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Musical sonification supports visual discrimination of color intensity

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ABSTRACT

Visual representations of data introduce several possible challenges for the human visual perception system in perceiving brightness levels. Overcoming these challenges might be simplified by adding sound to the representation. This is called sonification. As sonification provides additional information to the visual information, sonification could be useful in supporting the visual perception. In the present study, usefulness (in terms of accuracy and response time) of sonification was investigated with an interactive sonification test. In the test, participants were asked to identify the highest brightness level in a monochrome visual representation. The task was performed in four conditions, one with no sonification and three with different sonification settings. The results show that sonification is useful, as measured by higher task accuracy, and that the participant's musicality facilitates the use of sonification with better performance when sonification was used. The results were also supported by subjective measurements, where participants reported an experienced benefit of sonification.

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Interactive sonification; musical elements; multimodality; visual perception; visualisation

1. Introduction

Visualisation is a common way to present research data and share research results with other researchers, as well as with the public. It offers a way to communicate complex relations in a single glance and is convenient for data exploration. The primary goal of visual data exploration is to support a user in formulating questions or hypotheses about the data. These hypotheses may be useful for further stages of the data exploration process, such as cluster detection, important feature detection, or pattern and rule detection (Simoff, Bohlen, and Mazeika 2008). Seeing data visually also aids idea generation, shows the shape of the data, possibly reveals correlations between variables, and is a useful first step in the analysis process (Simoff, Bohlen, and Mazeika 2008), but only if the visual perception manages to convey the information needed. Because, as complexity in the visual representation increases, interpretation becomes more problematic and challenging. Apart from the sheer amount of data on the visual display that might present a considerable difficulty for an user, there are also challenges for the visual perception that can impair comprehension of the visual representation.

In order to facilitate visual analysis of large data sets and to reduce visual clutter in the representation, it is common to use transparency renderings based on data density (see for example Artero, deOliveira, and Levkowitz 2004; Ellis and Dix 2007). This is typically achieved by rendering semi-transparent objects and additively blending them together (see an example of a parallel coordinates plot with transparency rendering of density in Figure 1). This method can reveal structures and relationships in data that otherwise would have been missed. However, using transparency renderings for density information might be challenging for the perception, for example when perceiving simultaneous brightness contrast (Ware 2013) and when distinguishing between brightness levels. Thus, these renderings make it difficult to observe actual numbers of blended objects for different areas in the density representation, as well as making it hard to find areas of similar density or find areas of highest density.

The challenges, such as distinguishing between brightness levels, related to the inherent functions of visual perception can never be overcome by visualisation alone. However, they could be addressed by adding sound as a complementary modality to the visual representation. The combination of the visual and the aural modalities should make it possible to design more effective multimodal visual representations, as compared to when using visual stimuli alone (Rosli and Cabrera 2015).

Sonification, the transformation of data into sound, can be used to supplement the visual modality when a user studies a visualisation of data to further support understanding of the visual representation (Kramer et al. 2010; Hermann, Hunt, and Neuhoff 2011; Pinch

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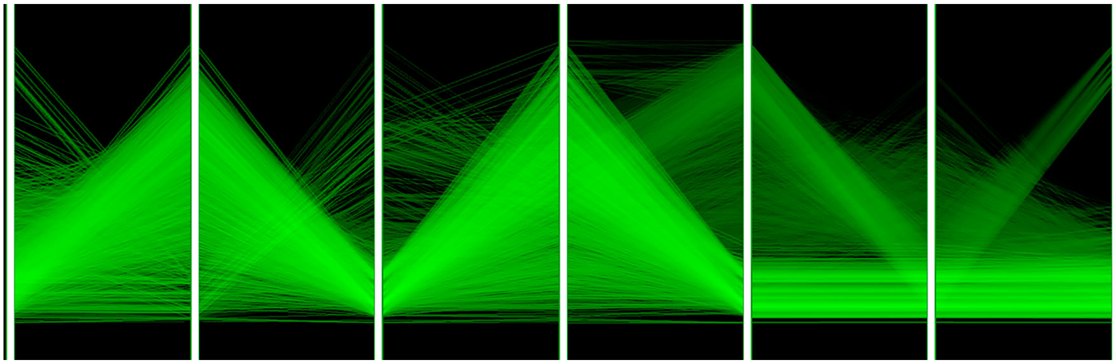

Figure 1. An example of a parallel coordinates plot where transparency rendering is based on the data density is used. (Illustration courtesy by Jimmy Johansson.)

and Bijsterveld 2012; Franinovic and Serafin 2013). Traditionally, sonification is audification of data, where data might be converted to a sound-wave or translated into frequencies (Hermann, Hunt, and Neuhoff 2011; Pinch and Bijsterveld 2012). However, it could be questioned to what extent this type of sonification is able to convey information and meaning to a user. Going beyond plain audification of data (Philipsen and Kjaergaard 2018), sonification can be approached by deliberately designing and composing musical sounds. Even though the concept of sonification for data exploration is not new (see for example Flowers, Buhman, and Turnage 2005), there are few examples of studies that evaluate visualisation and sonification as a combination (see for example Flowers, Buhman, and Turnage 1997; Nesbitt and Barrass 2002; Kasakevich et al. 2007; Riedenklau, Hermann, and Ritter 2010; Rau et al. 2015). These studies suggest that there is a benefit of sonification in connection to visualisation; however, few studies explored the appreciation of the sounds in the sonification or the use of musical sounds. Musical sounds are here referred to as deliberately designed and composed sounds, based on a music-theoretical and aesthetic approach.

Sonification using musical sounds is interesting as the use of musical elements give good control over the design of the sounds and enables the deployment of potentially useful musical components such as *timbre, harmonics, melody, rhythm, tempo,* and *amplitude* (Seashore 1967; Deliege and Sloboda 1997; Juslin and Laukka 2004; Levitin 2006). Previous studies have shown promising results for the concept of musical sonification (Ronnberg and Johansson 2016; Ronnberg, Lundberg, and Lowgren 2016; Ronnberg et al. 2016; Ronnberg 2017, 2019). As musical sounds are well adapted, at least on a more general level, to conveying meaning, information, and emotions (see for example discussions in Tsuchiya, Freeman, and Lerner 2006; Ronnberg and Lowgren 2016), musical sonification should be a fruitful approach to multimodal information visualisation. However, despite various research (see examples in Kramer et al. 2010 and in Hermann, Hunt, and Neuhoff 2011) it is not clear which musical elements, or combinations of musical elements, are most suitable to use in sonification.

1.1. Aims and objectives

The aim of the current study is to *investigate the benefit of sonification* using composed and deliberately designed musical sounds compared to no sonification in the context of information visualisation, to *evaluate the usefulness* (i.e. performance in terms of accuracy and response time) of the sonification, and finally to *explore a possible effect of the user's musicality* on the benefit of sonification. Musical elements used are: (1) a combination of Timbre and amplitude, (2) Pitch, and (3) Harmony. These sounds are used to interactively sonify intensity levels in visual representations containing gradients to mimic a visualisation of data.

2. Method

To explore the usefulness of sonification, and different musical elements in the sonification, an interactive test using musical sonification was devised to investigate: (1) which of three conditions with sonification would be most effective in combination with the visual representations, and (2) to what extent self-assessed musicality would affect the usefulness of the sonification conditions.

2.1. Creation of the visual representations

The visual representations (see examples in Figure 2 and in Figure 3) were designed to mimic cutouts of a complex visualisation of data such as transparency renderings based on data density (as illustrated in Figure 1), and challenge the visual perception. Similar representations can be

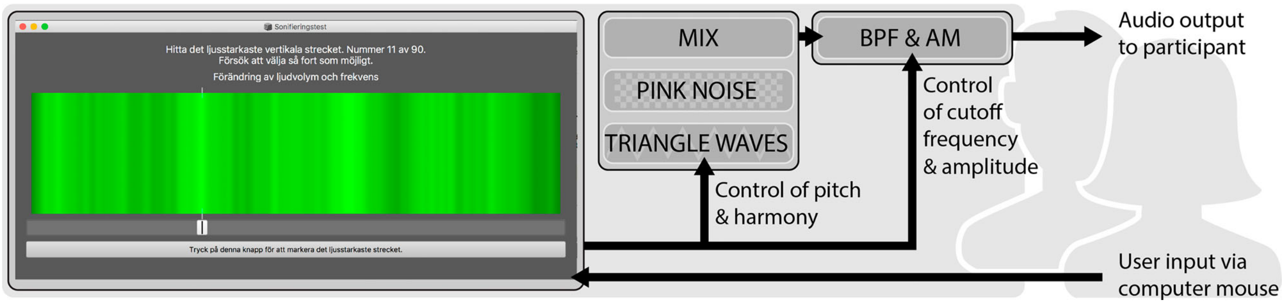

Figure 2. The structure of the experimental setup. The sound consisted of triangle waves and noise mixed together. Pitch, Harmony, and Timbre were adjusted according to the visual representation before the sound was output to the participant.

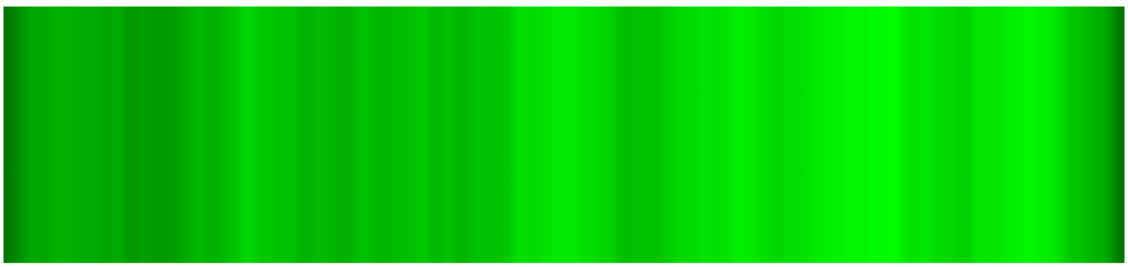

Figure 3. One example of the visual representations used in the test setup, showing the complexity of the grating. The grey scale intensity map were linearly transformed to the green RGB colour channel.

found in a variety of research disciplines, ranging from static social science data, via medical or climate change data, to temporal air traffic control data. As the perceptual challenges arise due to shortcomings in the perception of brightness levels (Ware 2013), it can be assumed that similar difficulties will be present in a visualisation with gradient bands. The visual representations were created in Matlab (R2016a) using a sine wave grating. This was done by mixing sinusoids in different frequencies, with an addition of low-level random ripples. A triangle wave was then multiplied with the combined wave form to create a peak level for the highest intensity level. Ten different output wave forms were created in this way by circularly shifting the elements in the array containing the sinusoids, by the randomness of the ripples, as well as by varying the slope and magnitude of the triangle wave. As the parameters were changed within sets of ten wave forms, the difficulty level was balanced within a set of ten images. A total of 90 images were then created. The wave form was scaled to 8-bit integers, and the values of this grey scale intensity map were linearly transformed to pixel values in the green RGB channel and saved as 24-bit RGB images in PNG format, ranging from no intensity (black) to full intensity (pure green).

The green colour channel was chosen over red or blue as the human visual perception is more sensible to contrasts in the green colour since green has higher perceived brightness than red or blue of equal power (Smith and Guild 1931; CIE 1932). There are other colour models better adapted to the human visual perception than RGB, however, the use of the RGB colour model is motivated since the visual representations used in the present study are monochromatic and intensity levels, rather than hue or saturation, are mapped to the sonification.

2.2. Design of the sonification

SuperCollider (3.8.0) was used to create the interactive sonification. SuperCollider is an environment and programming language for real-time audio synthesis (McCartney 1996, 2002). In SuperCollider a synth definition was created consisting of seven triangle waves (see Figure 2), somewhat detuned around the fundamental frequency (−6, −4, −2, +2, +4, and +6 cents). The sonification was then built up by eleven tones, creating a C-major chord (ranging from C2 to C8, i.e. 65.41 Hz to 4186.01 Hz). This chord was mixed with pink noise at a low sound level to create a rich harmonic content (i.e. the timbre of the sound), yet with a pleasant harmonic content (similar to the musical sound used in Ronnberg 2019). A demonstration can be found here: https://vimeo.com/261447212

2.3. Mapping between musical and visual elements

The mapping between musical and visual elements was designed to provide three different conditions with sonification (Timbre, Pitch, and Harmony, see Figure 2

Table 1. The mapping between the sonification and the visual representation for the three sonification conditions.

Sonification condition	Low brightness	High brightness
Timbre	Attenuated, more bass	Louder, more treble
Pitch	Low pitched tone	High pitched tone
Harmony	Much dissonance	Perfect harmony

and Table 1) as well as a condition with no sonification. The values of the grey scale map created in Matlab were transformed to different parameters in the interactive sonification.

The first sonification setting changed the cutoff frequency of a band-pass filter and the amplitude of the sound (hereafter referred to as *Timbre*). A soft or dull timbre is experienced as more negative compared to a brighter timbre (Juslin and Laukka 2004). A more complex timbre is more captivating with a greater (emotional) response as a result compared to a simpler timbre, and a louder sound is more activating and engaging compared to a less loud sound (Iakovides et al. 2004) and perception of loudness is also mapped to brightness via amplitude (Pridmore 1992). In this condition, the sound passed through a second order band-pass filter. The cutoff frequency was mapped via a linear to exponential conversion where the lowest intensity level generated a cutoff frequency of 100 Hz while the highest intensity levels yielded a cutoff frequency of 6000 Hz. The mapping between intensity levels in the visual representation and the sonification was done linearly to exponentially and consequently the sonification provided a higher level of information where the participant needed it the most to be able to provide an accurate answer. The choice of linear to exponential mapping is motivated by the fact that the human perception of amplitude as well as frequency is nonlinear Everest and Pohlmann (2015). After the band-pass filter, the sound was mapped via a linear to exponential conversion, where the amplitude level was almost completely attenuated for the lowest intensity level, while there was no attenuation for the highest intensity levels. Both these musical elements, frequency content of the overtones and amplitude, should provide potential sonic cues to help solve the task in the test setup.

In the second sonification condition, the pitch of the sonification was mapped to the intensity level (hereafter referred to as *Pitch*). An ascending pitch is generally perceived as more positive while a descending pitch is perceived as more negative (Juslin and Laukka 2004), which might correspond to the perception of brighter and darker areas in the visual representation (see for example discussions in Bresin 2005; Palmer, Langlois, and Schloss 2016; Best 2017). Furthermore, higher pitched tones are associated with lighter, brighter colours (Marks 1987; Collier and Hubbard 2004; Ward, Huckstep, and Tsakanikos 2006). The mapping between the intensity level in the visual representation and the pitch of the sonification was done linearly to exponentially for the same reason as for the Timbre condition. At the darkest region in the visual representation, the pitch of the sonification was two octaves below the area with the highest intensity level. Consequently, this sonification condition should also be able to provide useful sonic cues for the test task.

The third sonification condition used dissonance of the harmonic content of each tone in the sonification (hereafter referred to as *Harmony*). A more complex harmonic sound is more captivating for a listener compared to a simpler harmonic sound (Iakovides et al. 2004), and dissonant chords are experienced as more unpleasant compared to harmonious major or minor chords (Pallesen et al. 2005). In this sonification condition, the triangle waves creating each tone varied from seven tones in unison (perfect pitch) in the area with the highest intensity level to almost a halftone below and above the fundamental tone (−96, −64, −32, 0, +32, +64, +96 cents) in the lowest intensity area. For the Harmony condition the mapping was done linearly. As the harmonic components are further apart in frequency in relation to the fundamental frequency (as is the case in the darker areas in the visual representation) the interference between frequencies creates a beating (Winckel 1967). The beat frequency is equal to the difference in frequency of the notes that interfere (Roberts 2016). Perception of the two tones ranges from pleasant beating (when there is a small frequency difference) to roughness (when the difference grows larger) and eventually separation into two tones (when the frequency difference increases even more) (Sethares 2005). As a consequence, the beating decreases in tempo as the harmonic components come closer in frequency, and at the brightest vertical pixel column the beating stops and all harmonic components lock to the fundamental frequency. The physical behaviour of the frequencies involved creates a clear sonification clue that makes even small differences in harmonic content rather easily detectable. Consequently, the harmonic complexity of the sonification should provide sonic cues for the participants to solve the tasks in the test.

2.4. Participants

For the present study, 25 students at Linköping University (14 female and 11 male) with a median age of 22 (range 18–31) with normal, or corrected to normal, vision and self-reported normal hearing were recruited. No compensation for participating in the study was provided.

2.5. Experimental design and procedure

An interactive test was devised to explore a possible benefit of sonification (see Figure 2), and the effects of the different sonification conditions. The test session took 20 min at the most, and was initiated with learning trials for familiarising and to reduce learning effects. The learning trials consisted of all four sonification conditions. After the training, the test was divided into four parts according to the four sonification conditions with 20 visual representations in each, and a short break after each part where the participants answered a questionnaire about the particular sonification condition. The order of sonification conditions was balanced between subjects to avoid order effects.

The participants moved a slider by using the computer mouse, to mark the vertical pixel column with the highest brightness level in the visual representation, and the sonification was adjusted according to the intensity level for that pixel column (see Figure 3). The participants were asked to answer as quickly as possible. After marking a vertical pixel column, the participants pressed the large button beneath the slider and the next trial was automatically initiated. The accuracy for each trial was measured as the absolute difference between the highest intensity level in the visual representation and the participant's marked brightness level. Hence, a lower measure was equal to higher accuracy. The response time was also recorded. For the statistical analyses, the overall accuracy was calculated as the mean error for the 20 answers in each sonification condition, and the response time was the mean response time for each sonification condition. Accordingly, the experiment yielded both objective measures of sonification, accuracy and response time, and subjective measures from a questionnaire.

SuperCollider was used on a MacBook Pro, presenting visual stimuli on a 21″ computer screen and auditory stimuli via a Universal Audio Apollo Twin sound interface through a pair of Beyerdynamic DT-770 Pro headphones. The headphones provided an auditory stimulation of approximately 65 dB SPL. A quiet office was used for the test, and even if there were some ambient sounds, the test environment was deemed quiet enough not to affect the tests conducted.

2.6. Questionnaire

A questionnaire was used to record subjective data to complement the objective measures. In the beginning of the test the participants were asked to rate their musicality via a 5-point Likert scale from 1 (Not very extensive) to 5 (Very extensive). After each sonification condition (No sonification, Timbre, Pitch, Harmony) the participant answered questions about the difficulty level they experienced in finding the brightest vertical pixel column, and if they experienced a benefit of sonification (if sonification was used) in terms of accuracy and response time. Answers in the questionnaire were given ranging from 1 (Strongly disagree) to 5 (Strongly agree). Finally, after a total of 90 trials, the participants answered questions regarding if they experienced an overall benefit of the sonification or not.

3. Results

The participants were divided into two groups: Low musicality (n=12) for ratings from 1 to 3, and High musicality (n=13) for ratings 4 and 5. According to Kolmogorov–Smirnov tests the data were not normally distributed, thus non-parametric tests were used to analyse the data. Bonferroni correction for multiple comparisons was applied as appropriate. Descriptive statistics can be found in Table 2.

Accuracy was measured in terms of the mean errors made. A Friedman test showed a significant difference in mean errors between the four conditions ($\chi^2(3) = 38.57,\ p < 0.001$). Dunn-Bonferroni post-hoc tests showed only significant differences between No sonification and the three conditions with sonification; Timbre (p=0.001), Pitch (p<0.001), and Harmony (p<0.001), where there were less errors when sonification was used. However, no statistically significant differences were found between the three conditions with sonification. Mann–Whitney U tests showed significantly less errors for the High musicality group for Timbre (U=41.5, p=0.046), for Pitch (U=23.5, p=0.002), and for Harmony (U=20.0, p=0.001), but there were no significant difference between the groups for the No sonification condition.

For response time, a Friedman test showed significant differences between the four conditions ($\chi^2(3) = 42.81,\ p < 0.001$). Dunn-Bonferroni post-hoc tests showed only significant differences between No sonification and the three conditions with sonification; Timbre (p<0.001), Pitch (p<0.001), and Harmony (p<0.001), where response time were longer

Table 2. Descriptive statistics with mean errors and response time measurements (in seconds) for Low musicality and High musicality. Standard deviation in parentheses.

	No sonification	Timbre	Pitch	Harmony
Low musicality	13.9 (5.4)	4.0 (4.1)	3.5 (2.0)	3.6 (2.2)
High musicality	11.4 (9.4)	2.2 (1.2)	1.3 (0.8)	0.7 (0.8)
Response time	No sonification	Timbre	Pitch	Harmony
Low musicality	4.7 (1.6)	10.4 (4.0)	11.9 (4.5)	11.7 (4.6)
High musicality	8.6 (3.2)	14.9 (7.0)	16.9 (9.1)	15.9 (7.3)

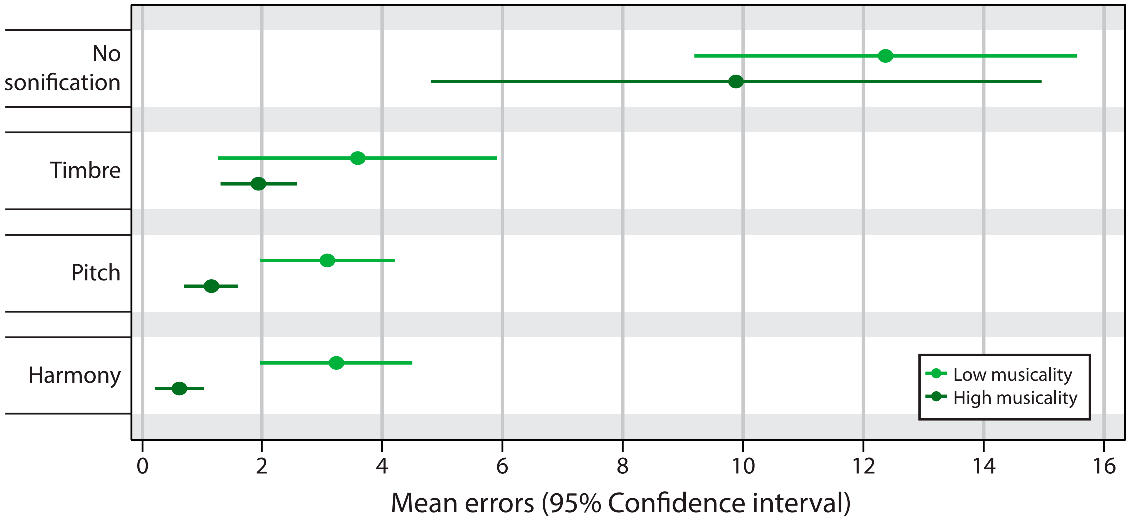

Figure 4. Generally, the mean error decreased when sonification was used. The High musicality group made less errors compared to the Low musicality group.

when sonification was used. There were no statistically significant differences between the three sonification settings. Mann–Whitney *U* tests showed significantly longer response time for the High musicality group in the condition with No sonification (U=24.0, p=0.002), but there were no significant difference between the groups for the conditions with sonification.

The subjective measures from the questionnaire showed that the participants generally experienced sonification as helpful, see Figure 6. The median ranking (1 = `Veryhard' to 5 = `Veryeasy') for difficulty in No sonification was 2 (range: 1–4), and in Sonification it was 4 (range: 3–5). These results suggest that the task was experienced as easier with sonification than without. The experienced difficulty for No sonification as well as for Sonification was similar for both groups (Low musicality and High musicality). The experienced help from sonification for improving accuracy was also measured (1 = `Nohelpatall' to 5 = `Muchhelp'). The median rating was 5 (range: 4–5), which suggests that the participants experienced a benefit of sonification. The experienced benefit of sonification was high and similar for both groups (Low musicality and High musicality).

Finally, the experienced benefit of sonification for giving a faster response was measured (1 = `Muchslower' to 5 = `Muchfaster'), where the median rating was 4 (range: 1–5), suggesting that most participants experienced that sonification supported them in giving faster responses. There were some differences between the groups, which suggest that participants in the Low musicality group generally perceived the sonification to support in giving a faster responses, while the High musicality group had a more diverse impression.

4. Discussion

4.1. Accuracy

The results found in the present study suggest that sonification can improve perception of colour brightness (see Table 2 and Figure 4). The additional information introduced by the sonification made it possible for the participants to improve their accuracy when the information in the visual modality was insufficient for giving an answer with high accuracy. Consequently, the sonification supported the visual perception in the task. This interpretation of the results was also supported by subjective measurements. Results from the questionnaire suggested that the difficulty level of the task was reduced and that the participants experienced the sonification as very helpful in improving the accuracy of their answers.

4.2. Response time

Response time was found to be longer when sonification was used, compared to the No sonification condition (see Table 2 and Figure 5). This indicates that the participants used the extra information provided by the sonification to refine their selection in the test, reaching a higher accuracy, and that this procedure took longer time. Interestingly, when considering the subjective ratings many of the participants stated that they experienced sonification to improve their response time as well as the accuracy, which was not the case according to the measured response times. It might be hypothesised that some participants believed that they performed the task faster, as they might have experienced the comparison between areas in the visual representation easier when sonification was used. Furthermore, as the amount

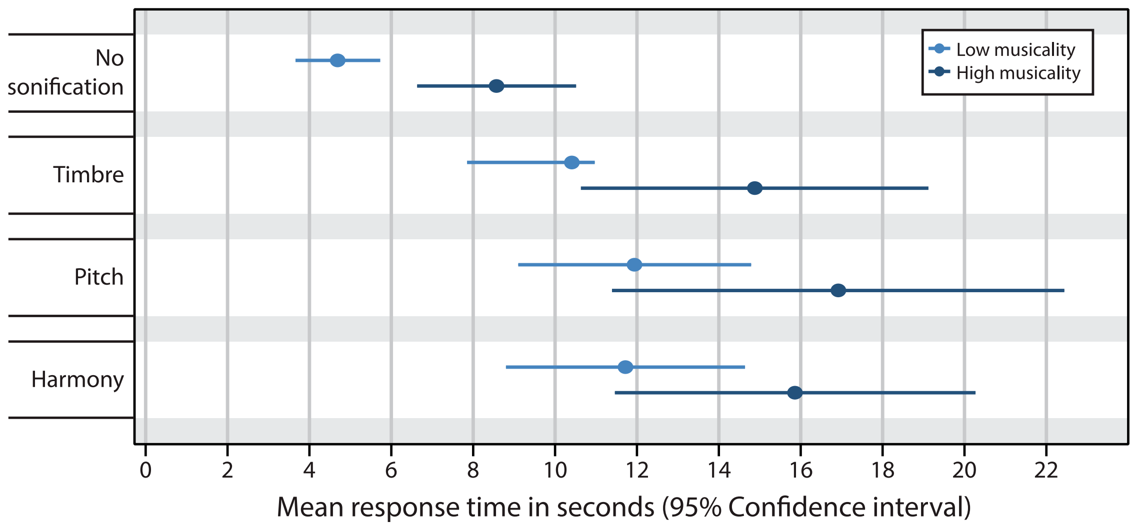

Figure 5. The mean response time was longer when sonification was used, and the High musicality group had longer response times compared to the Low musicality group.

of information was increased when sonification was used, the task became more demanding from a perceptual perspective, which in turn made the participants more deeply engaged in the task. In general, when someone is more engaged in a task, time is perceived to pass more quickly (Conti 2001; Chastona and Kingstone 2004; Sackett et al. 2010). This well-known phenomenon may be an explanation for the discrepancy between subjective experience and objective measures with regard to response times. The results show that sonification is useful in terms of higher accuracy, but this comes at the price of longer response times. It could be argued that in situations where accuracy is more important than response time, then sonification as used in the present study is useful. For example when a researcher is exploring an interactive multimodal visualisation for finding relationships in the data to gain new insights in a research question, or when sonification is used for clarifying a user interaction in an educational situation.

4.3. The participants' musicality

Even if the groups were small, musicality had effects on the results. The High musicality group had statistically significant higher accuracy in the conditions with sonification compared to the Low musicality group (see Table 2, Figures 4, and 5). The results suggest that the High musicality group used their experience and knowledge of musical sounds to reach a higher accuracy. Interestingly, the High musicality group had statistically significant longer response times in the condition with No sonification, further work needs to be done to explore if this result is repeatable and what the causes might be.

4.4. Sonification condition

There were no statistical significant differences between the conditions with sonification (Timbre, Pitch, or Harmony). This indicates that regardless of the specific musical element used in the sonification, and regardless of the participant's musicality, accuracy increased when sonification was used. These results are promising, as proficiency in music theory should not be required to hear the differences in a sonification. However, when studying mean and confidence intervals for accuracy there might be a trend discernible for the High musicality group, where Harmony had higher accuracy compared to Pitch, which in turn had higher accuracy compared to Timbre (see Table 2 and Figure 4). A similar trend was not present for the Low musicality group, where accuracy was more or less equal for all conditions with sonification. This might suggest that for participants with high musicality, who knew what musical cues to listen for, differences in Harmony and in Pitch provided stronger cues than Timbre. If this is the case, the use of such musical elements benefits participants with higher musicality more, compared to participants with lower musicality.

4.5. The visual representation and experimental task

The visual representations used in the experimental setup within the present study contained visual elements, i.e. differences in intensity levels, that challenged the perception of brightness levels. The visual representations used could therefore be seen as selections from a larger, more complex and real visual representation used for data exploration, where misconceptions due to

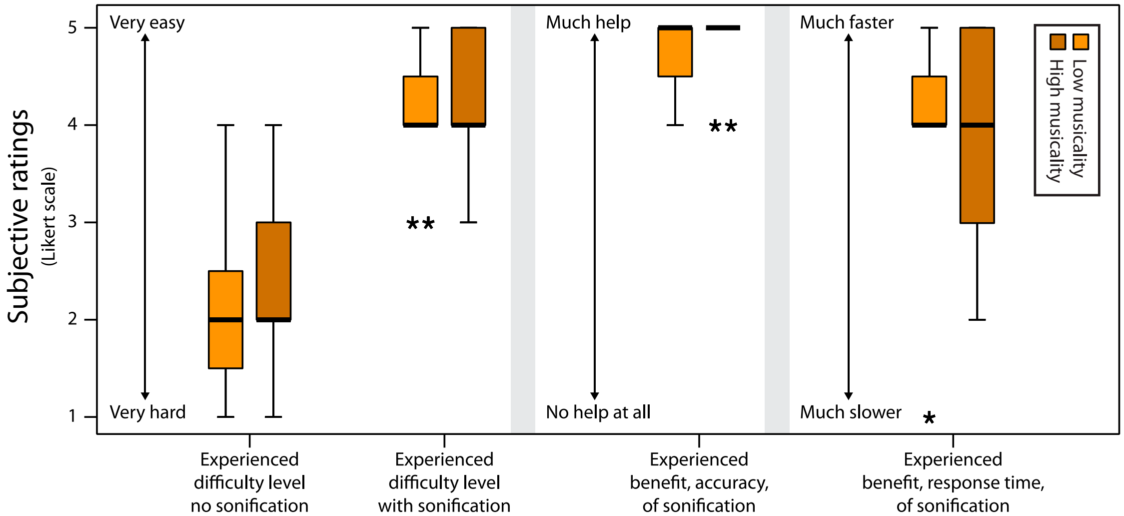

Figure 6. The subjective measures indicate that sonification made the task more easy and was experienced as helpful, but overall not as helpful for giving faster responses.

shortcomings in the visual perception could be a real and relevant drawback in interpretation of the data. Consequently, results found in, and the knowledge gained within, the present study should be generalisable to other visual representations as well.

Finding the highest brightness level in a data set might be solved using a mathematical operation. However, this is true if the user already knows what he or she is looking for in the data. The task used in the present study can therefore be considered a good simplification that enabled the examination of musical sonification and visual challenges in a controlled setting.

4.6. A possible learning effect

The highest intensity level was the same in all visual representations used in the test setup (i.e. 255 in the green RGB channel). Finding the brightest vertical pixel column could consequently have been facilitated by memorising the Timbre, Pitch, or Harmony from the previous trial and comparing it with the sonification in the current trial. The echoic memory is the sensory memory for sounds that have just been perceived (Carlson et al. 2009), and it is capable of storing auditory information for a short period of time. The stored sound resonates in the mind and is replayed for 3-4 s after the presentation of auditory stimuli (Radvansky 2005). The echoic memory encrypts moderately primitive aspects of the sound, such as pitch (Strous, Cowan, and Ritter 1995). Thus, the echoic memory could help in finding the brightest vertical pixel column, as this position would sound ”right” in the participant's mind. This reasoning suggests that the learning effect, if present, might thus have made the sonification to provide additional information, as well as making a comparison with the sound kept in memory possible. This can be seen as something useful, as this suggests that with learning how to use sonification, performance can be increased.

5. Conclusion

The present study evaluated the usefulness of sonification as a complement to visual representations. The results show that there was a benefit of sonification, in terms of increased accuracy, in selecting the vertical pixel column with the highest colour brightness in the visual representations. This suggests that sonification facilitated perception of colour brightness, and helped users overcome challenges for the visual perception in the visual representations. This result was also supported by the subjective measurements where an experienced benefit of sonification was reported. However, the use and processing of the additional information provided by the sonification took time, leading to a longer response time when sonification was used compared to the No sonification condition. This suggests that there is a speed/accuracy trade-off where the usefulness might decrease in situations where fast response times is of the essence. Finally, there was an effect of musicality in the statistical analysis, where participants with higher musicality had higher accuracy in the test conditions with sonification.

6. Future work

For future work, further musical elements such as tempo and rhythm would be interesting to explore. Also, the combination of musical elements such as amplitude and pitch, or harmony and timbre, could be deployed to investigate whether the combination could provide even stronger sonic cues, and if it is possible to provide different sonic cues simultaneously by using different musical elements. The application of musical sonification, using a musical theoretical approach, could also be evaluated in relation to the more classical form of purely data-driven sonification. These questions should be evaluated in relation to standardised tests of the participant's musicality and music perception skills (Law and Zentner 2001), to further explore to what extent an individual's musicality affects the perception of sonification.

Furthermore, it would be intriguing to evaluate sonification support for a wider range of visual representations and the use of real data, particularly with domain experts, and in relation to (for example) the Visual Information Seeking Mantra (Shneiderman 1996). Sonification could be studied as a way of creating an overview of an entire collection of data, or as a way to support the examination of relationships among data items. The information visualisation mantra provides a scaffold for further studies of the usefulness of sonification in visual data exploration and information seeking. Data for further studies could, for example, be obtained from bio-sensors used in the medical sciences, time cycles and activities in the social sciences, or climate change data. The use of real data and different visualisation techniques would indicate which musical elements in the sonification that are most suitable to use interactively in combination with which type of visualisation technique. These future inquires would generate an understanding of the implications of the sonification research, as well as suggest areas where sonification would be useful as an additional tool in visual data exploration.

Disclosure statement

No potential conflict of interest was reported by the author.

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