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ABSTRACT
In museum exhibition design, the experiential aspects of virtual reality and other immersive technologies are increasingly being explored. This study contributes to these explorations, focusing on the role of hearing and sound in visitors' experiences of a hybrid virtual environment designed for an architecture museum exhibition. Physically, the environment consisted of a full-scale, multi-level structure installed in a large gallery space. Virtually, visitors 'switched' between being in a contemporary villa and a natural shoreline biotope while moving in the physical installation, experiencing and comparing nature and architecture as "parallel realities." This study investigates visitors' experiences of realism in the soundscape and how this contributed to the immersive experience. Exit interviews with randomly selected visitors on the sound experience ($N = 82$) are primary data for this study. Visitor responses to questions related to sound ($N = 320$) and data collected from interviews and observations of recruited visitor pairs ($N = 16$) are complementary data. The study finds that visitors considered sound essential to the high degree of realism they experienced in the hybrid virtual environment, in the sense of "being there," and that this was dependent on signal types that were appropriate in type and variation. Additionally, relevant to exhibition design practice, issues of quality and delivery methods had minimal impact on the visitor experience.

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Soundscapes in museum space

Murray Schafer originally coined the term 'soundscape,' and his formative book *The Tuning of the World* was first published in 1977. In this book, he developed new terminology for describing our sonic surroundings, including the holistic concept of soundscape where the listener is also a participant, and how sound is an acting, dynamic element of both human-made and natural environments. Today, the term soundscape is often used to describe a complete sound environment (Davies et al., 2012). Soundscapes are composed of sounds from large and small activities, there are background sounds and foreground sounds, there are signal sounds that regulate activity, and there are sounds that tell the listener where s/he is and that reveal different intentions that exist in the surroundings. Thus, it is possible to say that soundscapes are

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constructs (Rudi, 2013), both in objective acoustic terms and in subjective psychoacoustic terms. Although listeners might interpret the audible information differently, they must all relate to the same semantic content, acoustically and psychologically. Meaning is constructed from resonance and recognition in the balance between realism and expectation (Rudi, 2008).

In studies of hearing and vision as qualities of experience, evidence from research in neurobiology suggests that attention to visual stimuli spreads to attention to auditory stimuli, and this underpins the notion of audiovisual integration in the brain (Degerman et al., 2007). Normally, vision overrides audition until unexpected sounds require attention, and mere hearing is replaced by listening. In the sound design for the exhibition in this study, then, the expectation was that the visitors would accept the constructed soundscape as fitting with the virtual visual models, and that they would feel that sound positively added to the experience. Therefore, there was research interest in the" natural responses" of the visitors, unprimed by any type of conditioning leading them to pay more attention to sound than what they would normally. The first research question explored in this study thus asks: in which ways does the soundscape in a virtual reality exhibition impact the visitor experience?

Studies have also found that sound can contribute to and enhance the sense of presence (Nordahl & Nilsson, 2014). In the context of a museum exhibition, sound thus has the potential to reduce distance between exhibit and visitor while increasing a sense of agency (Bubaris, 2014), opening possible trajectories of action for the visitor (Emirbayer & Mische, 1998). Similarly, adding sound to a virtual reality environment increases the sense of "being there" in the specific modeled location or context (Serafin & Serafin, 2004). Sense of presence depends on a perceived realism; the audio seems to belong in the visual scene, and coordinating the sound material with visitor *expectations* generated by the visual artificial environment further enhances this sense of presence (Chueng & Marsden, 2002). Chueng and Marsden (2002) propose that the fulfillment of *expectation* is more important than accurate *realism* in the sound material, and they underpin this position with examples from the film industry, where diverse sounds are often combined to create elements that are imagined to be realistic. This calls on what D'Escrivan (2009) calls *imaginary listening*. Regardless of how these perspectives are weighted, they all relate to the semantic content of sounds, and how this semantic content augments the experience. These perspectives served as background for the second research question explored in this study: to what extent is a sense of realism essential to the sense of presence in a hybrid virtual exhibition?

Much of the literature regarding sound in the museum argues for the value of including sound in different types of exhibitions, based on a range of perspectives and projects (Binter, 2014; Boon, 2014; Hutchison & Collins, 2009) and is often focused on opportunities to engage visitors in a broader and more pluralistic meaning making. Everrett (2019) presents an historical overview of sound in the museum and describes the design-based process for the exhibition *Sound by Design* (2017), as an example for curators on "how to incorporate sound design principles into their exhibition projects" (p. 313). Bubaris (2014) fields a discussion about how sound can underpin museum narratives, and more briefly about the effect this has on the total soundscape in the museum. He uses examples to show how "sound design effaces the traditional distance between the visitor and the 'exhibit'," and states that while "sounds are increasingly used in museum exhibitions, (…) the systematic development of the principles and potentials of their use is still lacking" (p. 399). For successful implementation of sound in museums, Stocker (1994) points to the need for competence in acoustics and hardware such as speakers and control systems. Given the interest in immersive experiences (Kidd & McEvoy, 2019) and social social presence (Oh et al., 2018) in museums, where a focus on immersive audio is largely absent, the third research question explored in this study addresses implications for exhibition practice: how is the quality and technical implementation of a soundscape relevant for exhibition design in museums?

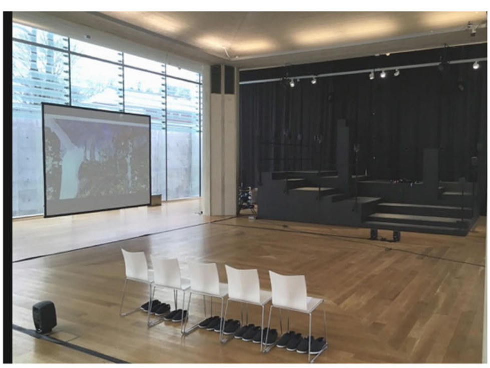
Exhibition and soundscape design process

An increasingly common approach used by architectural firms is to "extract" building forms from natural forms by means of a laser point cloud scan. This was the approach used by the firm Atelier Oslo in this study, in modeling the physical design of *The Forest in the House* exhibition (Figures 1a and 1b).

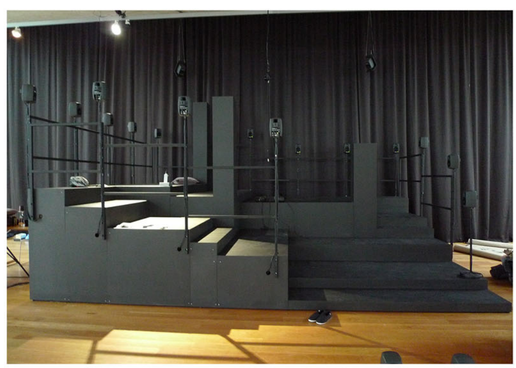
The architect's design of the virtual biotope, and subsequently, the design of the virtual villa, were largely extracted from a laser point cloud scan of a rugged shoreline location in Oslo (Figure 2a).[1] The soundscape design was based on a similar method, with impulse responses first recorded using a starting gun in the natural biotope and then used for processing the entire outdoor soundscape (Figure 2b). By using mainly sounds that belonged in the natural biotope, the design aimed to align with visitors' expectations (Chueng & Marsden, 2002) and thus foster a sense of presence and achieve a high degree of perceived realism in the outdoor environment.

The exhibition experience entailed visitors using a hand-held device to 'switch' between being in the natural shoreline biotope and being in a contemporary villa as they physically moved in the installation, bodily sensing, experiencing and comparing nature and architecture as "parallel realities" (Figure 3).

The physical exhibition installation was dimensioned as a full-scale section of the villa (approximately $5 \times 4\,m^2$), with the placement of levels and steps mirroring the natural terrain. Foot sensors and tracking devices mounted above allowed visitors to move



(a)



(b)

Figure 1. (a) Exhibition setting with large screen at left. Photo courtesy of the National Musem. (b) The physical model with 15 loudspeakers mounted along the perimeter; four speakers suspended above and speakers on the floor. Photo by Jøran Rudi.

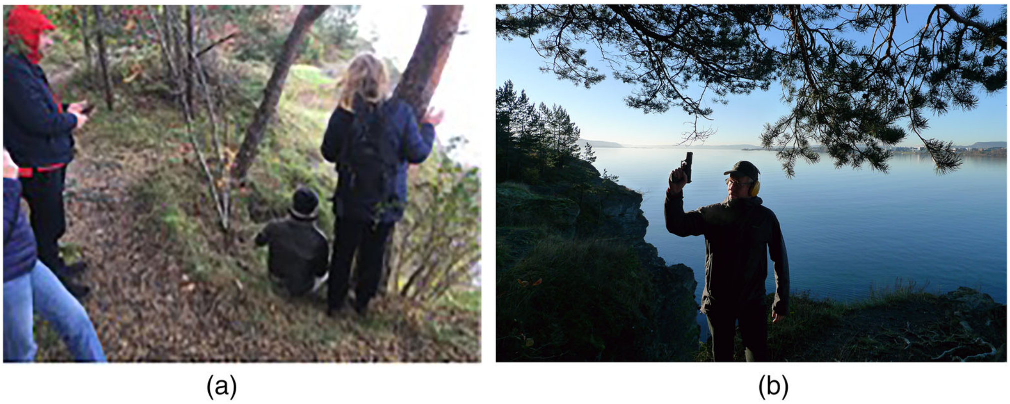


Figure 2. (a) The natural biotope that served as model for the physical and virtual exhibition. Photo by Rolf Steier. (b) Image from making location impulse recordings. Photo by Jøran Rudi.

Figure 3. The two virtual worlds: Reconstruction of the biotope from a recorded point cloud (left), and the "extracted" architectural model for the virtual villa (right). Digital renderings by Ole Petter Larsen.

Figure 4. Visitor pairs exploring *The Forest in the House* exhibition. Photos by: Annar Bjørgli, the National Museum.

around the physical exhibition wearing the VR-headset and seeing only the virtual environments (Figure 4). Two soundscapes were designed to enhance a sense of immersion in these environments, natural shoreline biotope and contemporary villa, with subtle transitions between soundscapes when toggling between them (Figure 3).[2]

Most of the sounds were distributed throughout a loudspeaker system (Figure 1), with speakers realistically placed. This means that sounds of airplanes and birds far afield came from speakers above, for example, while sounds of the ocean waves and a small brook were placed at floor level, below and in front of the physical model. Sound distribution also took into consideration sound sources that visitors could 'see' in the virtual environments and sounds that were experienced only by the direction from which they were heard. The crown of leaves on trees and the forest canopy, for example, would make it impossible to see the physical sources of airplane and bird sounds coming from above, and sounds of passing bicycles and horses were placed behind the model since their path was visually masked by the virtual forest. Dogs barking at a distance were also well beyond the visual horizon.

The acoustic profile for the indoor soundscape was then modeled on the properties of the building materials and the dimensions of the architectural space, taking open doors and windows into consideration. Indoor soundscapes are typically quieter than outdoor soundscapes, and in the indoor soundscape, outdoor sounds filtered in through an open doorway and an open window directly across from the door. The reverb was also calculated from materials and distances in the architectural model. Jazz softly playing from a radio, for example, was placed in one of the speakers and heard only through the reverberation, seeming to originate in an inaccessible hallway further back in the building. The source sounds that could be heard indoors were played from speakers, but since reverberation changes with user position and movement, the reverb was played only through the headset. This design aimed to allow visitors to better notice the acoustics as they moved around in the virtual model. Both modeled soundscapes included contrasting sounds, which were added to stand out against a backdrop of expectation.

Soundscape design features

Both nature and villa soundscapes were programmed for visitors' physical interactions with the virtual environment, with sounds and reverb changing according to where the visitor was moving in the installation. Central technical features of the design are presented below.

- The visual VR environments were delivered to the visitors through a standard HTC Vive headset, with a 'live feed' projected onto a screen in the pavilion.
- The sound was delivered through a combination of loudspeakers located around the installation and an open headset, utilizing different techniques for modeling 3D acoustics and projecting moving sound material.
- Following experimentation, a vector based panning method (VBAP, Pulkki, 1997) was chosen for the loudspeakers because it would give acceptable directionality in the physically small installation.
- Sounds in the headset were coded binaurally, mimicking the acoustic functions of the human head, pinnae and hearing canal. The binaural panner received information from the motion tracking system of the VR system and this was used to account for positional and rotational factors.

- In the field of proxemics, perception of space is often divided into four categories - intimate, personal, social and public, and sounds that were intended to be experienced in the intimate space, such as insects, rustling leaves underfoot and other incidental sounds, were delivered through the headset. The amplitude of sounds in the intimate sphere was low and the modeled reverb of the interior space was also very soft. The higher partials in these sounds were lifted through filtering, further augmenting the sensation of closeness, such as the experience of a flying insect suddenly circling your head that was heard only in the headphones.
- Adding sounds that would seem to stem directly from the visitors' movement, such as step sounds, was considered, but as pointed out in Nordahl et al. (2010), step sounds are highly dependent of the type of shoes and the kind of surface the visitor is walking on. The idea of step sounds was abandoned due largely to time and technical constraints, and all visitors were equipped with woolen slippers.
- The headphones used were an open-backed pair (Sennheiser HD 650) that allowed loudspeaker sounds to be heard and to allow for communication with the second visitor who did not wear headsets for either video or sound. Conversation between visitor pairs was a core feature of the experience design.
- The two soundscapes were rendered from 12 sound banks of content specifically designed for the installation. These included 'clips' of recorded sounds of birds, lapping waves, wind, rustling brush, rustling leaves, a brook, bees, dogs, passing horses, dogs, bicyclists and airplanes, as well as a variety of small incidental sounds.
- A flexible and easily configurable playback engine routed sounds to a sound card with 24 channels. The sound clips were continually re-sequenced when performed in the soundscape, and sounds from several banks could play simultaneously. The sounds from each of the banks were played back with irregular intervals to create a restrained semi-random environment where obvious repetition was avoided. A further constraint was that each entire bank of clips would have to be played before any one clip from the same bank could be played again.

Data collection from a visitor studies perspective

The exhibition experiment and studies of sound were conducted in the context of a larger research project (Biuso, 2020; Pierroux et al., in press; Steier, 2020). In terms of the experience design, each visitor was accompanied by a friend, family member or partner and began to freely explore the exhibit while in the natural scene. The partner was not wearing a headset but could share in the experience by viewing on a large screen what was seen in the virtual world in real time (Figures 1a and 4), conversing and assisting the other when needed. Each visitor spent an average time of about 15 minutes freely exploring the parallel realities (Figure 3).

The sound research focused on how sound contributed credibility and authenticity to the hybrid virtual experience, for example, by visitors being able to identify many of the sounds in the soundscape. Of particular interest was whether visitors expected sounds to be heard from their touch or steps in the physical and virtual models, and whether their critical listening made them miss or be bothered by certain sounds. The sound studies also had an interest also in how well a combination of delivery methods (speakers and headset) worked from a visitor perspective, for example, whether the sense of realism could be maintained using simplified methods in less than perfect acoustic conditions when measured against the typical technically demanding requirements of more advanced wavefront technologies. Since socially situated visitor studies are radically different from the highly controlled listening reporting in pure acoustic research, the research in the larger project was not set up to verify the accuracy of the acoustic modeling in itself, which was based on well-established methods. Neither were visitors specifically encouraged to place any particular focus on sound.

The research design for the larger project was collaboratively developed by members of the team, which included museum curators in architecture and education, learning researchers at a university, architects, virtual reality developer, and sound researcher (see Pierroux et al., in press). Different groups of informants were used, discussed in greater detail below. The data corpus includes video recordings, observations and interviews of recruited participants (N = 32), questionnaire responses from general public visitors (N = 320), and interviews on sound with visitors randomly selected from general public visitors (N = 82). The data are thus from a real-world environment, beneficial for maintaining a visitor studies perspective (Petrelli, 2019).

The first group consisted of 16 recruited pairs of visitors representing different age groups and types of architectural expertise. The pairs were videotaped during their exhibition experience and they were interviewed in pairs and individually afterwards using a semi-formal method, also recorded. The transcriptions of video recordings of the exhibition experience showed that being outfitted with headsets and feet sensors, becoming familiar with their virtual presence and avatar hands, and moving around using a handheld controller to switch between the two views took some time to manage for the visitors. However, after they became more familiar with the controller and tracking system, their experience was not hindered by the technology. Moving in an electronically generated environment in the physical installation nonetheless clearly demanded attention and coordination between the pairs, particularly since they were moving on several levels. Nearly all of the pairs noticed that sound was present (12 of 16 pairs), but they typically only discussed sound after having spent some time managing the main challenge of navigating the virtual and physical environment. Most of their conversations revolved around the visual environment and navigation in the installation using the VR technology, and their mention of sound was very brief. However, all of the reactions to sound were of positive surprise, for example, suddenly noticing the sound of a bee (which could be heard only by the person with the headset), waves, wind, birds and music (only playing when the visitor with the headset was in the villa environment). When contextual sound was mentioned in the video recordings, it was described as belonging to the visual scene.

After exiting the installation, the recruited visitors were interviewed about their experiences, and these reflections contributed a richer dataset. Due to the small sample set it is difficult to generalize, but analysis of the interview data showed that visitors emphasized the sense of naturalness in the sound, and how it in particular made the nature scene seem more credible. “Yes, the total experience with sound, I thought it worked very well. … giving, like more impression of being in the nature, being in the actual place, I mean. I think that was really important, to have the birds, and the ocean, and the, I mean, everything felt more real."[3] This is a favorable description of this specific environment, while other visitors had a more comprehensive perspective: "It had depth. It gave everything an extra dimension, it wasn't flat, like it, it had the whole surround type of sound. If felt as if it had added depth. … This just triggers memories in your, in your mind, and memories just give you additional, an additional dimension of perception."[4] Several interviewees also took notice of the near-field sound of a flying insect, and the soundscape change from outdoors to indoors, where reverberating music was projected from one of the corners:" I think that the acoustics inside the house is very important in relation to which room you're in, right? And that the reverb, or in another way, that is in the walls, where you hear that the music is coming from someplace, but that you hear it all the time. I think that was very well done in a way that makes you even, a greater conviction that you are where you are."[5]

The second group of informants was general public museum visitors (N = 320) who responded to one question on sound out of 24 questions in a larger survey.[6] Their response was an evaluation (rating 1-5) of the statement "the sound was important to my experience of authenticity." 71% of the visitors answered that sound was important or very important to their experience.

The third and primary group of informants (N = 82) for this study was visitors randomly selected from the general public to participate in a structured interview that specifically addressed the sound. The visitors first entered the exhibit, and upon exiting they were asked if they would participate in an interview about their experiences with the sound in the installation. In order to not prime the visitors beyond their normal attention to sound, the possibility of an interview about sound was not mentioned *before* their visit. Nearly all visitors that were asked agreed to interviews, which lasted approximately 20 minutes and were conducted near the exhibition entrance over three different days in a week-long period.

Results: Visitor survey and interview responses

The interview questions about sound were organized in three groups regarding: 1) the relevance and meaning of sound; how the soundscape impacted the visitor experience in the virtual reality installation, 2) credibility of the soundscapes; to what extent a sense of realism was essential to the sense of presence, and 3) assessment of importance of the technical quality in modeling and delivering of sound (see Appendix).

In response to the overall question about how sound contributed to the experience (Figure 5), nearly all visitors were positive to the inclusion of sound, and did not believe that the experience would have been better without it (79 of 82, 96%). All except one of the visitors who had an opinion on whether the sounds fit with the visuals were positive, and this correlates well with Chueng and Marsden (2002), where visitors felt that inclusion of sound improved navigation and sense of presence. Most visitors (56 of 82, 68%) felt that the soundscapes seemed authentic, thus fulfilling expectations inherent in the visual environments, while six visitors did not. This correlates fairly well with the general questionnaire, where 74% answered positively to the statement that sound contributed to the sensation of "realness."

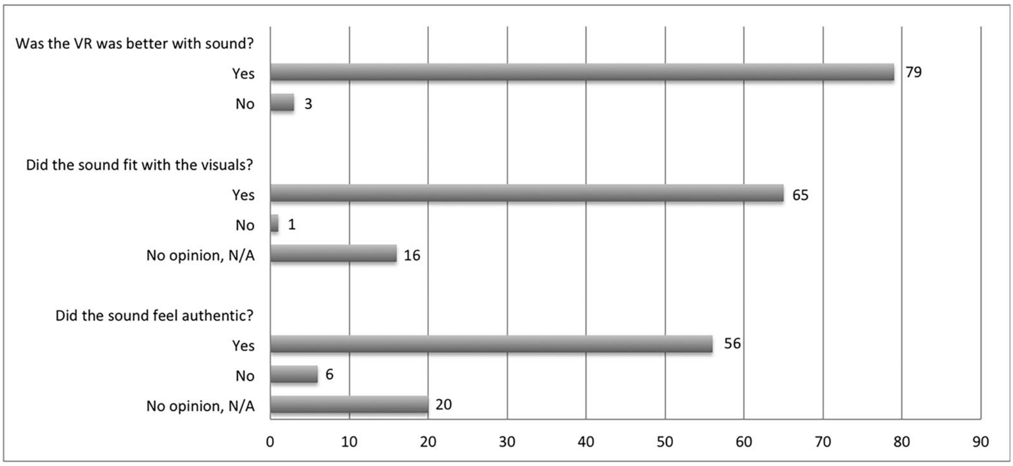


Figure 5. Responses to questions regarding relevance of sound in the installation.

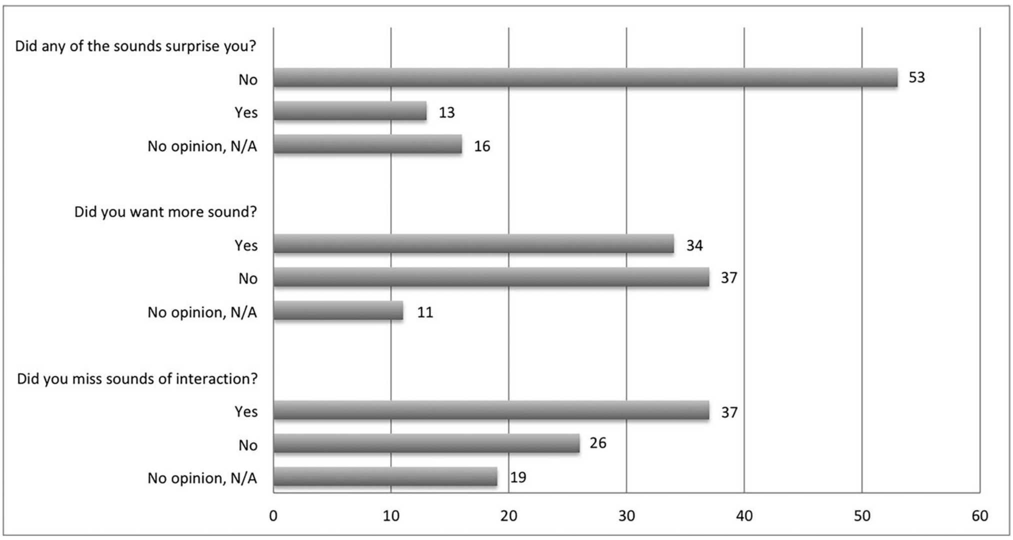


Figure 6. Responses to questions regarding credibility of the soundscapes.

However, and interestingly, when asked to name the sounds that they had heard, very few visitors remembered many different sounds. On average, visitors remembered only 3.3 sounds, with wind and waves remembered by nearly all. Very few visitors had noticed occasional sounds of trotting horses, and none had noticed the sounds of passing bicycles and airplanes in the distance. In sum, nearly all visitors felt that sound was important for their experience; approximately 79% felt that the soundscapes fit with the visuals, but almost no one remembered much of what they had heard.

Nearly two thirds of the visitors had not been surprised by any of the sounds they noticed (53 of 82, 64%), while 13 visitors (16%) had been surprised, mostly by sounds of dogs and insects (Figure 6). When asked whether they had missed any sounds, 34 of 82 visitors had not missed any sound in particular, while 37 (43%) had wanted more sounds.

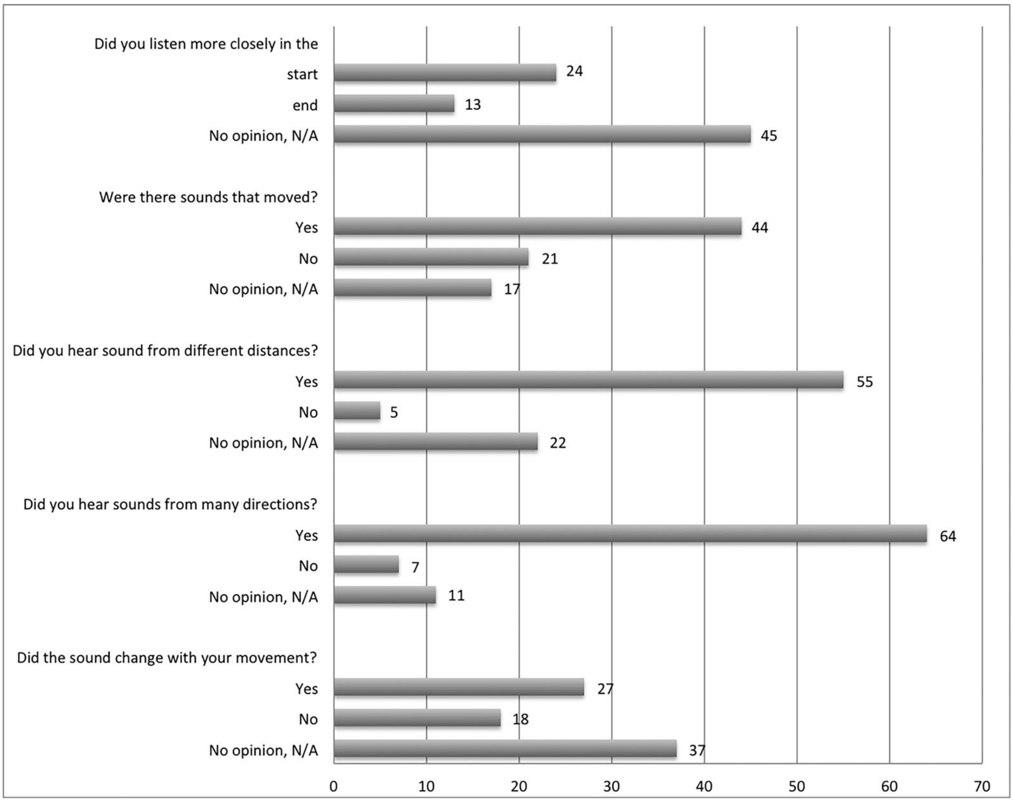


Figure 7. Responses to questions regarding critical listening.

The sounds they missed were typically from their own interactions with in the exhibition, such as step sounds, brushing sounds from virtual bushes and trees, and sounds of touch. On a second and more explicit question about whether they had missed hearing. sounds of their interactions, 37 visitors (43%) stated again that they had wanted to hear them, while 26 did not miss them and 19 offered no opinion. A few visitors also wished for a better experience of the architecture by having a richer sound environment unfold inside. Summing up, the soundscape was generally experienced as authentic and natural sounding (68%), even while it was not at the forefront of visitor attention. The other interesting finding was that 43% of the visitors wanted to hear sounds that linked their presence closer to the installation, making their interactions audible.

A majority of the visitors did not experience a difference in credibility between the outdoor environment and the villa environment (53 of 82, 64%). 37 of the visitors responded that they paid more attention to sound in the beginning or at the end of their exploration, while 45 reported no difference in attention (Figure 7). The exploration took about 15 minutes on average. Some visitors reported that their attention was stronger in the beginning because the situation was new and they "had all their antennas out," while others reported that they listened more toward the end, after having become used to the situation and could concentrate more on experience versus traversing the different levels of the installation. The museum guide encouraged visitors to sit down toward the end of their visit in the installation, and this also may have created a more reflective situation. Regarding quality of the delivery methods and the experience of more technical aspects of the sound, no one reported that sound had disturbed their experience or affected communication with their partners, or that the use of headset had been cumbersome. Only two visitors noticed that the sound material was split between loudspeakers and headset.

A little more than half of the visitors did not notice changes in the soundscapes when they toggled between worlds. A little more than half (44 of 82) noticed sounds that moved, 67% (55 of 82, surprisingly few) experienced the sounds as coming from different distances to the listener, and 78% (64 of 82, also surprisingly few) had noticed that sounds came from different directions, and mentioned insect sounds, birds and indoor acoustics. When queried specifically about how the sound in the indoor environment had changed with their movement and location in the installation, 18 visitors reported that they had not heard differences, while 33% (27 of 82) reported that they had been aware of differences in the loudness and acoustics of sound material. Several mentioned that outdoor sounds had been more prominent near the virtual door and window, and that the music sounded louder by the dining table (which it did), while others also noticed that this location was more quiet than the other sections of the installation. Again, a low attention to sonic details was apparent in the visitor data.

Discussion

Intervention-based research such as in this project yields subjective data on user experiences. Since many factors cannot be controlled for, the study might be a poor basis for making strong assertions. It is possible, for example, that reactions to the soundscapes would have been different if certain sounds had been added, or replaced some of the sounds that were included, especially if they signified something controversial. Sounds of a human passing crowd, for example, would probably have focused the listeners' attention on conversations in that crowd, and adding machine-sounds would have reduced the sense of both location and being in nature. Given a more distinct type of music chosen for the interior environment, musical tastes might have influenced the experience of being there. The discussion of soundscape construction must also include considerations of cognitive load – how much information curators and exhibition designers can realistically assume that visitors can process and for which level of complexity the experience should be designed. In this project, there were no indications that sound contributed any type of overload, rather, sound was accepted but did not become a focus for visitors.

The visitors encountered a relatively complex sound design, with 12 different banks of sounds. Each bank consisted of several similar but not identical sounds, which were played in semi-random order with irregular intervals in order to avoid repetition. This complexity was experienced by nearly all visitors as positive and was for a clear majority authentic-sounding. In other words, the sound enhanced the visitor experience in a positive manner and it is reasonable to assume that the complexity credibly simulated the natural situation, fulfilling expectations; from psychoacoustics we know that the auditory apparatus quickly goes into "surveillance-mode" and only reports unusual events.

The low levels of registered surprise and attention to placement and movement of sounds found in our study further indicate that the soundscapes were experienced as positive and natural parts of the VR experience. This is underpinned by the unsurprising fact that the average recognition of sounds was only 3.3, approximately 25% of the sound types in the installation. Despite this low recognition of the projected sounds, the soundscapes were unanimously experienced as positive, and the installation was believed to be better with sound than without. It seems clear that integration of complex soundscapes is beneficial for providing visitors with the sense of presence and being there, but that the complexity becomes “stripped down” to leave mainly an impression of authenticity. French philosopher Roland Barthes has described the difference between mere hearing and listening as the difference between a condition and a deliberate psychological action. This is also in keeping with the ideas of listening modes put forth by concrete music pioneer Pierre Schaeffer in his book *À la recherche d’une musique concrète* from 1952 and further confirmed by research in psychoacoustics. Three statements from visitors sum up this central finding: “You need ambient sound to complete the environment,”[7] “Sound added a layer of realism,”[8] “I probably noticed the sound more than I was aware of.”[9] The requests for interaction sounds confirm that the VR situation was a positive experience, and that the visitors wanted an even closer involvement in order to increase the realism and similarity with the physical world. Because human sensitivity to such interaction sounds constitutes important feedback in everyday experience, this is a particularly interesting area of research for gaining a better understanding of how accurate feedback sounds must be to address such expectations. The visitor statement “I missed hearing my own steps in the house”[10] points to step sounds as signs of interaction – the step sounds should capture the gait of one’s own steps. However, further research is needed to establish the complexity of step synthesis required for a credible experience.

It is commonly understood that the creation of a sound field with two loudspeakers or more increases engagement and emotional response when compared with single speakers (Västfjäll, 2003). High precision in wavefield synthesis, however, is complicated and expensive, as is an accurate construction of binaural sound. At the same time, there is a widespread notion that these advanced systems are necessary for rendering sounds that are credible enough for a sense of presence and realism. In this project, we investigated whether simplified and cheaper technologies could be adequate for achieving the desired result in AR/VR installations for museum use. A lower threshold can encourage more curators and designers to include sound in exhibitions, also in combination with newer technologies such as AR/VR. Presentation of 3 D compositions and soundscapes are preferably made in acoustically controlled conditions, but such spaces are not normally found in museums or galleries. The simplified configuration used in this project is hardly adequate for high levels of accuracy, but the visitor responses of satisfaction with both material and the sense of “being there” indicate that the technical aspects are less important for credibility than assumed by the 3 D sound community. This is an important finding in relation to the question about requirements for technical implementation. In the practical combination of loudspeakers for broad sound projection, and headset for near-field sounds and acoustic detail, these two playback systems tended to subjectively meld together – only one visitor was able to determine whether the sound was coming from the speakers or the headphones. This indicates that acoustically difficult spaces can be used for 3 D sound presentations as long as more critical and attention-demanding sounds and their movements can be rendered binaurally close to the ear. It is evident that this mix of sound sources can be quite robust, depending on the nature of the particular sounds.

However, the success of soundscape rendering also depends much on the content. The discourse in museum exhibitions is rarely focused on having sound quality carry significance, and simple VBAP projection augmented by binaural and head-tracking techniques for adjustment of virtual acoustics seems adequate for the absolute majority of exhibitions. It is important to make soundscapes complex enough to foster a sense of presence to emerge in the visitors, but not more complex than they need to be. More research is needed to better understand the level of complexity in soundscapes necessary for a simulation to be effective. Importantly, because this is a branch of research that differs from technical research on signal processing methods, it could well be initiated by the museum sector. The sound rendering optimized for the museum conditions in this project proved successful in regard to the visitor experience, indicating that 3 D sound can be robust without requiring specialized rooms to be effective in augmenting architectural exhibitions. This is interesting, since strong proponents of 3 D sound often insist that perfect acoustic conditions are crucial for the spatialization to have the desired effect.

Conclusion

This study found that sound added significantly to visitors' experiences of presence in a hybrid virtual exhibition, and that no visitors found sound to be disturbing. The study strongly suggests that inclusion of sound is beneficial for the successful sensation of realness, and that the sense of realness would have been less without sound. Although visitors could not name many of the sounds they had heard, the study showed high levels of recognition of distance, movement or other details in the sound. Regardless, visitors found the soundscapes to be authentic and natural-sounding, underscoring the psychoacoustic effect that hearing is replaced by listening when unexpected sounds appear. This is confirmed by the high level of recognition and recollection among visitors of a suddenly appearing sound of a flying insect. The strong correlation in positive reports on the inclusion of sound and realism of the sounding material suggests that authenticity in the surrounding soundscape is a valuable tool in electronically constructed environments.

Finally, the project shows clearly that visitors expected to hear sounds from their interaction. An analysis of complexity and credibility regarding such sound types are interesting for future research, to better understand how pure acoustic research of step sounds, for example, crucial for monitoring one's movements in any terrain, might be tempered by the social situation in an exhibition setting. Most visitors did not notice the hybrid delivery system for sound and none mentioned the exhibition space acoustics as having any impact on their experience of the audio. This implies that the operational mental filtering of sound is robust and that less-than-perfect acoustic conditions and technically downscaled audio models are sufficient for visitors to achieve a sense of value, authenticity and "being there." The findings thus serve as a basis for future work in evaluating the value of different complexity levels of 3 D sound modeling in exhibition contexts, and in studies of how previous listening experience affect listening in museum exhibits.

Notes

1. An early example of this approach is *Kroppsrom - Corporeal space*, and a presentation of this project can be found here: http://www.atelieroslo.no/index.php?id=77 Visited April 3, 2019
2. A short video shows the physical installation and the two views available through the VR headset: https://www.youtube.com/watch?v=luKCtHpnFfk Visited March 27, 2018
3. Video transcript 23.feb 2018, G1
4. Video transcript 22 feb. 2018, G3
5. Video transcript 22 feb. 2018, G4
6. Many of the survey questions on a general sense of immersion and feeling of presence were borrowed from the SOPI questionnaire, developed by researchers from Goldsmiths College. The ITC-Sense of Presence Inventory (ITC-SOPI) is a questionnaire that focuses on users experiences of media, with no reference to technical parameters. See: Lessiter, Jane, Jonathan Freeman, Edmund Keogh and Jules Davidoff (2001) "A Cross-Media Presence Questionnaire: The ITC-Sense of Presence Inventory." In *Presence Teleoperators and Virtual Environments,* 10(3), pp. 282-297.
7. Sound interview 63.
8. Sound interview 82.
9. Sound interview 46.
10. Sound interview 62.

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No potential conflict of interest was reported by the author(s).

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About the author

Jøran Rudi's first academic training was in social sciences, followed by a few years as a rock musician in one of the influential bands that emerged at the end of the 1970s. This brought him

in contact with electronic instruments and electroacoustic music, and he traveled to the United States and studied computer music at New York University. In 1990, he returned to Norway, and was brought in to be the founding director of NOTAM in 1993. From 1993 – 2010 he was responsible for the academic and artistic profiles of the institution, its research and development, mediation, education, administration and economy. Jøran Rudi stepped back to a researcher position at NOTAM in 2010. Rudi's research interests span wide, from educational issues arising from the use of music technology, via studies of artistic genres such as music, music animation, soundscape and sound art, to more conventional musicological work with a historical orientation. As a composer, Rudi has developed a portfolio of works for electronic instruments and/or fixed media, as well as for dance, film, performance art, installation and multimedia. His most significant artistic contributions are the computer music animations made in the mid- to late 1990s.

Appendix

Interview questions

The relevance and meaning of sound in the installation

- How did the sound contribute to the digital spaces, outside and inside?
- Would the experience have been better without sound?
- Did sound play a positive or negative role for the experience? How?
- Would you go so far as to say that the soundscapes sounded realistic?
- Which sounds did you hear?
- Did the sound fit with other aspects of the installation (visual, physical)
- Where did you like the sound the best – inside or outside?

Credibility of the soundscapes

- Did you hear sounds that surprised you or that seemed alien in the context?
- Were there sounds that you missed in the installation or would have liked to hear?
- Did you miss sounds from the interaction in the installation step sounds, sounds from touch, or other?
- Were you able to discriminate between the sounds heard from loudspeakers and headset?

Assessment of importance of technical quality in the delivery of sound

- Did the sound disturb your experience, did you feel that it was inappropriate in the experience?
- Did the sound disturb your communication with your partner?
- Did it feel cumbersome to wear a headset??
- Was the sound level to soft?
- Was the sound level to loud?
- Did the indoor environment sound more credible than the outdoor environment?
- Were you more attentive to the sound at the beginning or toward the end of your visit? Did the sound become more or less interesting?
- Did the sound environment change during your visit?
- Did you hear sounds that moved?
- Did you hear sounds from different directions? Can you mention some sounds and directions?
- Did you hear any difference in the distance to the sound sources?
- Did the sound environment change with your location in the installation?

And finally

- Is there anything else that you can say about what you heard?