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ORIGINAL PAPER

SonAir: the design of a sonification of radar data for air traffic control

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Abstract

Along with the increase of digitalization and automation, a new kind of working environment is emerging in the field of air traffic control. Instead of situating the control tower at the airport, it is now possible to remotely control the airport at any given location, i.e. in a remote tower center (RTC). However, by controlling the airport remotely, the situational awareness and sense of presence might be compromised. By using directional sound, a higher situational awareness could potentially be achieved while also offloading the visual perception which is heavily used in air traffic control. Suitable use cases for sonification in air traffic control were found through workshops with air traffic controllers. A sonification design named SonAir was developed based on the outcome of the workshops, and was integrated with an RTC simulator for evaluating to what degree SonAir could support air traffic controllers in their work. The results suggest that certain aspects of SonAir could be useful for air traffic controllers. A continuous sonification where the spatial positioning of aircraft were conveyed was experienced to be partially useful, but the intrusiveness of SonAir should be further considered to fit the air traffic controllers' needs. An earcon that conveyed when an aircraft enters the airspace and from which direction was considered useful to support situational awareness.

Keywords Sonification · Air traffic control · Situational awareness · User evaluation

1 Introduction

The field of air traffic control is currently experiencing a modernization process driven and necessitated by an ever-increasing density of aircraft where more efficient and cost-effective solutions replace older ones. This includes the digitalization of tools, such as replacing traditional paper flight strips with electronic flight strips [8]. An ongoing transition is to replace the function of physical control towers with remote control towers. With remote control towers, the traditional tower with air traffic controllers is replaced with camera towers capturing the outside view, and microphones recording audio from the airport. These remote control towers are monitored in a remote tower center (RTC), which can be placed at a separate location. This limits the amount of man-hours of an air traffic controller (ATCo) at the airport when there would only be a limited number of departures and arrivals for one day. An RTC includes a panoramic screen setup, as well as smaller screens for radar and interaction with the electronic flight strips. This enables a versatile environment where it is possible to control and monitor several airports simultaneously. However, it could lead to a more remote environment both physically and mentally, where situational awareness and sense of presence might be compromised. Furthermore, when remotely controlling an airport with low traffic density, it is important that the ATCo keeps the attention and focus necessary to complete the tasks.

As automation becomes more prevalent in air traffic control, ATCos believe that increased automation will increase the complexity of systems, making it more difficult to maintain situational awareness and stay in the loop [55]. This added information would be shown on visual displays, creating more visual clutter and cognitive overload [24]. The use of a digital solution in an RTC opens up opportuni-

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ties to convey information not only through visual displays. Informative sound is partly present in physical towers, where the sound of a starting aircraft engine can be heard outside of the tower, indicating that the aircraft will soon head for the runway, even before a request from the pilot has been received. This information is obtained in remote control towers through microphone input from the airport. What is heard through the microphones is the near-field audio from aircraft breaking upon landing, going along the taxiway, as well as taking off, providing awareness of the airport environment. However, surveillance of the airspace around the airport is monitored mainly through the radar display. By extending the auditory monitoring to the terminal manoeuvring area (TMA), a higher situational awareness could potentially be achieved for ATCos [6]. Moreover, sound has the potential to convey additional information on top of the already used visual modality without overloading it. Conveying information through sound is called sonification, which has the potential to complement the information and visualization of the radar display to support the ATCos in their work, and guide the visual focus of the ATCo to where the attention is needed the most [3].

The project aims to investigate the use of sonification in remote control towers. The aim of the study in this work was to develop one such sonification design based on the feedback from ideation workshops with air traffic controllers. By using directional sound, aircraft can be spatially positioned to their origin from the perspective of the control tower, creating an intuitive and immersive supplement to the radar display and the tower view. Feedback from workshops with ATCos was used to create a sonification design named SonAir. This design was evaluated with ATCos to test its helpfulness and usefulness in an RTC simulator (see Fig. 1). The contributions of the present study are as follows:

- The design of a novel sonification concept for continuous and real-time monitoring of airspace for RTCs.
- The integration of a real-time sonification of radar data with an RTC simulator.
- Analysis of qualitative evaluation results from ATCos of a real-time sonification in a simulator environment.
- Reflection of the design process of the sonification and the lessons learned throughout it.

2 Background and related work

Information is often presented visually in process control of dynamic processes. However, there is a risk of cognitive overload if too much information is presented in the visual modality [34,43,61,66]. This, in turn, might lead to neglected, ignored, or completely missed information [31,35,63]. In

Fig. 1 The remote tower center (RTC) simulator where the sonification was integrated and evaluated

work environments, sound is mainly used for warning sounds and the focus of the sound design is to distinguish these from the ambient sound of the environment [10,45]. However, when extensively using the auditory modality for alarms, there is a risk of inattentional deafness [5], also called alarm fatigue [44]. When designing a sonification approach for process control, a continuous sonification approach has been shown to improve situational awareness [14,22,25,27]. Sonification for process control can be approached with various types of sonification design, such as earcons, auditory icons, and parameter mapping sonification [17,20,21].

Situational awareness is "*the perception of environmental elements and events with respect to time or space, the comprehension of their meaning, and the projection of their future status*" [11]. In the context of air traffic control, it is related to the ATCo's ability to generate what is commonly referred to as "the Picture" of on-going air traffic [12]. Situational awareness is on the one hand their current Picture, that they rely on for decision-making. On the other hand, situational awareness itself is a continuous process of sampling information from the environment, and annotating the environment for future sampling. When an ATCo gives a landing clearance, for instance, the eyes follow a scan pattern to refresh and challenge their picture of the situation [59]. This pattern is intertwined with their overarching work pattern [32,33,54]. The awareness does not just reside in the head. It is a process that occurs in a situational awareness system of human and environment. The design of this environment is therefore crucial to the ability of maintaining situational awareness. They must be able to pick up cues for what is about to happen, as well as monitoring what goes on to discover deviations, while also working with specific parameters such as aircraft flight plans, altitudes and speeds [32]. The use of a remote tower center might compromise the situational awareness and therefore also the sense of presence (or embodied cognition

[15]) in the air traffic control environment. It has been argued that the use of multi-sensory integration can contribute to the spatial orientation in an environment [28].

Different studies have explored sonification for situational awareness in monitoring of dynamic processes [24]. Sonification can be used for the detection of anomalous events, periodicities, and dynamic changes [2,49]. Parameter mapping sonification can be used to support situational awareness of surveillance operators when monitoring video data, where different video features are mapped to sound parameters (stereo panning to horizontal position, sound frequency to vertical position, loudness to activity) [23]. Sonification can be used to support driver's situational awareness about traffic environment [16,29,41], and also to facilitate the monitoring of computer network activity [13]. By using auditory icons, e.g. recorded natural sounds, sonification can represent the real-time status of the network traffic environment and provide situational awareness for monitoring of network traffic features [7,58].

Sonification has been used to peripherally convey inbound and outbound aircraft around an airport [50]. The findings of the study highlighted that sonifying peripheral information created a positive addition to the visual information. It was found through interviews with ATCos that sound and sonification would fit best in a low to medium workload situation, when the operator's concentration and attention might need additional support. Other studies have also explored sonification of peripheral information for monitoring of dynamic processes [1,19,30], suggesting that audio is important for peripheral perception and that interactive sonification is a suitable approach for this purpose. The work of Reynal et al. [47] specifically concerned the use of spatial sonification in a multiple remote air traffic control environment, where a sonification concept was created to spatially position sounds to where aircraft around the airport were located [48]. The results of the study showed that the perceived locations of aircraft were more accurate during poor visibility conditions with sonification, although with longer reaction times. The sonification concept helped to improve the mental representation of an immersive environment and that it allowed ATCos to be more precise in the perceived location of spatial sound elements.

3 Method

The method to investigate the use of sonification in air traffic control in the present study was inspired by design studies in neighboring fields such as visualization [40,53]. Various validation methods were conducted throughout the project to ensure that relevant topics were covered, which are shown in Fig. 2. To investigate how sonification could support ATCos in their work, workshops were conducted where ATCos where interviewed as a group around how sound is and could be used in air traffic control. Next, a sonification design named SonAir was integrated with a remote tower center (RTC) simulator, and was designed according to the feedback from the concept workshop. SonAir conveyed the position and altitude of aircraft surrounding the airport and its airspace, which served as a complement to the radar display. Lastly, evaluations were performed to validate the usefulness of SonAir.

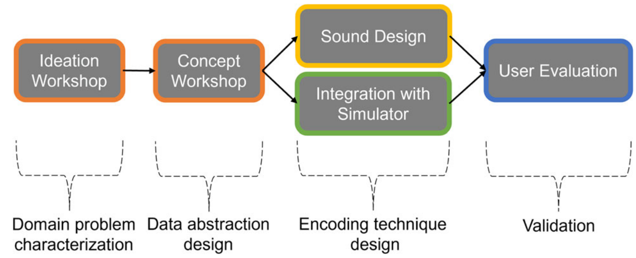

Fig. 2 The design process was inspired by design study frameworks in the field of visualization, and consisted of two workshops, a sound design and integration phase, as well as a final user evaluation

3.1 Ideation workshop

To identify problems and generate ideas related to using sound in an air traffic control environment, an ideation workshop was conducted to investigate how sonification could help ATCos in their work. This was done through a semi-structured group interview, where a number of topics were presented that the ATCos discussed around. The workshop was performed with three ATCos, with work experience ranging from military towers to large commercial towers in Sweden and Thailand, with an average work experience of 18 years (range 15–20 years).

During the workshop, it was suggested that sonification would be most suitable in low to medium workloads, where informative sounds can keep the ATCo in the loop, while in critical situations, adding sonification could lead to more cognitive overload. Peripheral information of aircraft was said to be useful, especially if it is combined with clearance such that events that are nominal are not presented. It was discussed whether the sound design of the sonification should resemble that of the real-life sound of an aircraft. A case could however be made that future remote ATCos would not relate to the real-life sounds that would otherwise be heard from physical towers.

Sonification concepts were created to concretize the feedback that was received from the ideation workshop. The concepts were created in SuperCollider [37], a real-time audio synthesizer software, where the sound synthesizer and images where used to create audiovisual concepts. A template was made in which an aircraft could be moved using

Fig. 3 Screenshot of a concept demonstrated in the concept workshop, where a layer of fog was added to the tower view to demonstrate low visibility operations. *Photo credit: Thor Balkhed*

computer mouse input to portray different situations from the aspect of the tower view. An example of one of the concepts can be seen in Fig. 3, where the sonification would convey the position of an aircraft to make up for the lost visuals in poor viewing conditions.

3.2 Concept workshop

The concepts that had been created were demonstrated at the concept workshop. Similar to the ideation workshop, this was done through a semi-structured group interview where video clips of the interactive concepts were shown to the participants (see Electronic Supplementary File 1). The workshop was performed with the same three participants as the ideation workshop, with the addition of a human factor researcher and a safety expert researcher in air traffic control.

An example of a sonification in poor viewing conditions was demonstrated during the workshop, as shown in Fig. 3. The concept was deemed useful since the sonification would give an earlier indication of an approach. Although the microphone input from the airport serves this purpose as well, the sonification could work as an extension of this, especially for aircraft that are landing since they are less audible. It was said to be useful to have this feedback as a continuous sound, to continuously monitor the landing. An example of a sonification to notify the ATCo of incoming and outgoing aircraft was demonstrated, which was said to possibly be redundant, since the controller receives radio calls from incoming aircraft for clearance. However, it was also said that it could be useful to sonify the different steps of clearances to release load from the visual modality.

Considering the positive feedback regarding the spatial sound positioning of aircraft, a continuous process monitoring sonification [22] for RTCs of a single airport was chosen to be implemented. This would support the situational awareness of ATCos by conveying the position and altitude of aircraft in the airspace through sound.

3.3 Integration with simulator

To enable prototyping and evaluations in a realistic environment, the sonification was integrated with an RTC simulator. The simulator transmits data using the Asterix (All Purpose Structured Eurocontrol Surveillance Information Exchange) standard, which is the most commonly used data format for real-life air traffic services [65]. The format is divided into separate categories, and is optimized for a limited bandwidth to be useful in constrained situations. The Asterix data of the simulated scenario is transferred to the different displays and devices through the simulator platform, which consequently was transferred to a computer to receive the data to use it in the sonification. The same data that was used by the simulator would therefore be used in the sonification. The data was decoded using the Python library *asterix4py*[1] and was sent to SuperCollider via Open Sound Control (OSC) [64]. The Asterix data of the RTC simulator contained the following data categories (also shown in Fig. 4): track number (ID), longitude, latitude, and altitude of aircraft in the simulation. The ID enabled to separate which altitude and positional data belonged to which aircraft. Since Asterix data is obtained through radar, only aircraft being airborne in the simulation would transmit information and would do so every fifth second, which would serve as a limitation to the sonification. From the Asterix data, new variables were created to be used in the sonification. Longitude and latitude data was used to create a Cartesian coordinate system that was converted to a polar coordinate system with the airport in the center. This acquired the radius, which together with the altitude gave the distance between an aircraft and the airport. The polar coordinate system also gave the horizontal angle an aircraft has with respect to the airport. The coordinate system was shifted to mirror the point of view of the tower view, such that zero degrees in the coordinate system corresponds to looking at the center of the runway. The converted data from the simulator was then mapped to sonification parameters to convey the information by using SuperCollider.

3.4 Sound design

By using the converted data from the simulator, a sonification design named SonAir was created that complemented the radar display by using the same data from the radar but conveying it through sound. To convey the presence of an aircraft in the airspace, every aircraft within the TMA of the airport outputs band-passed filtered brown noise, which was chosen to create an association of the sound of an aircraft engine, but not to the extent that it was a true simulation of the sound. By using parameter mapping sonification, the properties of the band-passed filtered brown noise were modified

[1] asterix4py: https://pypi.org/project/asterix4py.

according to the data. The following mappings were used in SonAir (also shown in Fig. 4):

- The position of an aircraft was mapped to the panning of the sound.
- The altitude of an aircraft was mapped to the center frequency of the band-pass filter that was applied to the sound.
- The distance an aircraft had to the airport was conveyed by modulating the band-pass filter that was applied to the sound.
- A notification sound was played when an aircraft entered the airspace of the airport.
- A continuous or pulsating envelope was used depending on if the aircraft was situated in the control zone or TMA.

SonAir was heard from the perspective of the tower view, which created a combination of perceiving the information from the radar display through the perspective of the tower view. SonAir continuously conveyed the altitude of aircraft, a property that is not visualized but is instead only visible numerically on the radar display. Additionally, SonAir notified when an aircraft has entered the airspace of the airport through a notification sound. By using SonAir, it was thought that the ATCo can maintain a higher situational awareness of the airspace by creating a mental model with the sonification.

The design decisions of the mappings were grounded in design guidelines from the field of sonification. The position and altitude mapping was used due to its frequent and tested use in other applications of sonification [9,39], while the distance mapping and sound characteristic contributed to the sense of presence and relatability of the sonification. The choice of mappings was also grounded in the results of the workshops with ATCos, where a general approach of the sonification was defined to offer mappings that were intuitive and relatable to the ATCos. Apart from the sonification design of SonAir, no other design was further developed or tested. The rest of this section gives further motivations of the mappings of SonAir and describes how they were implemented, which is also shown in Fig. 5.

The **position** of an aircraft was mapped to the panning of the sound, which was implemented using the Ambisonic Toolkit[2] in SuperCollider, which allows the positioning of sound independently of which audio output setup is used. Additionally, by using an head-related transfer function (HRTF), an elevation cue could be achieved through headphones. The horizontal panning was mapped to the position of an aircraft, while the elevation parameter was mapped to the altitude of an aircraft. However, while the human horizontal distinguishment of sound is fairly accurate, vertical distinguishment is less so [36]. This is due to that vertical differences are derived from spectral changes in the sound that is being heard, which are harder to both perceive and simulate, especially if only a generalized HRTF is used, which was the case in the present study [62]. Therefore, vertical separation through HRTF was considered a complementary mapping for altitude and was not evaluated. Consequently, an additional mapping was added to convey altitude.

The **altitude** of an aircraft was also mapped to the center frequency of the band-pass filter for the brown noise, which acted as the primary mapping for altitude. This was done such that a higher altitude corresponds to a higher frequency of the sound, similar to how an increase in height or value would result in a higher frequency of the sound in an auditory graph [38]. Since aircraft would only be audible within the TMA, the altitude interval was set to be from the ground to 9500ft above mean sea level. This interval was linearly mapped to a frequency interval of 100–5000 Hz. Since the radar only

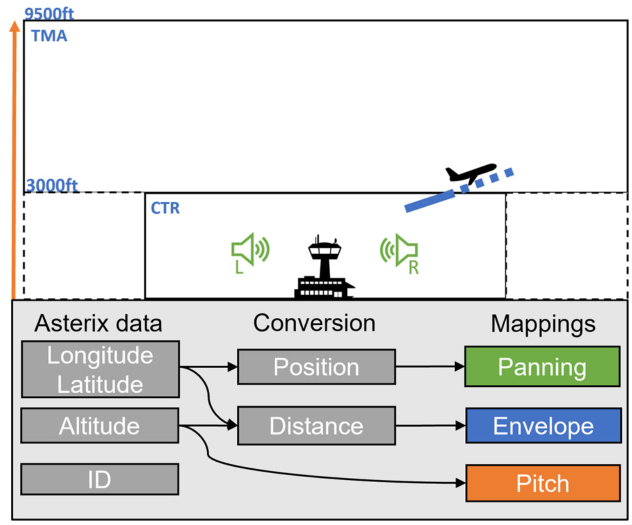

Fig. 4 Data and mappings used in the sonification design SonAir. The mappings are color coded to represent how they are used in the mapping illustration

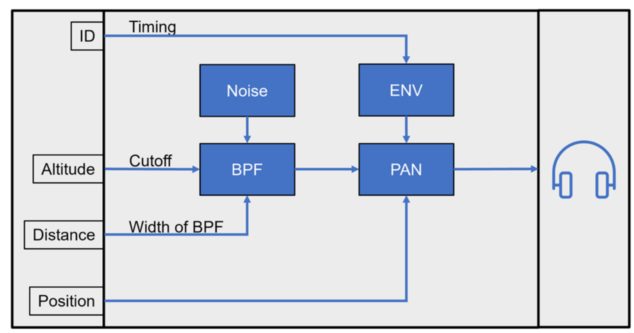

Fig. 5 The mappings of SonAir and how they were implemented. Bandpassed-filtered noise was heard for each aircraft in the airspace, and was modified according to the altitude, position and distance of the aircraft

[2] Ambisonic Toolkit: www.ambisonictoolkit.net.

registers airborne aircraft, the sound of an aircraft fades out over one minute to indicate that the aircraft has landed.

The **distance** an aircraft has to the airport was mapped to the width of the band-pass filter. This caused an aircraft closer to the airport to have a wider band-pass filter (up to a value of 0.2 for the reciprocal of the Q factor), which outputs more noise, while an aircraft further away would have a narrower band-pass filter (down to a value of 0.002 for the reciprocal of the Q factor). The wider band-pass filter would resemble the characteristic of the noise a real aircraft would emit, while the narrow band pass filter would resemble the sound of whistling. Additionally, when an aircraft enters the TMA of the airport, a short notification sound was played in the form of an earcon [18]. This sound was created by letting the sound transition from the lowest possible value for altitude and distance to the actual value of the aircraft over three seconds. This in turn creates an upward going frequency sweep, creating an auditory analogy of an aircraft "popping up" on the radar. Since it was part of the SonAir design and not an individual sound, it was also positioned according to where the aircraft appears, conveying to the ATCo from which direction the new aircraft entered the TMA.

SonAir consists of two different envelopes of the aircraft sound, depending on which area of the airspace the aircraft is located in, which is illustrated in Fig. 4 as the blue solid and dashed line. In the control zone, a continuous envelope was applied to the aircraft sound, meaning that it was continuously sounding while it was present in the control zone. When an aircraft is in the TMA of the airport, a pulsating envelope was used to convey the sound as a three second long pulse (similar to the characteristic of a sonar ping), which outputs a sound that quickly fades in and slowly fades out every time a new data point was received from the simulator. The pulsating envelope was used since aircraft further away from the airport are of less importance for the ATCo, therefore emitting less sound. It also creates a so called acoustic beacon, which is beneficial for the localization of auditory objects [57,60]. A new data point was received every fifth second and was done so sequentially for each aircraft, making it possible to monitor several aircraft at the same time. To convey the difference in position and altitude between two data points of an aircraft, a lag time was added to the change of the sound frequency and panning for both the continuous and pulsating envelope. For the continuous envelope, a lag time of five seconds was used to create a continuous transition between the data points. For the pulsating envelope, a lag time of three seconds was used to match the release time of the pulse, which enabled the listener to hear the altitude difference within the pulse itself.

Headphones were primarily used to output the sonification since it enables a 360-degree panning that the sonification was designed for, and that it is not dependent on the listeners placement. As described in Sect. 3.5, speakers would still be used in a version of the evaluation. This was motivated through the evaluation design, where more feedback could be collected with the ATCo while they were experiencing the sonification.

3.5 User evaluation

To validate the mappings and the usefulness of SonAir, pilot tests were performed during the design process. Initial tests of the implementation and evaluation procedure were performed with two of the ATCos that were part of the workshops, as well as with one research assistant involved in ATC. Improvements to the implementation were made according to the feedback from these tests, such as limiting the audible area of SonAir to the TMA of the airport, and having clearer distinctions between the control zone and the TMA.

For the final evaluation, SonAir was evaluated in three levels of realism with respect to the physical environment of the evaluation. The **Simulator** evaluation was situated in the RTC simulator which provided the highest level of realism, including an animated tower view, radar display, and electronic flight strip interaction, as shown in Fig. 6. The evaluation participant could see a fully animated tower view with aircraft driving on the taxiway, landing and taking off. Through the radar display, one could see the position and altitude of aircraft, as well as what callsign every aircraft had. Through a Wacom touch screen on the table, the participant could operate the electronic flight strips, giving clearance to incoming and outgoing aircraft during the scenario. The participant listened to the sonification through a pair of Beyerdynamic DT-770 Pro headphones. Closed-back headphones were used to attenuate sound from the simulator room and to reduce feedback loops as instructions were given to the participant through a microphone.

A **Desk** evaluation was set up in an office environment (as shown in Fig. 7) to enable more evaluations with ATCos compared to what would be possible in the simulator alone. It included the same scenario and questions as the Simulator evaluation and provided a similar kind of radar display, but lacked the animated tower view and flight strip interaction, therefore offering a lower level of realism. The setup consisted of two Genelec 8010A speakers that were positioned approximately 30 degrees from each side of the seating area and were connected to a Motu 8A audio interface. A computer monitor was used to give the impression of having the simulator tower view in front of the participant, although only displaying a still image. The laptop screen displayed a real-time radar display of the airport and its surroundings. As it was not possible to simulate the flight strip interaction, the participant was encouraged to listen to the sonification together with looking at the radar display, giving feedback about the sonification while listening to it, which was more suitable when using speakers.

Fig. 6 The RTC simulator used for the evaluations, including annotations for the different components. 1: Animated 3D Tower View of the runway. 2: Radar display for the airspace surrounding the airport. 3: Touch screen for interacting with the electronic flight strips. 4: Headphones used to listen to the sonification

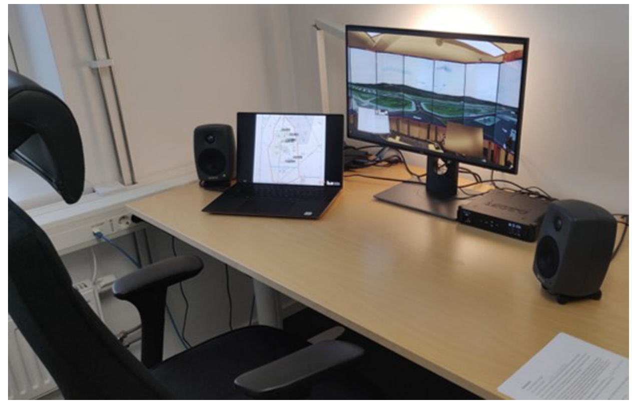

Fig. 7 The Desk evaluation environment, including a radar display, computer monitor showing an image of the tower view in the simulator, and speakers used to listen to the sonification

The Simulator and Desk evaluations were conducted in a qualitative manner to validate the design choices of SonAir. Additionally, an **Online** evaluation was conducted to further evaluate how understandable the mappings of SonAir were in a quantative manner. The Online evaluation was evaluated purely through sound, thus focusing only on the sonification, and was carried out with non-ATCos to allow a greater number of participants (considering the limited availability of ATCos). The Online evaluation was an online form which contained 15 audio samples of selected parts of the same scenario used in the previous evaluations (see Electronic supplementary File 3 and Electronic Supplementary File 6 for more details). After reading a tutorial of the mappings of SonAir, the participant would choose out of three options which best described the event that they heard for every audio sample. This would include where the aircraft was located with respect to the airport, and if the aircraft was increasing or decreasing in altitude. The last of the audio samples would include a scenario of several aircraft, where it was asked how many aircraft were heard and how they related to each other in terms of position and altitude.

The procedure for the Simulator evaluation started by introducing the participant to the study, informing about the context and that audio would be recorded during the session for analysis at a later time. Demographic questions were then asked, which included the participant's age, years of working as an ATCo and previous experience with RTCs. A tutorial was conducted for the mappings of SonAir. This was done through presenting different situations that would occur in the scenario, and how the sonification would convey this information during these situations. Moreover, another tutorial was used to explain the visual displays and possible interactions with the simulator. The entire introduction lasted approximately 10 min.

The actual evaluation then began by starting the scenario on the simulator. The scenario started with an aircraft appearing outside of the TMA of the airport. Shortly after that, an aircraft requests to take off from the airport to perform a touch-and-go landing training procedure. This essentially made the aircraft take off and then fly around the airport to land again, which demonstrated the positional sound panning in a concrete manner, while it was also possible to view the aircraft from the tower view. Throughout the scenario, at most four aircraft were airborne simultaneously. The scenario was considered to be of medium traffic density for a small airport. When the scenario was finished (which took approximately 25 min), the participant was given a questionnaire containing three sections, which was answered using a 5-point Likert scale. The first section asked about helpfulness, accuracy, situational awareness, workload and sense of presence in regards to SonAir. The second section asked about how suitable SonAir would be in different ATC environments and situations, which included physical tower, single remote tower, multiple remote tower, and low visibility operations. The content of these two sections was inspired by the evaluation form made by Reynal et al. [47]. Lastly, the third section contained a selection of statements from the BUZZ questionnaire [56], covering the general aspects of SonAir, such as how interesting, pleasant, and understandable it was perceived. For all statements in the questionnaire, a high rating corresponded to being in favor of the use of the sonification (see Electronic supplementary File 5 for more details). After answering each section, the participant was encouraged to comment on the ratings to give further qualitative insight. When the questionnaire was filled out, the participant was asked open-ended questions, which included how the participant would want to customize SonAir, such as limiting the audible area, and if there were any more kinds of data or events that was thought to be useful to sonify. After answering these questions the evaluation was completed, which typically took about an hour in total to complete. The Desk evaluation used the same evaluation procedure and scenario as explained for the Simulator evaluation, but instead lasted for about 40 min. A video showing a tutorial of SonAir and a snippet of the scenario used in the evaluation can be seen here (see Electronic supplementary File 2)[3].

3.6 Participants

Eight ATCos were part of the final evaluations, all of which operated in Swedish airports. Three ATCos participated in the Simulator evaluation, while five ATCos, as well as one person in ATCo education, participated in the Desk evaluation. The average age of the ATCos was 56 years (range 47–66 years), and the average of years working as an ATCo was 25 years (range 11–40 years). Five of the ATCos had experience of RTCs in different degrees. None of the participants had any previous experience with SonAir ahead of the evaluation. For the Online evaluation, 66 participants were part of the evaluation, which were students that were recruited through mailing lists as well as using the online service Surveyswap[4].

3.7 Analysis of evaluation results

The qualitative results of the Simulator and Desk evaluations were analyzed by summarizing the most mentioned topics, and by determining if a comment towards a questionnaire statement was positive or negative. However, the participants did not always have something more to add verbally, which is why the metric of these statements does not always add up to 9 participants. The quantitative results of the evaluation were summarized and displayed as a box plot, where 50% of the data is presented inside each box, and the rest of the data is distributed along the upper and lower quantiles. The thick horizontal line within the box displays the median value, and the **x** represents the mean value. For the Online evaluation, the result was summarized as a percentage of the number of correct answers for the altitude and position mapping. The quantitative results of the questionnaire answered by the ATCos are shown in Fig. 8.

4 Results

The results are from both the Simulator and Desk evaluation, considering that the ATCos took part of the same scenario and questions, see Fig. 8. The following subsections present the results of the questionnaire according to three different themes (support, experience and suitability), as well as presenting how the ATCos commented on their rating and whether it was positive or negative towards SonAir. The results of the Online evaluation are mentioned in conjunction with the ratings for the accuracy of SonAir to support the claims mentioned for this aspect.

4.1 Support from sonification

The majority of the ATCos (6 positive, 3 negative, where the 3 negative where all part of the desk evaluation) could see SonAir as a helpful tool, but only to a certain extent, giving it a median rating of 3 (mean 3.0). Overall, the aspect of SonAir that the ATCos saw most useful was the notification sound when an aircraft entered the TMA, especially for aircraft that would not contact the ATCo beforehand. In general, the ATCos suggested to only use a subset of SonAir, such as dividing the control zone and the TMA into separate audible areas. The ATCos gave a median rating of 3 (mean 3.2) regarding the overall accuracy of SonAir. It was said that SonAir might not be accurate enough to support precise decision-making, but instead to increase situational awareness and get an overview of the activity in the airspace. When judging the accuracy for position and altitude separately, the ATCos gave a median rating of 4 (mean 3.7) and 4 (mean 3.4) for the accuracy of position and altitude respectively. The ratings aligned with the results of the Online evaluation, where the participants answered 85% correctly on questions regarding the position of an aircraft, and 83% correctly regarding the altitude of an aircraft. Regarding situational awareness, which was given a median rating of 4 (mean 3.7), it was said (4 positive, 1 against) that SonAir had the potential to increase situational awareness, but that the intruvsiveness of SonAir needed to be considered. A couple of ATCos positively reacted on that they could form a conception of the airspace purely by listening. Regarding workload, which got the lowest median rating of 2 (mean 2.8), the ATCos stated that SonAir would affect workload negatively (2 positive towards it, 7 negative towards it), or at least distract from the task. The reason for this was said to be that SonAir was partly continuous and could be deemed too intrusive. However, one ATCo suggested that by listening through speakers the ATCo could more voluntarily listen to it, and that the aspect of getting continuous feedback when an aircraft started to land was deemed useful. Regarding the sense of presence at the airport, which was given a median rating of 4 (mean 3.7), if there was no microphone input from the airport, SonAir would increase the presence of the airport and the airspace.

4.2 Experience of sonification

The ATCos found SonAir to be interesting, giving it the highest median rating of 4 (mean 4.3), which was expressed by all

[3] Link to demo of SonAir: https://vimeo.com/693507203.

[4] SurveySwap: https://surveyswap.io

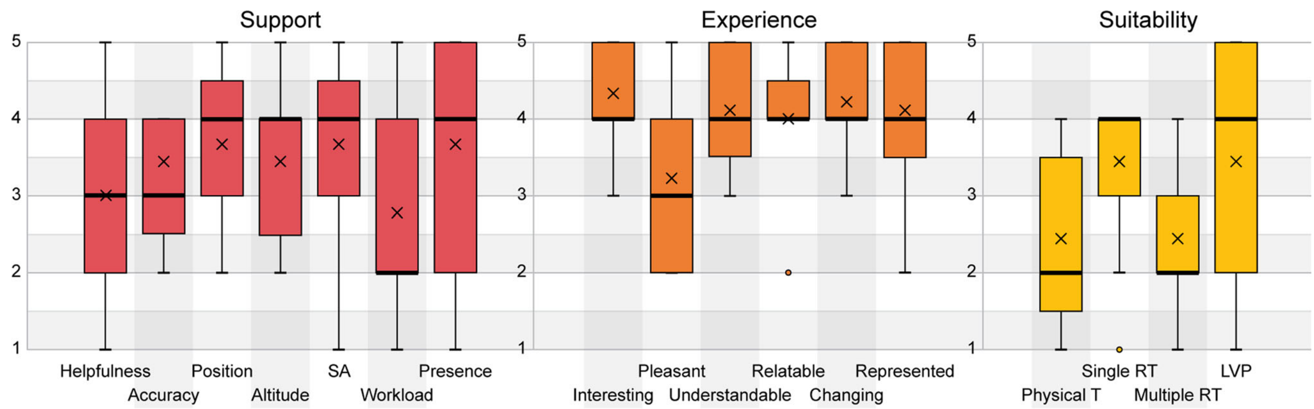

Fig. 8 Subjective ratings of the quantitative results for the eight ATCos and one person in ATC education, in both the Simulator and Desk evaluations. A higher rating corresponds to being more in favor of the use of the sonification for all of the statements. T: Tower, R: Remote, LVP: Low Visibility Procedures, SA: Situational awareness. The thick horizontal line within the box displays the median value, and the **x** represents the mean value

of the ATCos. The ATCos gave a median rating of 3 (mean 3.2) of how pleasant SonAir was to listen to, which was the lowest rating regarding the experience of the sonification. This was said to mostly relate to the amount of sound that was heard, and not necessarily to the characteristics of the sound itself. It was suggested by the ATCos to interactively be able to adjust the amount of sound by, for example, setting at which altitude an aircraft would be heard continuously. Some of the ATCos had difficulty hearing the higher frequencies of SonAir (2 had difficulty, 1 mentioned it). ATCos of older age and known hearing problems identified this issue, while the ATCos of younger age did not mention it. The ATCos also found SonAir easy to understand and relatable, giving a median rating of 4 (mean 4.1) and 4 (mean 4.0) respectively, referring to the tutorial that was done in the beginning of the evaluation.

4.3 Suitability of sonification

The ATCos rated that SonAir would be more applicable to single remote towers and during low visibility operations (giving a median rating of 4 (mean 3.4) for both contexts) compared to a physical tower and multiple remote tower, where a median rating of 2 (mean 2.4) was given to both contexts. For physical towers, it was deemed not as useful since it is a more crowded and noisy environment, and for multiple remote towers some ATCos saw opportunities while others saw difficulties (4 positive, 5 negative, where 1 of the 4 positives where from the simulator evaluation). For single remote towers, it was said that SonAir could be useful, especially in low traffic densities where the ATCo needs support to stay in the loop. For low visibility operations, the ATCos found SonAir to be applicable, considering that the visual modality is limited in these situations, and that every clue of the aircraft status and position is important to the ATCo.

Six of the ATCos repeatedly mentioned that sound was an important factor in air traffic control. As told by an ATCo, sound input from the airport was first not considered when developing remote towers since it was mostly seen as a side effect for the physical tower not being sufficiently soundproofed. However, it was later found that by removing sound, useful information was lost, which consequently lead to the implementation of microphones on the airport for remote towers. It was mentioned that SonAir had the potential to be used to support and build on top of the current microphone input implementation. Moreover, with increased automation in the future, it was said that the purpose of monitoring the airspace would increase, and that SonAir would fit to help with this task.

5 Discussion

Based on the outcome of two workshops with ATCos, a sonification design for aircraft monitoring named SonAir was developed to complement the radar display and tower view. The results of the evaluation with ATCos showed that SonAir was interesting, understandable, easy to relate to, and that there was potential for SonAir to be a useful tool. The intrusiveness of SonAir needed to be considered however, since it was stated that SonAir would negatively affect workload in its current state. Therefore, in an applied environment, only a subset of SonAir might be deemed necessary. The intrusiveness also negatively impacted the perceived pleasantness of SonAir. Since an ATCo would be exposed to the sonification during a longer period of time in a real working environment, the pleasantness of SonAir should be further considered while still keeping it informative.

The results showed that the altitude mapping of SonAir was deemed accurate enough for the purpose of the sonification, but less so compared to the position mapping since the exact altitude was not conveyed through the sonification. However, since SonAir acted as a complement to the radar display, an ATCo could still monitor the exact altitude of the aircraft when needed. The results also showed that the usage of high-frequency sound should be taken into consideration in the design process of a sonification, since that is an area where the perception of sound can differ the most between individuals, mostly due to declining high frequency sound perception with older age [46]. This was exemplified in the evaluation when an aircraft entered the TMA from its highest altitude, and then slowly decreased in altitude, creating a situation where the center frequency of the band-pass filter was 5000 Hz and the width of it was at its smallest. The reason for including high-frequency sound in SonAir was to have as wide of a frequency interval as possible, since if this interval was too small the altitude differences would not be as noticeable. A different scale instead of linearly to linearly could have been used for the altitude mapping, but since it was desired to put more emphasis on the lower altitude range, a linear mapping was chosen. Additionally, the use of different envelopes for the sonification helped to create a distinction between two intervals of altitude.

According to the results, the ATCos would think of SonAir as being divided into separate parts, and that the notification sound of an aircraft entering the airspace was seen as the most useful part of it. A design question that arose from this situation was whether SonAir should be treated as one comprehensive sonification with different aspects that are conveyed, or if it should be treated as separate sonifications. The benefit of one comprehensive sonification is that the different mappings can be more integrated with each other, creating a more unified soundscape. The notification sound for incoming aircraft was for example not a separate sound, but was instead the first sound SonAir would output when an aircraft entered the airspace. The benefit of this approach was that it could utilize the spatial positioning and that it would better fit with the soundscape that was already implemented. The disadvantage with this approach however was that it would be harder to separate the sonifications. Separate sonifications would for example be useful if the ATCo would want to choose which sonifications should be audible, or that automation in future applications could decide what parts of SonAir would be audible at different times, for example depending on traffic density.

The main evaluation environment was the RTC simulator, which was complemented with additional evaluations in an office environment, using the same scenario and questionnaire. The three ATCos that did not see SonAir as a helpful tool were all part of the desk evaluation, which could indicate that it was harder to see the potential of the sonification when it was not evaluated with the target platform. Regarding the time constraints of the evaluation, one ATCo mentioned that there would be a learning curve to become familiar with the concept (similarly to visual ATC displays [51,67]), requiring more time with the sonification to truly evaluate its usefulness. Not only was there a limited time to go through the tutorial that was needed for the ATCos to understand the mappings, but the fundamental task of understanding information through sound is one that has to be trained over a longer period of time [4,42,52]. Additionally, non-experts were part of a quantitative evaluation of SonAir, which is a common approach when there is limited availability of domain experts [51].

5.1 Future work

The evaluation procedure for the present study was conducted such that the ATCo would listen to SonAir and compare it to their normal working environment. Future work could evaluate SonAir in a more comparative manner, such as running a scenario with and without SonAir to evaluate it in a more quantitative manner to determine how and to what degree it supports the ATCo. This would enable a stronger basis for the use of sonification in air traffic control. Additionally, repeated evaluations of SonAir over a longer period of time could be conducted to further investigate how the level of familiarization with SonAir affects the outcome of the evaluations.

The sound design used in the present study was based on band-passed filtered brown noise, which resembled the sound characteristics of a jet engine. A further development of SonAir could be to create stronger associations to the type of aircraft in the airspace, such as distinguishing between commercial and general aviation, or even to distinguish between specific aircraft or airlines. SonAir could also be extended to convey ground vehicles at the airport, notifying when there is a vehicle on the runway. This aspect was however not investigated since there was no radar coverage on the ground for the simulated airport. In contrast, other sonification approaches with different aesthetics could also be developed and evaluated to compare the implementation made in the present study to other sonification designs.

Considering the appreciation of the notification sound that notifies when an aircraft enters the airspace, more concepts could be developed where earcons can be used as spatial notification sounds together with the continuous sonification. The positioning of radio calls to their location could be added to the design of SonAir, since the aircraft location is already included. A more developed concept for multiple remote tower could also be created, to further investigate the opportunities and challenges of sonifying data from two or more airports. Moreover, the design concepts of SonAir could be transferred to other domains where monitoring of dynamic processes is of importance, such as unmanned traffic management [26] and cybersecurity [13].

6 Conclusion

The work presented in this paper aimed to develop one sonification design based on the feedback from ideation workshops and to evaluate this design with air traffic controllers in an RTC simulator. Domain characterization was formed through an ideation workshop with ATCos, and design concepts were validated through a concept workshop. A sonification design named SonAir was developed based on the outcome of the workshops, and was integrated with an RTC simulator to enable evaluations in an realistic environment. Nine individuals with ATC experience participated in the final evaluation, where the result suggests that sonification can be useful in air traffic control. An earcon that conveyed when an aircraft enters the airspace and from which direction was considered useful for situational awareness. The spatial positioning of aircraft conveyed through a continuous sonification was said to be partially useful, but that the intrusiveness of it should be investigated to fit the ATCos needs. The results also showed that the use of high-frequency sound in sonification should be considered, as the perception of this varies between individuals, and specially with age. Overall, the results gave knowledge that could be applicable to other domains where process monitoring is of importance, such unmanned traffic management and cybersecurity.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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