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Interactive Sonification of Weather Data for *The Locust Wrath*, a Multimedia Dance Performance

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Abstract

To work flexibly with the sound design for *The Locust Wrath*, a multimedia dance performance on the topic of climate change software was developed for interactive sonification of climate data. An open-ended approach to parameter mapping allowed tweaking and improvisation during rehearsals, resulting in a large range of musical expression. The sonifications represented weather systems pushing through South-East Asia in complex patterns. The climate was rendered as a piece of electroacoustic music, whose compositional form—gesture, timbre, intensity, harmony, spatiality—was determined by the data. The article discusses aspects of aesthetic sonification, reports the process of developing the present work, and contextualizes the design decisions within theories of crossmodal perception and listening modes.

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Abstract

To work flexibly with the sound design for *The Locust Wrath*, a multimedia dance performance on the topic of climate change software was developed for interactive sonification of climate data. An open-ended approach to parameter mapping allowed tweaking and improvisation during rehearsals, resulting in a large range of musical expression. The sonifications represented weather systems pushing through South-East Asia in complex patterns. The climate was rendered as a piece of electroacoustic music, whose compositional form—gesture, timbre, intensity, harmony, spatiality—was determined by the data. The article discusses aspects of aesthetic sonification, reports the process of developing the present work, and contextualizes the design decisions within theories of crossmodal perception and listening modes.

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Aesthetic and Scientific Sonification

In "[Equation]", Aphex Twin sent a convoluted message to his fans: the music is me. More prosaically, the audio contained a sonification of his head [1]. It is ironic that fans might not have heard the message, but rather viewed it in a spectrogram. In either case, it was not a novel idea. Almost a century earlier, Dayton Miller had proposed to make an audio waveform from the portrait of a woman's profile, so that "beauty of form may be likened to beauty of tone color, that is, to the beauty of a certain harmonious blending of sounds" ([2] p. 120).

Georges Grinstein's introduction of the domain-neutral term "perceptualization" [3] came at a point in time when sonification started to mature as a field of research. The term perceptualization covers all ways of data transformation—sonification, visualization, even "sculpturization"—that have the aim of making structures in complex data apparent to the senses. A recent publication*, The Sonification Handbook*, edited by Thomas Hermann, Andy Hunt and John Neuhoff (admirably in Open Access) provides both depth and overview of the task of making such structures audible.

The excellent temporal resolution of the auditory system and an effective spatial localisation capacity are the main qualities of aural perceptualization over other modalities. To Gregory Kramer's somewhat classic definition of sonification as "the use of non-speech audio to convey information [and] the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation" [4] might be added, as a corollary, Hermann's inverse perspective, namely that "sonification is the data-dependent generation of sound, if the transformation is systematic, objective and reproducible, so that it can be used as scientific method" [5]. While the first definition emphasises the perceptual qualities of sonification as understood by a receiver, the second outlines the requirements of a computer generating audio. But where do these perspectives leave art? Since all communication involving humans possesses a degree of aesthetic appreciation, and if sonification is the layer between human and machine enabling interaction, does it not follow that it is equally necessary to consider sonification as an aesthetic method?

Scot Gresham-Lancaster criticised casting definitions solely in terms of objectivity, and pointed out that "more complex interrelationship between the arts and using data as a direct determinate"

risk being ignored. He advocated an inclusive approach allowing "juxtapositions that are less logical" ([6] p. 208). While sonification might offer "uniquely ineffable" qualities suitable for artistic expression, he warned that such utilisations remained a "poorly defined and under-examined part of the field" ([6] p. 212; see also [7]).

In this article, we have attempted to address this lacuna by analysing our recent work through the lenses of the Aesthetic Perspective Space developed by Paul Vickers and collaborators [8,9] and the framework of listening modes proposed by Kai Tuuri and Tuomas Eerola [10]. Vickers considered sonification as a set of methods to create sound both for aesthetic experiences and scientific exploration. The Aesthetic Perspective Space is spanned by two continuous dimensions. One is anchored by the concepts "informatica" and "musica," and identifies the intended (or perceived) purpose of sound. The other, orthogonal to the first, is labelled "indexicality" and identifies the ecological congruence (or affordance) of sound. This complementarity in perceptual perspectives is echoed in Tuuri and Eerola's taxonomy, which is based on Pierre Schaeffer's "quatre écoutes" and elaborates a complex hierarchy of listening intentionality. For example, the "reduced" listening mode is quality-oriented and might be appropriate for scientific sonification, and "causal" and "semantic" modes are source-oriented and more relevant for aesthetic sonification. In the latter case, cognising audio information is largely denotative, relying on acoustic features sharing properties with innate or acquired affordance structures from the physical, real world; that is, they are modes of ecological perception.

The Locust Wrath

R. Murray Schafer wrote that "impression is only half of perception: the other half is expression" [11]. In earlier work, we have applied principles of sonification in two ways, as audification [12] and "musicalization" [13]. Audification is a sonification technique where the time proportions of the underlying data are strictly maintained [4], [5]. By "musicalization," we have referred to a symbolic score to be interpreted by musicians that is an aesthetic sonification of a source material, in particular the spoken voice [14].

We started developing a software for interactive sonification in 2013 for the multimedia dance performance *The Locust Wrath* [15]. It was subsequently used in two multichannel sound

installations and in "Make It New: Future Feed" [16]. Technical aspects of the latter work are presented in [17] while the present article focusses on the initial development and aesthetics of the system.

In *The Locust Wrath*, dance is the primary attraction. Choreographer Angela Liong initiated the creative process with an overarching concept and a narrative structure associated with a set of movement schemas based on gestures and postures constituting an "alphabet." The physical and mental demands placed on the dancers were considerable: many movements were novel and/or awkward. During rehearsals, the alphabet movements were composed to form longer sequences. Each dancer had to integrate in body-memory all the sequences, and eventually the whole performance. Memorisation largely relied on kinesthetic cues from other dancers, something akin to flocking dynamics. The choreographer would often use insect metaphors to describe the kind of movements, mental foci, and intentions that she wanted. Composer Joyce Beetuan Koh conceived the electroacoustic music in relation to the choreography, and PerMagnus Lindborg developed the sonification software to generate sonic material for the composition.

Creative decisions were made in close collaboration between choreographer, composer, and sonification designer. While some decisions were made on beforehand, many more were settled during the rehearsals in a process of discussing, testing, and evaluating proposed solutions. Questions regarding the relationship between music and movement could be: "Mimicry or counterpoint? Same level of intensity and speed as the movements, or different? Should the music affect or reflect the choreography?" At each point in the multimodal composition there were decisions to be made. We relied on amodal correspondences (i.e. the alignment of perceptual dimensions in different sensory modalities; see [18]), and the basic strategy was to make the musical expression go in parallel with that of the choreographic intention (cf. [19,20]). Multimodal counterpoint was used sparingly since the creative team concurred that complex layering risked saturating the senses of audiences.

Having worked with dance companies on earlier occasions, the composer and sonification designer were familiar with the way in which rehearsals are taken. We have found that in order to gain the respect of and interest from practitioners in other domains, the sounds must have a

"core," a coherent identity. It is not necessary that they are immediately liked, but the listeners we are communicating with—in this case, the dancers—need to be given keys to understanding the instruments and the integrity of the music that these produce. Especially for sonification, such understanding pushes listeners towards reduced listening [10], and allows them to grasp the reality portrayed in the data.

Climate data

Several sonification projects have employed meteorological data (e.g. [21,22]). For *The Locust Wrath,* climate researcher Liong Shie-Yui and his team at the Tropical Marine Science Institute (National University of Singapore) provided us with two sets of data. One consisted of measurements from 1961–2000 in a 352-point lattice covering 25,000 km2 of South-East Asia, and another contained predictions for 2081–2100. See Fig. 1 for a map overlaid with the point lattice.
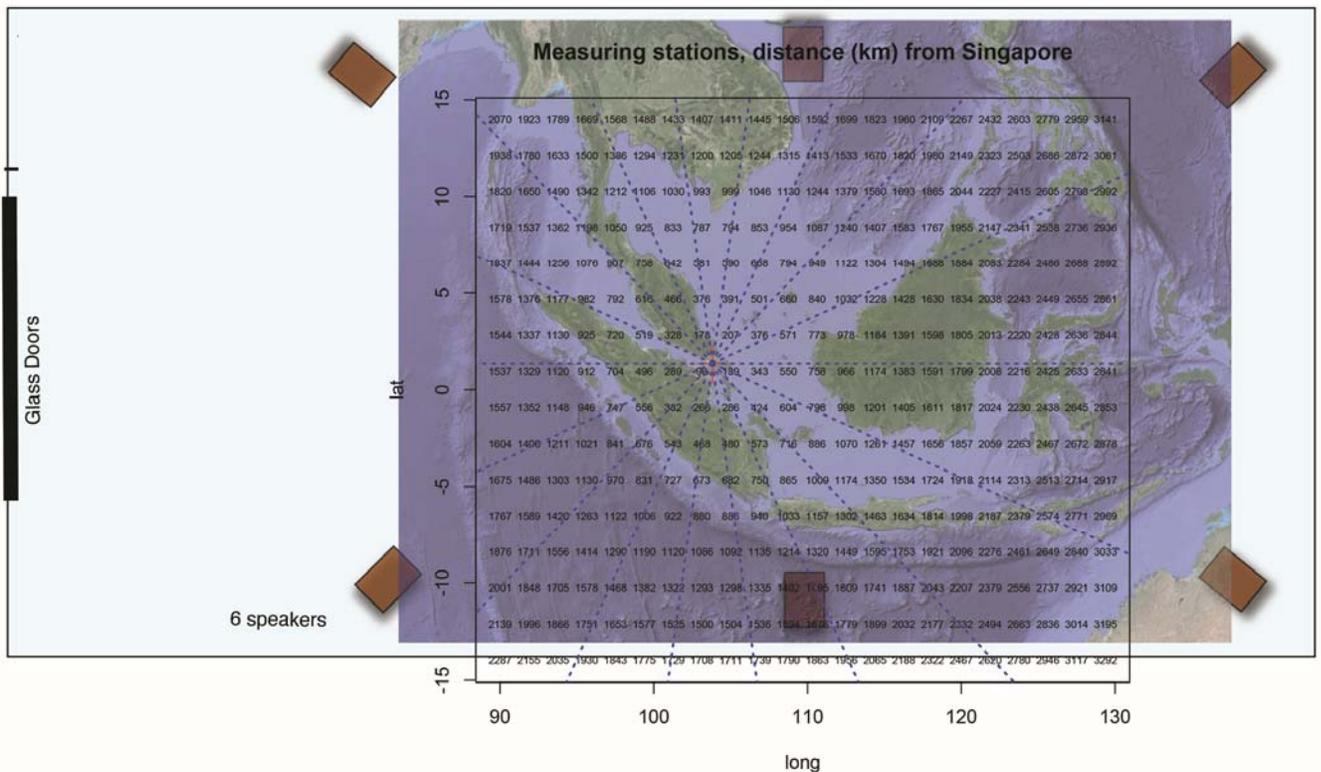

Fig. 1. Superposition of map, lattice and performance space. (© PerMagnus Lindborg)

Time series of precipitation, wind speed, humidity, atmospheric pressure, and temperature were available for each lattice point. The two sets contained ~38.5 million values. Global and local characteristics of the data were analysed with diagnostic statistics and visualisations such in Figs 2 and 3.
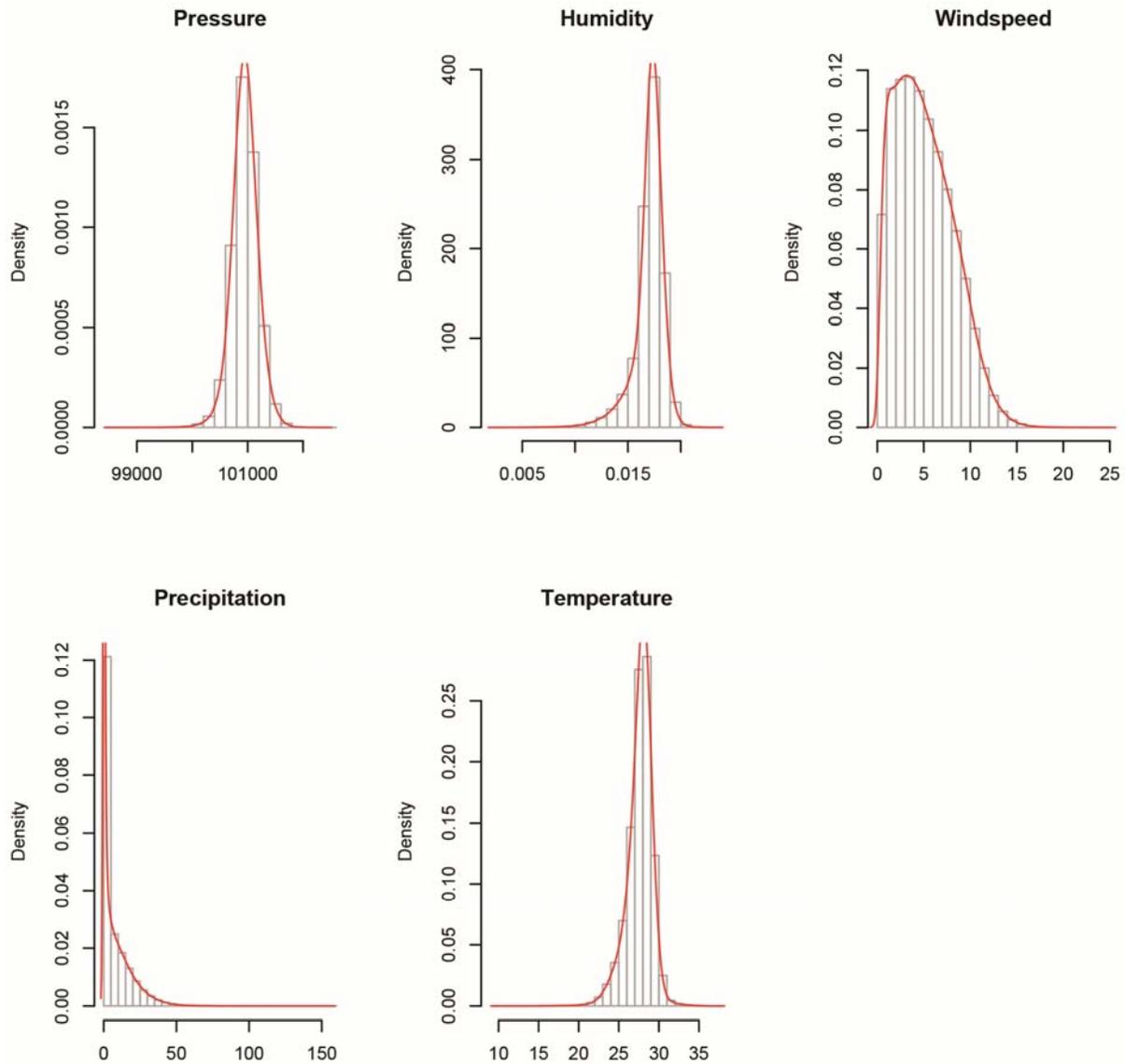

Fig. 2. Histograms of meteorological records in South-East Asia, 1961–2000.
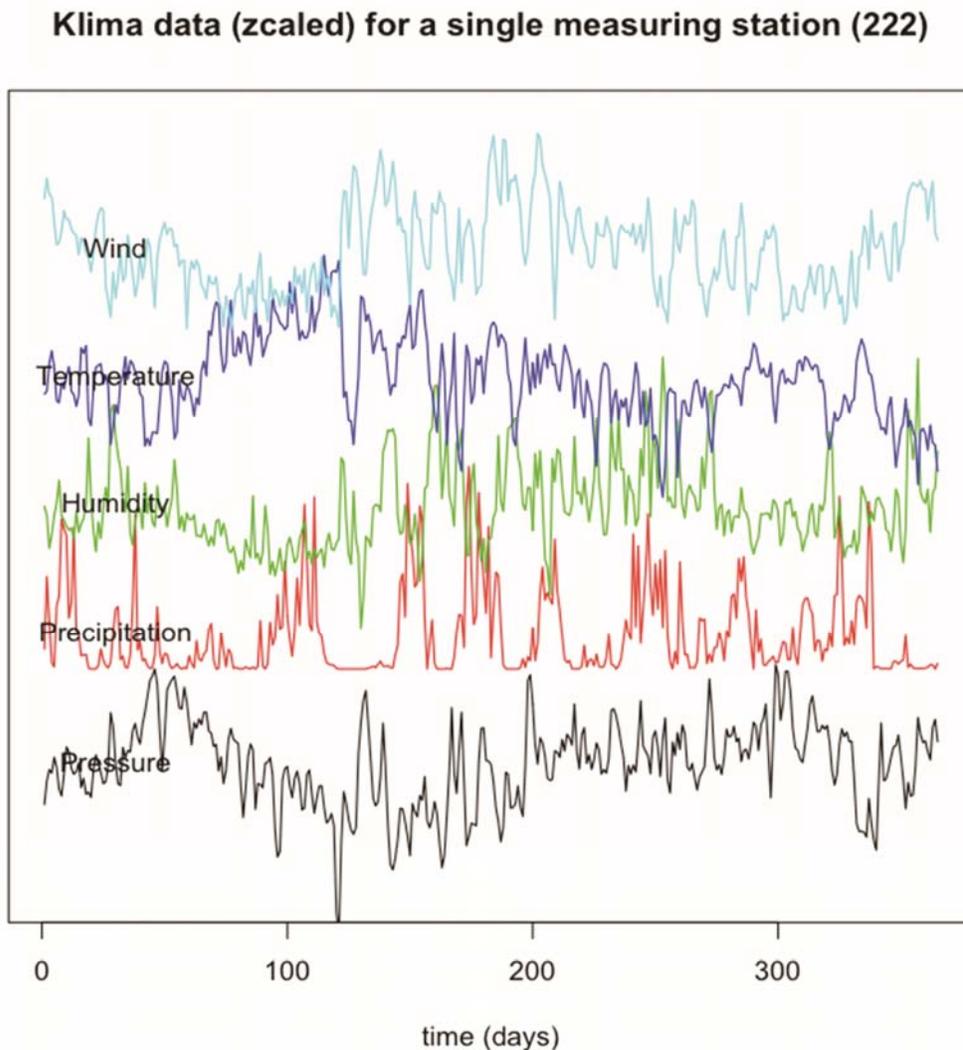(© PerMagnus Lindborg)

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Fig. 3. Plot of meteorological records for one lattice point (west of Sumatra) over one year (1961). (© PerMagnus Lindborg)

Sonification method

When perceptualizing data, the level of representation is not immediately given. Till Bovermann, Julian Rohrhuber, and Alberto de Campo pointed out the "tentative character" of data, considering the amount of time a researcher might spend on encoding raw data and developing appropriate sonic representations. To make sense of data, they wrote, a working understanding of the domain is indispensable ([23] p. 241; also discussed in [22]). Higher-level categorisation of data is akin to Gresham-Lancaster's distinction between "first-order sonification," the direct linkage between data and sonic rendering, and "second-order sonification," the definition of

algorithmic processes driven by clusters within the data. The clustering can be automatic or defined by culturally bound decisions which serve to frame the output within the formal structures of a musical context ([6] p. 210).

For *The Locust Wrath*, the creative team first aimed for a "purist" audification approach, that is, to compress 140 years of climate data (with a large gap) directly onto the target duration of the performance, 60 minutes. As this would have led to an impossibly high compression rate, portions of the data had to be selected. Moreover, a static mapping strategy (more on this below) was rejected when it became clear that this would yield a very fine-grained perceptual variation, deemed undramatic.

A more pragmatic approach was requested of the sonification designer. The working situation demanded an interactive system that could be tweaked during rehearsals so as to offer different musical outcomes to the choreographer, composer, and dancers. The parameter mappings of tuning, tessitura, data flow speed, and so forth had to be understandable. CPU limitations meant that only a portion of the multichannel surround sound could play in real-time on a portable computer, but it was sufficient to communicate a musical idea. What transpired in the process was that manipulating a small number of first-order mappings to coincide with basic musical perceptual dimensions worked well. The degree of complexity did not overload the dancers/listeners, and offered plenty of scope for creative design solutions.

The technique of audification problematizes temporal relations between (imagined) real-life properties of the original phenomenon that is represented in the data, and the (actual) sonic gestures in the auditory display [22]. In *The Locust Wrath*, we noted that the choice of data flow rate was intertwined with decisions regarding timbre, spatial distribution, and other properties of the music. For each segment of the performance, we needed to find the speed that maximised the perceived correspondence between sound and other concurrent elements of the performance. Effectively, the decision of which specific time portions of the climate data to use became an additional conceptual layer of the composition. While it was important to maintain the overall linkage between the chronological order of the data and their appearance in the performance, segmentation decisions were justified through metaphor as well as by dramatic needs. We decided early on that the Introduction would be a slow-rate (0.45 Hz) audification of recorded

data between 27 February and 9 August 1965 because this was a defining period in Singapore's political history leading up to the declaration of independence. At the other end of the performance, the Epilogue would be a fast-rate (10.6 Hz) audification of predicted data from 5 April 2091, the designer's 123rd birthday, to 31 December 2099, the last day in the set. Segments in between would have intermediary flow rates, adjusted to suit local compositional needs. We were aware that associations of this kind risked being perceived as arbitrary, constituting "a rather tenuous semiotic link" ([6] p. 208). Rather than claiming a great deal of importance for them, the point is that deciding on segmentations this way allowed other aspects of the design to emerge during the working process, where the choreographer and dancers provided essential shaping forces.

Interactive mapping

Most of the programming work was dedicated to developing an interactive mapping system. Mapping is a central technique in sonification, with two parts: linkages, i.e. specifying which perceptual sonic dimension will represent a given physical dimension represented in the data, and transformations, i.e.. specifying the functions and input-output ranges for each linkage (adapted from [24,20]). For details to emerge in sonification, Bovermann stated, it is crucial that the acoustic phenomena produced by the synthesis be perceptually salient ([23] p. 241). Beyond this criterion, we believe that for listeners to hear sonification designs as convincing and poetic, the parameter mapping strategy would have to be informed by insights into listening modes and how meaning-making is conditioned on ecological perception ([10,18]; see also [25]).

The primary mappings for *The Locust Wrath* were made together with the co-creators during the conceptual phase of the work. The sonification designer received bits of data from the scientists, tested various methods and mapping, and generated audio files that were passed on to composer and choreographer together with descriptions of the data. Their responses, informed by artistic sensitivity and overview of the performance, indicated which sonic qualities and mapping metaphors were attractive and understandable. Through this conversation the over-arching concept of harps emerged, and it was eventually applied both in sound synthesis and in the design of stage props, as can be seen in Fig. 4.

The next sections will frame the development of mapping linkages within the context of listening modes and crossmodal association. We identify three levels of importance which correspond to Tuuri's "experiential" modes [10].

Precipitation → Pluck, Pressure → Detuning

The most important task for the auditory system is to alert for potential immediate dangers. Reflexive responses are conditioned on structural, innate crossmodal associations [18]. In the context of music, things are rarely crucial to survival. When evaluating possible sonification linkages, we first considered the kinaesthetic affordances of perceptual experiences, answering the question: "How does the sound physically manifest itself?" ([10] p. 148). These crossmodal associations are mostly acquired statistically, through exposure ([18] p. 987).

In *The Locust Wrath*, the first mapping had to convey a simple yet strong idea. An image appeared in a dream, of harp-like structures scattered on a hill, lying on their back in the rain, with each drop causing a string to sound. The ecological association was that "the pluck of a string is like a drop of rain." Once established, the inverse perspective (cf. [5] and the Introduction) that "precipitation causes string excitation" was acceptable and could be implemented in synthesis. A Karplus-Strong physical model of a resonating string was tweaked to produce the desired sound. The sonification system has multiple copies of this basic unit, one for each point in the lattice. Several strings together constitute a 'virtual harp'. While the virtual strings have fixed pitches, they can be detuned, just like a musician can apply pressure on the wooden frame of a harp to change the string tension and thereby the overall tuning.

Geographical lattice --> Spatialization and Tessitura

At the second level of importance, audition tries to answer the question "Where does the sound come from? Is it approaching or receding?" As the processing of spatial cues is largely pre-attentive, this level, as the previous, is dependent on kinaesthetic action-sound couplings ([10] p. 146).

Working with surround sound, Edward Childs created a multichannel sonification of hail storms [26]. This suggested how to deal with the 22 x 16 grid of geographical points in our data. *The Locust Wrath* was going to be performed in a white-box gallery, and we decided to create a

surround sonification that corresponded to actual compass directions. Fig. 1 illustrates the superimposition of physical and virtual spaces. Furthermore, the spatial layout influenced the design of musical dimensions, in particular tonality. We imagined the lattice points as individual strings within a set of 18 virtual harps laid out like fans, each covering a 20˚ sector around a centre coincident with the physical location of the performance. Inspired by the techniques and aesthetics of spectralist composers, a common fundamental frequency was employed, and the strings tuned as the partials of this fundamental. Points close to the centre were mapped to strings of low partial number, and points further away (within the sector) to higher partials. In the different segments of the performance, the fundamental frequency was set to 12.25, 14.57, or 17.32 Hz, corresponding to G, Bb, and Db in the octave below the low A of a piano. The range of partial numbers was between 3 and 60, so that the pitch of the highest string was slightly over 1 kHz, in the 3rd octave of a piano. The given data lattice was such that the centre point, 'Singapore', appeared slightly off-centre (an expression of modesty?). This implied different numbers of strings for the harps, between 18 and 41 for each. Because the same range was applied to all, the harps sounded as if they were of different size, i.e. "thin" or "thick". This created a variation within the instrumentarium that was aesthetically pleasing.

Temperature --> Resonance, Humidity --> Vibrato depth, and Wind Speed --> Sharpness
At the third level of experiential listening our perception is connotative, trying to answer the question "What does the sound evoke in me? Is it aggressive or inviting?" ([10] p. 148). This listening mode depends on semantic or emotional crossmodal associations that condition cognitive appraisal of response alternatives (cf. "decisional consequences," [18] p. 987).

The timbral features of the virtual strings were explored interactively during the rehearsals. Different acoustic features of the instrument, such as the sharpness of plucking plectrum, how long time the string resonates, the depth and speed of vibrato, and so forth, were mapped from the data. The one-to-one relationship was always maintained, for reasons of understandability discussed above, until a satisfactory design solution emerged. For example, large vibrato depth would make an individual string stand out when several are struck together; this parameter was mapped from humidity. The duration of resonance (a function of the comb filter feedback amount) was mapped from temperature. Finally, in the synthesis unit, the comb filter was excited by a click smoothened with a ramp of variable duration (between 0 and 22 samples; a

compressor compensated for the loudness variation produced). In a reduced, reflective mode of listening, the onset attack character is associated with source qualities (cf. [10] p. 141). For example, a sound that is rich in high partials (elicited by a steep excitation ramp) is heard as sharp; variation in such characteristics produces perceptual salience. Moreover, the listener (who is already imagining a harp) might crossmodally attribute the timbral change to a material or kinesthetic cause, such as a hard plectrum or the pluck position moving towards the bridge. Largely due to this, *The Locust Wrath* harps reminded the dancers of "a huge guzheng or pipa," and deemed the sound suitable from a cultural point of view. The designer then adjusted the ranges of timbral mappings to strengthen the metaphor.

Summary

The instrumentarium for *The Locust Wrath* was made up of virtual harps surrounding the performance space. The sonification mappings were developed interactively together with choreographer and dancers, and can be expressed as crossmodal metaphors, as follows. If there was rainfall in a geographical area on a certain day, a specific string was struck at the corresponding time in the piece. If it happened to be hot that day, the string resonated longer, and in addition, high humidity gave it a deeper vibrato. Extreme atmospheric pressures produced inharmonic timbres. The wind speed affected the quality of the plectrum that plucks the string, so that stronger wind produced a sharper tone. The mapping linkages were maintained throughout, but data flow rates and transformation output ranges were adjusted to meet the dramatic requirements of each segment in the multimodal composition.

Fig. 4. Photo from a performance of *The Locust Wrath*. (© PerMagnus Lindborg)

Discussion

Bovermann and collaborators warned that having aesthetic intentions can be a source of problems. They stated that "if one assumes that listeners will prefer hearing traditional musical instruments over more abstract sounds, then pitch differences will likely sound 'wrong' rather than interesting. If one then designs the sonifications to be more 'music-like'… one loses essential details, introduces potentially misleading artefacts, and will likely still not end up with something that is worthwhile music." ([23] p. 241). To this somewhat rhetorical statement we would like to respond with a reflection on the instrumentarium of *The Locust Wrath* and an observation from the rehearsals.

We included five separate segments with a duration between 3 and 6 minutes in the performance. On the one hand, we sought to vary their musical identity by making large differences e.g. in data flow rates, and on the other hand, we sought to establish perceptual coherence by subjecting each segment to local and strict audification. By staying the same throughout, the

instrumentarium, in particular the spatial arrangement and the straightforward first-order mappings, established the "core" sound. Thus, the instrumentarium had an orchestra-like character, further strengthened by the treatment of harmony as in spectral music, and the sonification aesthetic embraced aspects of electroacoustic composition.

The dancers were the main intended listeners. They heard the sonifications many times as they developed, first over small loudspeakers in the studio and then from a large surround system during the last two days of work in the performance space. They spontaneously reacted to the sounds as a piece of electroacoustic music, something they were familiar with from earlier productions. This perception of the sonifications might be placed in the "abstract music" part of the Aesthetic Perspective Space. In rehearsals, elaborate movement schemas were developed to be perceptually aligned with the most prominent perceptual dimensions of the music, but not its details. This, we believe, agrees with default nature of experiential listening in non-experts. However, when asked to "attend carefully" ([8] p. 215) to the way that sounds represented climate, the dancers recalled physical experiences of rain, wind, and so forth. With mental effort (and not while physically moving) they would enter a mode of reduced listening. Their perception of the music thus moved towards the "concrete sonification" part of the Aesthetic Perspective Space. While the cognitive interpretation of specific mappings was less meaningful for them than grasping the body-feel of how the weather shifts were reflected in the music, such as seasonal rhythms (through patterns repeating every 30 seconds or so), north-south differences in annual monsoon patterns (through the knowledge that geography was projected onto the performance space), and movements of tropical storms (evidenced in disruptions in the spatialization density and patterns of movement), the observation that the dancers could consciously change listening perspective hints at how strongly perception can be modulated by directed attention.

The border between aesthetic sonification and electroacoustic music is blurred, and whether such a distinction is meaningful or not is an open question. Vickers concluded that "the difference… is largely one of perspective." ([8] p. 215). The authors argued that "musical sonifications" might suffer from poor internal ecological validity, making listening to them difficult ([8] p. 210), and speculated that negative appraisal could result when the logic of mapping strategies was inconsistent. In our understanding, this still seems to be a scientifically biased perspective on

sonification. Could it not be possible, that perceived listening friction might arise even from a logically coherent generative system, if the underlying mapping principles are incongruent with the affordances of sonic environments? That is, if the sound design does not engage with either the ecological principles that our auditory system is preconditioned to handle, or the soundscapes that we are culturally habituated towards? If so, it implies that good principles for successful aesthetic sonification can be found in experiences of natural, non-designed environments. It also implies that sonification should embrace soundscape research [27] as well as music. Listeners "might be able to recognise structural elements in music that represent the conventions or rules of the cultural field… [the] meanings of semantic listening [are] affordances of cultural behaviour (i.e. habituation)" ([10] p. 140).

To what extent is the perceiver expected to understand—through listening alone—the relationships between source phenomenon, data, and sound? Which metaphors are essential to convey artistically, and which can be used in design, but are of little importance for the appreciation of a work? For the intended listeners in our case—the dancers—a sense of emotional coherence between sound and other modalities was more important than anything else. Evaluating parameter mappings as beautiful or not was not on their mind. Yet the music, to paraphrase Aphex Twin, became part of them.

Florian Grond wrote that "a sonification that works is therefore the successful struggle to create a message that points beyond the medium." [28]. We believe that in *The Locust Wrath*, exactly because the sonification strategy appealed to pre-attentive listening modes, the method became a means for creating an aesthetic experience. Scientific objectivity might thus have limited relevance to evaluating the project. However, the software design is open-ended and we are developing an interface whereby the user can navigate within a low-dimensional space of pre-set "musicalizations." We aim to probe its potential for scientific applications through empirical investigations with climatologists.

Acknowledgments

Bibliography

Main sources

AIS: Special Issue: Sonification: what where how why artistic practice relating sonification to environments, Sinclair Peter (ed.), Ai& Society (<http://link.springer.com/journal/146/27/2/page/1>) 27:2, (SpringerLink 2012).

TSH: Thomas Hermann, Andy Hunt & John G. Neuhoff, (ed.), The Sonification Handbook, (COST Office and Logos Verlag Berlin GmbH, 2011), <http://sonification.de/handbook/>, acc. 30 May 2015.

References

1. Aphex Twin a.k.a. Richard D. James, [Equation], (Warp Records 1999).

2. Dayton Clarence Miller, *The Science of Musical Sounds*, (New York The Macmillan Company, 1916), <http://www.questia.com/read/3758500>, acc. 30 May 2015.

3. Georges Grinstein & Stuart Smith, "Perceptualization of scientific data," Proc. SPIE/SPSE (Extracting Meaning from Complex Data: Processing, Display, Interaction) 1259, pp. 190–199, (1990).

4. Gregory Kramer, *Auditory display: Sonification, audification, and auditory interfaces*, (Addison-Wesley 1994).

5. Thomas Hermann, "Sonification: a definition," (2008), <http://sonification.de/son/definition>, acc. 30 May 2015.

6. Scot Gresham-Lancaster, "Relationships of sonification to music and sound art," AIS, 207–212.

7. Gil Weinberg & Travis Thatcher, "Interactive Sonification: Aesthetics, Functionality and Performance," *Leonardo* 16, 9–12, (2006).

8. Paul Vickers & Bennett Hogg, "Sonification abstraite/sonification concrete: An 'Æsthetic perspective space' for classifying auditory displays in the ars musica domain." Proc. ICAD 2006, pp. 210–216, (London, U.K.).

9. Stephen Barrass & Paul Vickers, "Sonification Design and Aesthetics," TSH ch. 7.

10. Kai Tuuri & Tuomas Eerola, "Formulating a Revised Taxonomy for Modes of Listening," *Journal of New Music Research* 41:2, 137–152, (2012).

11. R. Murray Schafer, *The Soundscape: Our Sonic Environment and the Tuning of the World*, (Inner Traditions & Bear, U.S.A., 2nd edition, 1993).

12. PerMagnus Lindborg, MessagierEsquisses, electroacoustic music, (Music Information Centre, Norway, 2005).

13. PerMagnus Lindborg, TreeTorika, score, (Music Information Centre, Norway, 2006).

14. PerMagnus Lindborg, "About TreeTorika: Rhetorics, CAAC and Mao," in Bresson, Agon, & Assayag (ed.), OM Composer's Book #2, (Éditions Delatour France & Ircam—Centre Pompidou, 2008).

15. Angela Liong, Joyce Beetuan Koh, & PerMagnus Lindborg, *The Locust Wrath*, multimedia dance performance, (The Arts Fission Dance Company, 2013), <http://www.artsfission.org>, acc. 30 May 2015.

16. Angela Liong, Joyce Beetuan Koh, PerMagnus Lindborg et al., Make It New: Future Feed, 10 days of multimedia dance performances and installations at the National Design Centre, Singapore, (The Arts Fission Dance Company, 2015), <http://www.artsfission.org>, acc. 30 May 2015.

17. PerMagnus Lindborg & Liu Yuning David, "Locust Wrath: an iOS Audience Participatory Auditory Display," Proc. ICAD 2015, (Graz, Austria).

18. Charles Spence, "Crossmodal correspondences: A tutorial review." Atten. Perceptual *Psychophysiology* 73, 971–995, DOI 10.3758/s13414-010-0073-7, (2011).

19. Bruce Walker, Magnitude estimation of conceptual data dimensions for use in sonification, Ph.D. Thesis, (Rice University, USA, 2000).

20. Gaël Dubus & Roberto Bresin, "A Systematic Review of Mapping Strategies for the Sonification of Physical Quantities," *PLOS One*, DOI:10.1371/journal.pone.0082491, (2013).

21. Andrea Polli, "Atmospherics/Weather Works: A Spatialized Meteorological Data Sonification Project," *Leonardo* 38:1, 31–36, (2005).

22. John Flowers & Douglas Grafel, "Perception of Sonified Daily Weather Records". Proc. Human Factors & Ergonomics Society 46:17, pp. 1579–1583, (2002).

23. Till Bovermann, Julian Rohrhuber & Alberto de Campo, "Laboratory Methods for Experimental Sonification," TSH ch. 10.

24. Bruce Walker & Michael Nees, "Theory of Sonification," TSH ch. 2.

25. PerMagnus Lindborg, "Colour Association to Music Is Mediated by Emotion: Evidence from an Experiment Ysing a CIE Lab Interface and Interviews," (2015, in review).

26. Edward Childs & Ville Pulkki, "Using Multi-channel Spatialization in Sonification: A Case Study with Meteorological Data," Proc. ICAD 2003, (Boston, U.S.A.).

27. Scot Gresham-Lancaster & Peter Sinclair, "Sonification and Acoustic Environments," *Leonardo* 22, 67–71, (2005).

28. Florian Grond & Thomas Hermann, "Aesthetic strategies in sonification," AIS, 213–222.

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