoring setting. However, it is not clear how to design this sonification for monitoring. Therefore, this pilot study aims to examine the following questions:

1. What musical elements are suitable to be used to sonify data from dynamic processes?
2. Can stereo spatial audio be used to support perception of sonification?

An experimental study with an interactive search task was performed to address these questions.

2. METHOD

To examine the use of musical elements and to assess whether a user could distinguish between different levels within each musical element, an interactive search task was designed. In this experimental setup three positions (left, center, right) were sonified (see a screen-shot of the test interface in Figure 3). For one of these positions the sonification changed over time due to the underlying data. The participant's task was to mark the position for which the sonification changed, and when in time the sonification deviated most from the normal state. This is not a typical monitoring situation, but rather a way to assess whether the different sonification design ideas could be useful for future research.

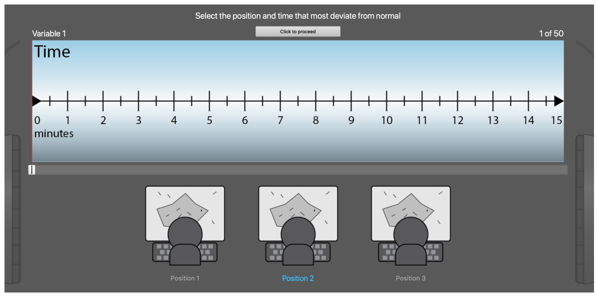

Figure 3: *The user interface used in the experiment. The three positions were selected by clicking on the corresponding icon, the position on the time line was selected by moving the horizontal slider, and the selections were confirmed by clicking on the button (marked "Click to proceed").*

2.1. Simulation of data

The present study uses simulated data, inspired by data that could be obtained in monitoring of dynamic processes. The data was constructed to mimic time-varying continuous data, as well as time-varying discrete data consisting of three levels: 1 - normal levels, 2 - intermediate levels, and 3 - high levels. The continuous data will hereafter be referred to as Data-A, and the discrete data will hereafter be referred to as Data-B. All data was computed using Matlab R_2018b. The data in Data-A could be seen as representative of heart rate, temperature, or stress levels, while data in Data-B could be representative of number of incursions, level of warnings, or severity of conditions.

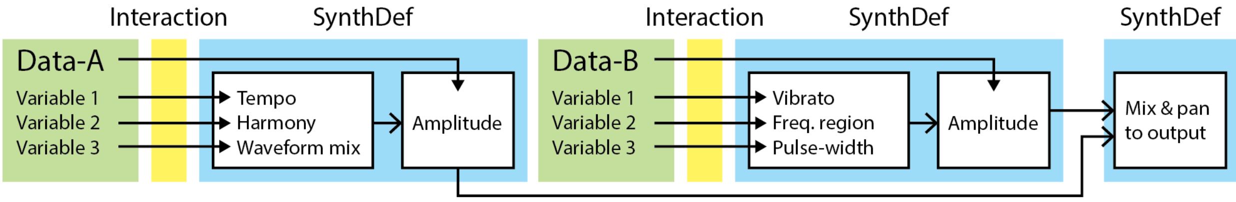

Figure 4: *A model of the sonification implemented in SuperCollider. Showing variables (in green), interaction (in yellow), and synth definitions (in blue).*

2.2. Implementation

The experiment was implemented in SuperCollider 3.10 [33, 34], which is a real-time audio synthesis programming environment. Interaction was implemented using a computer mouse, the participant moved a time bar and the sonification was changed according to the underlying (and invisible to the participant) data (see Figures 3 and 4)). For exploring a sonification of a set of data a static auditory display/graph is not enough, but for a user to be able to compare different positions (left, center, right), interaction is necessary (see further discussions on sonification and interaction in [20, 21]). A questionnaire, printed on paper, was administered to the participants for recording of subjective data.

A short video demonstration can be found here:
https://vimeo.com/353209351

SuperCollider was run on a MacBook Pro computer, presenting the user interface on a 21” computer screen and sound through a Universal Audio Apollo X8 sound interface and a pair of AKG K271 MKII headphones. The headphones provided an auditory stimulation of approximately 65 dB SPL. All experiments were conducted in a quiet office. Even if some ambient sounds was present in the background, the experimental environment was deemed quiet enough not to affect the outcome of the experiments.

2.3. Design of the sonification

The sonification was designed to allow the exploration of different musical elements such as sound level, tempo, harmony, timbre by wave form mix, vibrato, frequency region of pink noise, and timbre by variation of pulse-width. Three positions (left, center, right) were used in the experimental setup. These positions could reflect three operators or three machines being monitored. Each position was sonified using one tone each for Data-A, as well as two additional tones each for Data-B. These tones were C, E, G, and thus formed a major C chord [35] (see Table 1).

Table 1: The tones used for the three positions, and for the different types of data, displaying the corresponding note on a piano keyboard, the MIDI note number, and the frequency in Hz.

Position	Type of data	Note	MIDI	Frequency (Hz)
Position 1 (left)	Data-A Data-B	C4 C3, E3	60 48, 52	261.63 130.81, 164.81
Position 2 (center)	Data-A Data-B	E4 E3, G3	64 52, 55	329.63 164.81, 196.00
Position 3 (right)	Data-A Data-B	G4 G3, C4	67 55, 60	392.00 196.00, 261.63

2.4. Musical elements and mapping to data

The sonification was designed to provide information about individual variables, but still work in combination where multiple variables varied simultaneously. The sonifications of Data-A always used the same basic sound, built up by triangle waves, in different pitch for each individual position (left, center, right). The data in Data-A was mapped to clearly distinguishable levels with some variability within each level. This created almost discrete levels in the data (normal levels, intermediate levels, and high levels), somewhat similar to the discrete data in Data-B. For Data-B, the sonification of two variables used the tones, built up by square waves, creating the basic underlying musical sonification (see Table 1). One variable used pink noise. The sonification parameters were designed to be able to both function alone as well as in combination (see Table 2 and Figure 4).

Table 2: Sonification settings for the different simulated data types in the three different levels.

Simulated data	Level 1 - normal	Level 2 - intermediate	Level 3 - high
Data-A	normal sound level	increased sound level	more increased sound level
Variable 1 *Tempo*	60 bpm, 30% sound level of beat	110 bpm, 50% sound level of beat	170 bpm, 80% sound level of beat
Variable 2 *Harmony*	1.5 cent, harmonic, not much beating of frequencies	26 cents, a bit disharmonic, some beating of frequencies	50 cents, disharmonic, beating of frequencies
Variable 3 *Waveform mix*	100% triangle, 0% sawtooth waves	60% triangle, 40% sawtooth waves	10% triangle, 90% sawtooth waves
Data-B	normal sound level, somewhat attenuated high frequencies	increased sound level, more high frequency content	even more increased sound level, most high frequencies
Variable 1 *Vibrato*	no perceivable vibrato	increased vibrato depth	most noticeable vibrato
Variable 2 *Frequency region*	pink noise, 10% output level, BPF cutoff freq. 500 Hz	pink noise, 55% output level, BPF cutoff freq. 1000 Hz	pink noise, 100% output level, BPF cutoff freq. 1500 Hz
Variable 3 *Pulse-width*	50% pulse-width	70% pulse-width	90% pulse-width

Sound level was used in connection with other musical elements for all variables in Data-A. The data level (normal, intermediate, high) in each variable were mapped linearly to exponentially to the amplitude. Thus, as the data increased in level, the amplitude of that specific sonification condition increased as well. A louder sound level might give rise to a higher activity in the listener compared to a lower sound level [36, 37] why sound level should be useful in sonification. No amplitude normalization for different frequencies was performed.

Tempo was used to sonify the first variable in Data-A. The sonification for all three positions had a basic beat tempo 60 beats per minute (bpm), where an envelope generator was re-triggered for every beat. The tempo of this beat changed in one position according to the data, and was at the intermediate level 110 bpm, and 170 bpm at the highest level. The beat was mixed together with a steady tone to create a continuous signal with a periodic rhythmic pulse. The intensity of the envelope generator increased from 30% sound level in low, to 50% sound level in intermediate, to 80% sound level in high. Consequently, as the data level increased, the tempo of the beat also increased in speed and became more prominent. A faster tempo gives a stronger arousal when listening to music [38] or to sonification, consequently, a faster tempo should suggest an increased level of urgency.

Harmony was used to sonify the second variable in Data-A. Each tone used for Data-A for each position consisted of 5 tones, one at the fundamental frequency and two tones somewhat below respectively above the fundamental frequency. The distance from the fundamental frequency of these harmonics ranged from 1.5 cent at the lowest levels of in the data to 50 cents at the highest levels. Cent is a logarithmic unit, where the interval between each semitone is divided into 100 cent [39]. As harmonic components are further apart in relation to the fundamental frequency the interference between these frequencies creates a beating [40] which is equal to the difference in frequency of the notes that interfere [41, 42]. Thus, as data level increased in one position, the amount of dissonance also increased for that specific position, and the beating created of these frequencies increased.

Waveform mix, i.e. timbre, was used to sonify the third variable in Data-A. Timbre might be described as the ”color” of the sound, the tone quality, formed by the different sounds and their inherent characteristics. A softer and more dull timbre might be experienced as more negative compared to brighter timbre [37], and a more complex timbre might be more captivating evoking greater (emotional) responses compared to a simpler timbre [36]. The tones used at each position for Data-A was built up with triangle waves. Triangle waves consists of odd harmonics with quite steep roll off [43] why the triangle wave is perceived as quite soft, a bit round, and without too much high frequency content. As the level in the data increased, sawtooth waves were mixed together with the triangle waves. Sawtooth waves have both even and odd harmonics why the sawtooth is much richer of high frequency components [43] and might therefore be perceived as harsher and sharper. Consequently, as the data level increased, the amount of high frequency content in the sonification increased as well, creating a more distinct and piercing sound.

Sound level and cutoff frequency of a low pass filter (LPF) was used in connection with other musical elements for all variables in Data-B. Similar as for Data-A, the data level (normal, intermediate, high) was mapped linearly to exponentially to the amplitude of the sonification. The cutoff frequency was mapped to be between about 250 to 1200 Hz depending on the level in Data-B as well as the fundamental note used in the sonification. Consequently, as the level in the data increased, the sonification for that data increased in sound level as well as in high frequency content.

Vibrato was used to sonify the first variable in Data-B. Two tones were used together for sonifying the variables in Data-B. The data in the first variable in Data-B was linearly mapped to vibrato depth of the two tones, from not perceivable vibrato at the lowest data level to a vibrato that was +/- a quarter tone of the fundamental frequency. The vibrato speed was set to 4 Hz creating a quite nice sounding vibrato giving a noticeable vibrato effect and, as the data level increased the depth or intensity of the vibrato increased.

Frequency region of pink noise was used to sonify the second variable in Data-B. The pink noise passed through a band-pass filter (BPF). The data level was linearly mapped to the cutoff frequency of the BPF, between 500 (for the low level) to 1500 Hz (for the highest level). The data level was also linearly mapped to the output level of the filter from almost completely attenuated noise at the low level (10% of the output level) to full sound at the highest level. Therefore, as the level in the data increased for one position, the pink noise also increased in sound level and in more high frequency content for that specific position.

Pulse-width variation, i.e. timbre, was used to sonify the third variable in Data-B. The data level was linearly mapped to the pulse-width of the square waves, where the normal level was mapped to 50% pulse-width, intermediate level to 70%, and high to 90% pulse-width. As the pulse-width increases (or decreases) from 50% the amount of harmonics increases [43]. As the harmonics increases the timbre of the sound changes to become richer and more complex. Consequently, as data level increased, the sound quality of the sonification became richer in harmonics and more salient for that position compared to the normal level in the data.

2.5. Panning and sonification level

To explore if stereo panning (left, center, right) could support perception of the sonification, the sonification was used in stereo. The stereophonic sound image always placed position 1 to the left relative the other positions, position 2 in the center, and position 3 to the right (see Figure 5. When a position was selected this position was panned to the center in the stereophonic sound image, and the other positions moved correspondingly. The experienced loudness of a stereo sound is dependent on the panning, and consequently sounds were attenuated appropriately to maintain a good perception of all sounds (see Table 3). The user selected the desired position by clicking on the corresponding operator image, the stereo panning and attenuation was instantly performed and the position of the operator images was also moved accordingly.

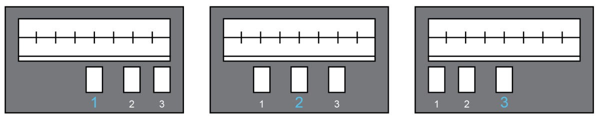

Figure 5: *The panning was positioning the selected position to the center of the stereophonic sound image. Left: position 1 is selected. Middle: position 2 is selected. Right: position 3 is selected.*

Table 3: The panning and attenuation settings for all selected positions.

Selected position	Setting	Position 1	Position 2	Position 3
Position 1 (left)	Panning Level	0 0.707	0.65 0.84	1 1
Position 2 (center)	Panning Level	-0.65 0.84	0 0.707	0.65 0.84
Position 3 (right)	Panning Level	-1 1	-0.65 0.84	0 0.707

2.6. Participants

For the present pilot study, 15 participants were recruited, (8 female) with a median age of 30 (range 23 to 52) with normal, or corrected to normal, vision and self-reported normal hearing. No compensation for participating in the study was provided.

2.7. Experimental procedure and questionnaire

Each test session was initiated by the participant giving a subjective rating of their musical experience, by answering two questions using a 5-point Likert scale. These questions asked whether the participant listens to music from 1 (Not very often) to 5 (All the time), and whether the participant 1 never sang or played an instrument to 5 is playing or singing regularly.

Each sonification condition as well as the user interface was then introduced to the participant for familiarization. The participants task was to mark, using the computer mouse, where on the timeline the sonification changed the most compared to the normal level (which was present in the beginning of the time line), and for which position (left, center, right) this change was connected to (see Figure 3). After the introduction followed either one of the three sonification conditions connected to Data-A or Data-B. The order of these was balanced between participants to avoid order effects. The position that was affected by the increased levels in the data was randomized but overall balanced within each experiment.

After each sonification condition the participant answered two questions in a questionnaire about their subjective experience of the sonification. These questions concerned the experienced difficulty level in finding the position that had a sonification suggesting a deviation from the normal level, as well as the difficulty in finding the time where the sonification differed as most from the normal level. Answer alternatives ranged from 1 (very hard) to 5 (very easy). In total 50 sonification conditions were used in the experiment. After the test the participant answered some final questions in the questionnaire considering to what extent the stereo panning supported in providing answers, as well as to what extent the different tones contributed to providing the answers. Possible answer alternatives ranged from 1 (very little) to 5 (very much).

The experiment yielded subjective accuracy data for how well the participant managed to mark the time and position where the sonification most deviated from the normal, as well as subjective ratings of experience of the sonification.

3. RESULTS

According to Kolmogorov–Smirnov tests the data was not normal distributed, thus non-parametric tests were used. Bonferroni correction for multiple comparisons was applied as appropriate.

Accuracy was measured in terms of the percentage of correct responses given for that sonification condition. Generally the accuracy was high for all six sonification conditions, with a mean accuracy of over 65% in all conditions (see Figure 6). A Friedman test showed no significant differences in accuracy between the six conditions (*tempo, harmony, waveform-mix, vibrato, frequency region, pulse-width*), $\chi^2(5) = 6.81, p = 0.235$. There were no effects of age, gender, or musical experience. However, considering the low number of participants in the present pilot study, studying mean values and 95% confidence intervals might suggest trends in the data. Consequently the accuracy for *harmony* as well as *vibrato* might be less compared to the other sonification conditions.

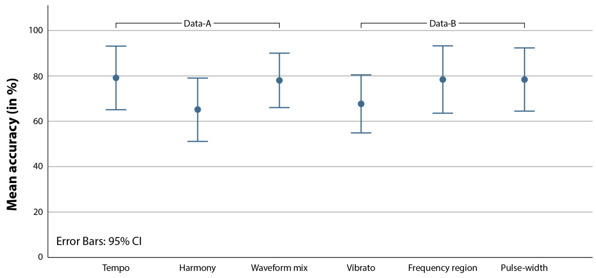

Figure 6: *Error bar graph showing mean accuracy and 95% confidence intervals for the six sonification conditions.*

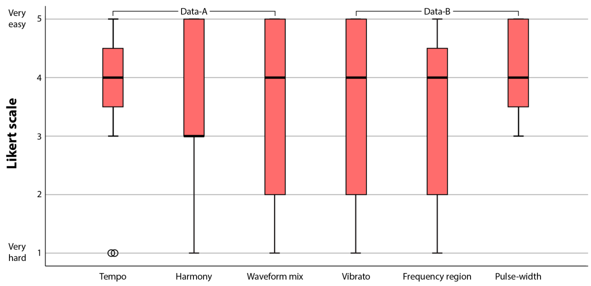

Figure 7: *Box plot showing subjective ratings of experienced difficulty for selecting the correct position.*

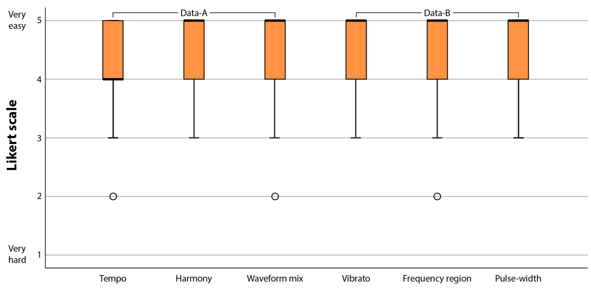

Figure 8: *Box plot showing subjective ratings of experienced difficulty for finding the correct time.*

For subjective measurements, i.e. the difficulty in finding the correct position (left, center, right), and the difficulty in finding the time that most deviated from the normal level, there were no significant differences between sonification conditions (see Figure 7 and Figure 8). Generally, the participants experienced distinguishing between the three positions as fairly easy, and finding the time that most differentiated from the normal level as easy. When comparing the ratings between the position and the time, then maybe finding the time was experienced as somewhat easier than finding the right position (see average rankings in Figure 9). Also, in general the stereo panning was experienced as helpful in as well as the different pitch used for the three positions (see Figure 9).

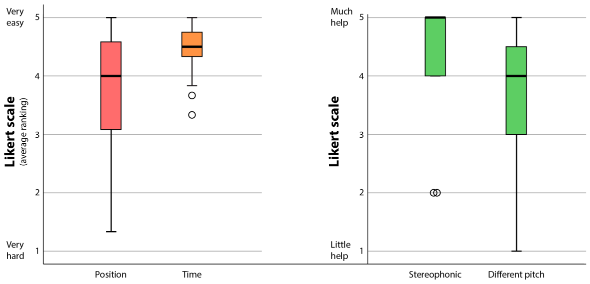

Figure 9: *Box plot showing subjective ratings of difficulty in solving the task (left), and ratings of experienced help (right).*

4. DISCUSSION

It is important to remember that the present pilot study evaluated different sonification design approaches for future studies in sonification for monitoring, but used an interactive search task to assess the perception of the musical elements used to sonify changes in the data. The amount of interaction and the available time for exploring data in a typical monitoring situation is most likely limited compared the present pilot study. The case might be that the operator that monitors a dynamic process has no possibility to interact with the monitored data, but rather needs to attend to changes in the sonification solemnly. The focus of the present study was the use and perception of different musical elements, and therefore the interactive search task was used to assess the sonification. The mean accuracy for finding the highest level in the sonification, was high in all sonification conditions, and the lack of statistically significant differences in accuracy between conditions suggests that all sonification conditions provided enough information for the participants to solve the tasks in the experiment. This result was also supported by the subjective rankings.

The measured accuracy was overall high, which might suggest that the task in the experimental setup was simple, maybe too simple. As the experiment aimed to assess whether the levels in the data was perceivable in the sonification or not, the high accuracy was interpreted as something promising for the sonification approaches. However, response time was not recorded why it is not possible to determine whether all sonification conditions had similar response time or not. It is possible that the same level of accuracy was achieved but with considerably longer response times for some conditions. A future experimental setup where the participants are asked to provide as swift answers as possible, or where there is a time constraint, might reveal differences between the sonification conditions not discernible in the present pilot study.

The number of participants in the present pilot study was low, and consequently the results, and the interpretation of the results, must be considered with this in mind. Despite this, the results give nevertheless some valuable insights for further studies. **Firstly**, *harmony* did not seem to support the participants as much as the other sonification conditions. Maybe the effect of harmony is a more challenging sonification condition, which might put higher demands on the musical experience of the user, even if there were no effects of this found in the present study. This could be due to the low number of participants. Nevertheless, the effect of dissonance could be increased by increasing the range of the mapping in the sonification, and thus create an effect that is more pronounced and noticeable. **Secondly**, there might be a tendency to an effect of *vibrato* with slightly less good accuracy for some participants compared to the other sonification conditions (apart from *harmony*). Also this could be explained by the low number of participants. Nevertheless, in this sonification condition the vibrato depth was altered in relation to the data but the speed of the vibrato, the vibrato frequency, was fixed. It might be hard for the participants to distinguish and perceive the vibrato depth, the amount of vibrato, as implemented in the present study, why an even stronger vibrato could be used in a future study. The vibrato depth could also be mapped to the data together with vibrato speed to create a sonification that might be easier to perceive. **Thirdly**, *tempo* could also be further evolved. The mapping was performed as 60 bpm to 110 bpm to 170 bpm for this highest level, but a mapping such as 60 bpm to 130 bpm to 220 bpm (or similar) could provide more clear and distinguishable steps that would support the users more. **Fourthly**, all three sonification conditions using different methods to alter the *timbre* seemed to provide clear sonification cues for the users, why timbre or the quality of the sounds used in sonification seem important to keep in mind while designing future sonifications. **Fifthly**, there was not an effect of musical experience found for accuracy or subjective ratings for any of the sonification conditions. This is something positive as this suggests that the sonification is useful regardless of musical experience. In a real-life setting, an operator or controller can not be expected to have a music degree to be able to monitor a system and ongoing processes. **Sixthly**, even if the accuracy was overall high, it was not 100%. If sonification would be used in a monitoring setting somewhat similar to the experiment in the present study, the sonification would be present in a context with detailed visual information available as well. The sonification would then be able to provide peripheral sonic information about states in a system, providing cues about changes and developments, while the visual information would provide in-depth information for the user if needed. Furthermore, in such a setting the amount of training on the system would be substantially greater than the introduction and training trials used in the present study.

The sonification conditions used in the present pilot study, were designed to be able to function in combinations. Such combinations could either be two or three sonification conditions mapped to the same data, creating an even stronger sonic cue about the conditions in the data, or used simultaneously to sonify different data providing even more information to a user. However, this was not evaluated in the present study.

The stereo panning was experienced as supportive in finding the position (left, center, right) where the data deviated from the normal level. Positions are consequently of help for separating the sonification and position that deviated from the normal. In the present study the sound level of the stereo panned sounds were compensated to be at the same sound level in the stereophonic sound (see Table 3). This compensation could be omitted making the center sound the loudest, thus making the sound in focus for the user more pronounced and perceivable. The stereo width could also be extended, moving the positions not in focus further away from the center position.

The data were sonified differently for the three different positions, by using tones in different pitch. It would be a near impossible task to determine which position at which point in time that deviates from the normal level without using different pitch. However, in the present study there was an overlap in pitch between positions, consequently the range in pitch could be extended which might further support the distinction between positions. As a possible consequence, the use of different pitch did not seem to be experienced as that useful for the participants.

The sonification used in the present study was not normalized in audibility. The three positions in different pitch were not normalized in relation to each other, while some degree of masking might have occurred. Consequently, this might have made the perception of the changes in the higher pitch somewhat harder to discern as these frequencies to some degree might have been masked by a lower pitch. The perception of the variations in the different musical elements caused by the sonification of the data, were also not normalized, which night have made some of the sonification conditions easier to perceive than others. This is something that must be taken into account in future stages of research, but also when analysing the results in the present study. Despite this, the results found in the present pilot study gives promising suggestions on musical elements to be used in further stages of investigations of sonification for monitoring of dynamic processes.

5. CONCLUSION

The present pilot study investigated the use of different musical elements in sonification of simulated data using an interactive search task. This pilot work has provided a good foundation towards sonification in monitoring of dynamic processes.

The results suggest that all sonification conditions used in the experiment provided enough information for the participants, regardless of musical experience, to solve the experimental task. Even if there were no statistically significant differences between sonification conditions, when studying mean performance and 95% confidence intervals *harmony* and *vibrato* seemed to be less good in providing information to the participants. The changes in sonification conditions were also, in general, rated as easy to perceive and supported in finding both the position (left, center, right) and the time point that deviated most from the normal level.

6. FUTURE WORK

The pilot work done in the present study has provided interesting ideas for future work to further explore the use of sonification for monitoring of dynamic processes. Future research could:

- assess if there is differences in performance between sonification conditions by measuring and analysing response time.
- further explore the use of musical elements and combinations of musical elements in sonification for monitoring.
- evolve and expand the use of stereophonic/spatial sound for sonification in relation to monitoring.
- investigate simultaneous use of different musical elements to sonify different data for different positions, and not only changes in data for one position at a time. This type of inquiry would answer if it is possible to discern changes in different or the same data variable for different positions, the sonification would then both provide an overview of the entire system as well as providing detailed information of the different positions.
- deploy sonification of real data sets in real and streaming monitoring situations with domain experts to further understand the usefulness, the support and benefit, of sonification in a real-life setting/environment, for example process control in industrial manufacturing, air traffic control, or monitoring of steam and gas turbines.

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