Auralization uses in acoustical design: A survey study of acoustical consultants

David Thery,[1,a)] Vincent Boccara,[1] and Brian F. G. Katz[2]
[1]*Paris-Saclay Université, LIMSI-CNRS, UPR 3251, F-91400 Orsay, France*
[2]*Sorbonne Université, CNRS, Institut Jean Le Rond d'Alembert, UMR 7190, F-75005 Paris, France*

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While auralization technology is used in a variety of fields, particularly in architectural acoustics, there is a lack of data on the auralization tools used and actual practices. In this perspective, this work presents the results of a survey study on auralization uses in the acoustical design and consulting community, targeting acoustical consultants. The objectives are (1) to identify the tools and methods used by acousticians to create auralizations as well as effective uses so as to understand the benefits and changes provided by this technology, and (2) to highlight the difficulties and limitations linked to the use of auralizations in concrete projects. Based on the theory of acceptability and use of technology, the study was conducted from a mix of quantitative and qualitative data collection approaches, combining a questionnaire answered by 74 respondents with semi-directed interviews with nine practitioners. Results highlight the main uses of auralizations, the diversity of projects in which auralizations are applied, and how auralizations are currently used in real-world situations. The benefits of using this technology, inherent weaknesses in the tools, and practical difficulties are also discussed.
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[MV] Pages: 3446–3456

I. INTRODUCTION

Analogous to visualization, auralization describes the audible rendering of an acoustic simulation (Kleiner *et al.*, 1993; Lokki *et al.*, 2002). Room acoustic simulations have been used for over 50 years, since Krokstad *et al.* (1968) first presented a method for computing room acoustic responses for different receiver positions. Computer processing power has since increased, enabling the improvement of auralization renderings. Such simulated auralizations have been subjectively comparable to measured ones (Postma and Katz, 2016), providing confidence for use in concrete industrial projects.

Three main components are used in order to describe the process of auralization (Vorländer *et al.*, 2015): (1) the audio source material, to be convolved with (2) the impulse responses of a given space at given positions, resulting in an auralization to be rendered on (3) a given sound rendering system (Headphones, Multi-speaker layouts,…).

Impulse responses are either measured or simulated. In the latter case, several methods exist, from ray/cone-tracing algorithms, to image-source, wave-based, or even hybrid methods. It is generally agreed that ray/cone tracing algorithms and image-source methods (generally used in commercial software dating from the early 1990s such as CATT-Acoustic[1], EASE[2], and ODEON[3]) are more efficient (in terms of computation time) and better suited for mid and high frequencies, while wave-based algorithms are more precise at lower frequencies, while being computationally more demanding.

[a)]Electronic mail: david.thery@limsi.fr

Auralizations have been extensively studied in research, with numerous studies assessing the quality of simulations (Postma and Katz, 2016; Pätynen *et al.*, 2008), but also for archaeological investigations (reconstitution of the acoustics of past venues (Murphy, 2006; Suárez *et al.*, 2018). Three-dimensional (3D) reconstitutions have also been presented in virtual reality (VR) (Poirier-Quinot *et al.*, 2016; Savioja *et al.*, 2003), opening the door to multimodal perception studies. To support the shift from research to industrial applications, recent developments have focused on ways to better integrate auralizations in architect workflows; for example, Pelzer *et al.* (2014) developed a real-time auralization plugin directly integrated into Sketchup,[4] a well-known modeling tool for architectural modelling.

In the acoustical consulting community, auralizations are particularly suited for the design of public spaces, restaurants (Hochgraf, 2017), and art-oriented spaces such as concert halls or museums (Azevedo and Sacks, 2014). These studies show the diversity of potential applications for auralizations, as well as actual examples of use in architectural acoustics projects, including design variables and requirements that clearly depend on the type of project. For instance, Hochgraf (2017) shared their experience with auralizations and identified four main uses: (1) they are useful to communicate with clients, enabling them to have a direct listening experience of the space without being confused with acoustical terms; (2) they help very much in design decision-making, enabling the simulation of different configurations and potential uses of the space to be built/renovated; (3) they help to eliminate unwanted defects once the space is finished; and (4) they build enthusiasm and can be used as a fund-raising tool. She also insisted on the importance of

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calibrating levels, the inclusion of Lombard effect modelin (Stowe and Golob, 2013), and the use of appropriate high-quality anechoic material as audio source (Pätynen *et al.*, 2008), to be able to realistically simulate the space. From the same firm, Azevedo and Sacks (2014) recall these same uses and advantages of using auralizations by reviewing different use cases. This has driven them to choose real-time convolution auralization renderings (using Max[5] with pre-computed impulse) rather than pre-convolved auralizations, due to the required responsiveness in architectural projects with aggressive deadlines, but also to reduce the time and associated cost. This type of real-time auralization enables them to easily toggle between configurations, letting the client better understand the differences between design options. These experiences also demonstrated that using auralizations can reduce/avoid extra project costs. Whereas this technology has been used in a variety of projects (and particularly in architectural acoustics), except these cited studies, there is a clear lack of data regarding the tools used, their usability, and actual practices in the acoustical consulting community.

In the related field of VR technology, Woksepp and Olofsson (2008) investigated the use of VR models *in situ* by following projects of large constructions. With that methodology they studied how VR models were experienced and assessed by involved professionals, and "to what extent VR can complement the use of traditional 2D CAD drawings" and other types of visualizations such as hand-drawings. They also investigated how VR models were applied and accepted by professionals in the design and planning process. They concluded that VR was very useful for large constructions, being helpful in design decision-making by facilitating information handling and being a performance catalyst. That study focused on the users, which is necessary for the assessment of adoption of the technology. In the same way, Defays *et al.* (2014) investigated the benefits of providing visual cues for the task of evaluating the reverberation of a given space, in the context of the design process of a multimodal 3D simulation environment. They investigated the effect of expertise level by comparing the performance of architects versus non-architects, showing that architects performed better in the task. The degree of adoption of VR technologies in architecture has been investigated in a few studies (e.g., Atkins, 2017; Castronovo *et al.*, 2013). Atkins (2017) suggested that these technologies have the potential to improve productivity but are not yet adopted by the architectural community. However, such investigations have never been carried out regarding auralizations and the acoustic design and consultant community.

In this context, the current work presents the results of a survey study on auralization uses in the acoustical design and consulting community in order to assess the needs of acoustical consultants and orient the developments of the next generation of auralizations tools. To address these questions, two main objectives drive this study:

(1) Identify the actual practices and the tools used by acousticians to create auralizations.
(2) Highlight the benefits, as well as the difficulties and limitations, linked to the use of auralizations.

Section II introduces the theoretical framework that oriented the survey on auralization uses: the acceptability theory model. Section III describes the method used for this survey. Results are presented in Sec. IV, followed by a discussion on their contributions for the next generation of auralization tools in Sec. V, and a conclusion in Sec. VI.

II. THEORETICAL FRAMEWORK

Currently, it is well-known that technology development and product design need to integrate final users and usage analysis very early in the processes (ISO 13407:1999, 1999; ISO 9241-210:2010, 2010). However, when and how to integrate user's needs and usage for a new tool remain a challenge (Bobillier-Chaumon, 2013). The term *use* primarily refers to a human action in the real-world - the fact of using something by someone to reach a goal. However, in design, it can also refer to a function or a purpose (Buisine *et al.*, 2010). Studying declared and effective *uses* is then a mean to identify the functions of a new tool coherent with the user practices. Use also concerns a more general dimension including customs and practices. Use is then a representation of all of the social practices linked to the tool. It also includes habits, and appears as the result of experiences and beliefs, whether individual or collective ones.

To understand this phenomenon, researchers have developed technology acceptability theories. Barcenilla and Bastien (2009) defined acceptability as *"the degree of integration and appropriation of an object in a context of use"* (p. 311), linked to the notions of adoption and diffusion of the technology. *Integration* refers here to the manner in which the technology is integrated in the user's effective practices in real-world situations. *Appropriation* refers to how the user has invested him- or herself in the technology, and how the user can effectively use the technology to attempt their own goals. There are three complementary acceptability-theory approaches: social, practical, and situated (Bobillier-Chaumon, 2013).

Social acceptability is a predictive approach. It aims at studying the use of a technology beforehand, to anticipate its acceptance before the design phase. Studies are generally model-based, including Technology Acceptance Models (TAMs) and Unified Theory of Acceptance and Use of the Technology (UTAUT) (Venkatesh *et al.*, 2003; Williams, 2015) models. In this approach, relevant dimensions are *perception and behaviors*, *perceived utility* and *usability*, and *social influence*, which are assessed with questionnaires. A good review of social acceptability studies can be found in Williams (2015).

Practical acceptability concerns essentially the user experience, taking into account human-machine interaction difficulties and aiming at optimizing the ergonomy of the tools. This can be assessed through needs analysis, use survey, or usability study. The dimensions that are assessed are *utility*, *usability*, and *accessibility* (including cost, compatibility, and reliability), as detailed in Fig. 1. An example of a study using this approach is Weistroffer *et al.* (2013), where questionnaires were used to assess the acceptability of human-robot collaboration using VR environments.

Considering these approaches insufficient to study technology acceptance, Bobillier-Chaumon (2013) proposed the

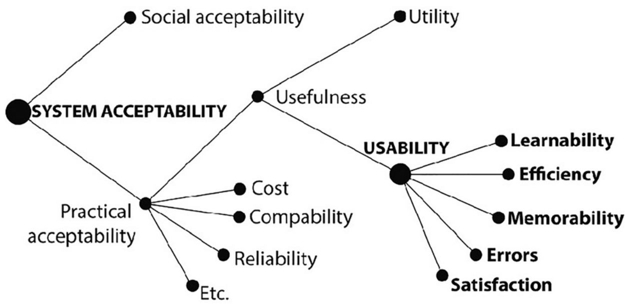

FIG. 1. Nielsen's acceptability model (Nielsen, 1994, Fig. 1).

concept of *situated acceptability*, as a descriptive and comprehensive approach (Béguin, 2007). Here, acceptation focuses on concrete experiences and actual situations of use of the technology, taking into account the dynamic and unpredictable character of the user's activity (the technology's function, how the user interacts with it), which is dependent on the user, his/her goals and the characteristic of the environment. In other words, the situation's characteristics influence how the technology is used, and this phenomenon impacts the individual and collective activities by redefining procedures and exchanges. Studying effective uses in this approach requires an ergonomic analysis. While the methodology to assess this situated acceptability are still unsteady (Ianeva *et al.*, 2017), ergonomics analysis traditionally combines interviews and observation in real-world situations in order to understand the effective and potential uses of the technology.

This survey aims at identifying rather than predicting auralizations uses, and therefore focuses on practical acceptability; the survey also aims at obtaining descriptions of real situations of use and is consequently also supported by the situated approach. The definition of the dimensions contained in the practical acceptability (as depicted in Fig. 1) are detailed here:

- Cost, Compatibility with the activities, Reliability (of the system and the results)
- Usefulness
  - (a) Utility: what the technology is used for? Is it useful regarding your activities?
  - (b) Usability
    - (i) Learnability: can be measured by the time it takes to reach a certain level. One should keep in mind that users normally do not take the time to learn the entire system before starting to use it. Easy to understand messages, possible to do useful work before having learned all of it, availability of undo, confirmation questions before execution of risky commands.
    - (ii) Efficiency: refers to the expert user's level of performance at the time when the learning curve flattens out.
    - (iii) Memorability: time it takes to remember how to use it.
    - (iv) Errors: users should make as few errors as possible when using the system. Errors could be more catastrophic in nature as they are not discovered by the user.
    - (v) Subjective satisfaction: the amount of time users spend does not matter if they enjoy using it (related also to the aptitude to use it and the entertainment value of the technology).

III. METHODOLOGY

A. Global approach

The analysis of auralization uses has been addressed in two phases, a quantitative and qualitative one. The quantitative phase was an online questionnaire sent to acoustical design offices around the world, while the qualitative one consisted in semi-directed interviews with a few consultants having previously answered to the questionnaire.

The quantitative phase aimed at identifying tools and uses, assessing the practical acceptability of the technology, as well as its evolution and potential future uses. To complement these quantitative data, the qualitative phase provides more detailed verbal descriptions of effective use-cases and common practices using auralizations in the acoustical design community.

B. Quantitative survey

1. Population

The online questionnaire[6] containing 53 questions was electronically submitted to 460 acoustical design offices around the world (312 located in France and 148 in other countries). Recipients were identified through lists available via the National Council of Acoustical Consultants (NCAC) and the French Acoustical Society (SFA). The invitation was resent an additional two times, at ten day intervals.

Response rate: From the 460 invitations sent, 74 complete responses were received (56 from France and 28 from other countries), leading to an 18.2% response rate. A similar percentage only partially responded to the questionnaire (17.6%), but these incomplete unexploitable responses were not taken into account in the analysis.

Profiles of the respondents: Respondents were essentially male (95%). Ages varied from 21 to 60+years, with a significant proportion aged 50+ (40%). A majority were experienced acousticians (65% with more than 10 years and 25% with 5 to 10 years of experience), generally holding at least a Master's or engineer degree (62%, 20% having a Ph.D.). Four job roles were identified: director (38%), senior manager (26%), consultant (10%), and team manager (6%) with the remaining respondents indicating other job roles such as staff scientist, independent acoustician, or professor.

Company sizes varied from small (< 10 employees, 50%) to medium (10 to 50, 27%), with the remaining working at large companies (more than 50).

2. Questionnaire structure

As the study is based on the practical acceptability, the questionnaire was designed with the objective to assess each of its dimensions (see Fig. 1). The reasons for the non-use of the auralizations were also investigated, with a section dedicated to these non-users. The tools used and the current and future uses were also investigated in specific sections. Question types included single and multiple responses, Likert Scale responses (4 or 5 points depending on the questions), and open-ended questions. In total, the questionnaire contained the following six sections, with 53 questions, in the following order:

(1) *General Information* to gather general information about the respondent and company profiles (12 questions).
(2) *Reasons for the non-use of auralizations* to understand why the non-users do not actually use the technology – *Only presented to non-users (four questions).*
(3) *Tools* identified the different methods/tools used to create auralizations (seven questions).
(4) *Uses of auralizations* identified current uses of auralization (ten questions).
(5) *Assessment of practical acceptability* addressed the dimensions of the practical acceptability, assessed using Likert scales (15 questions).
(6) *Future uses and the evolution of the technology* (five questions).

C. Qualitative survey

1. Population

Corpus description: Nine acousticians were interviewed, all having previously answered the questionnaire. Subject IDs were assigned chronologically (see Table I, Subject S1 being the first one interviewed). Interviews were carried out either in person (3 of 9) or by video-call (6 of 9), depending on the location of the interviewee. These interviews bring valuable descriptions of actual uses, difficulties, and benefits, and assist in the understanding and interpretation of the questionnaire results. However, the number of interviews and their duration does not allow the application of quantitative analysis to the data (e.g., counting the occurrences of a category).

Table I summarizes the background information, duration, and quantity of content production for each interviewee. Three interviews lasted approximately 20 min, four lasted 27 to 38 min, and two lasted roughly 1 h. In terms of speech production, there were generally ~100 words/min, with three faster speakers at around ~150 words/min. All discourse of the interviewees was processed using thematic coding. In total, 776 segments were manually thematically coded, as described later, in Sec. III C 3.

Profiles of interviewed consultants: Six interviewees were American, three were French. As shown in Table I, two had never used auralizations. There were also two rare users of auralizations (from two to nine projects), two occasional users (10 to 50 projects), and three intensive users (more than 50 projects), providing a panel covering a large range of levels of experience with the technology. It should be noted that they were all (very) experienced acousticians (with minimum five years of experience in acoustics, the majority having more than 10 years of experience).

2. Interview guide

After a brief reminder of the objectives of the study (the interviewer recalled "*In this interview, I am looking for insights into the opinions and attitudes that acoustical consultants have towards the auralization technology. This research was launched since only few resources exist on the actual uses. Therefore, we seek to understand the use of auralizations in acoustical design offices, investigating in particular the advantages and the limitations of its usage*."). An initial interview guide was prepared to complement the data obtained from the questionnaire; it was composed of the four following categories:

- *Tools*: software used, advantages/drawbacks, auralization creation process, reliability of the results, rendering system used, visual, or VR coupling.
- *Modalities and conditions of use:* what the technology is used for, how it is used, which actors are involved in the use of the auralization.
- *Difficulties, constraints, limitations:* whether regarding the tools or practical aspects of the projects.
- *Future and evolution* of the technology, intended use of the technology with regards to improvement of computers performance and accessibility of tools.

This interview guide was progressively enriched from interview to interview in an iterative way, as described in Sec. III C 3.

TABLE I. Profile information for interviewed consultants: Country/Language (English = En, French = Fr), Age, Number of Years of Experience in Acoustics, User or not of auralizations, Number of employees (acousticians) in the acoustical design office, Number of projects per year, Average budget per project (with or without auralizations, Duration of the interview, and Talking rate.

Subject ID	1	2	3	4	5	6	7	8	9
Country/Language	France/Fr	US/En	US/En	Australia/En	US/En	France/En	US/En	France/Fr	US/En
Age	30–39	40–49	50–59	40–49	60+	40–49	60+	40–49	30–39
Years of Experience	5/10	5/10	10+	10+	10+	10+	10+	10+	10+
User of auralizations	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Number of employees	1	50–250	2—9	5000+	10–49	2–9	1	10–49	50–250
Overall number of projects with auralizations	0	50+	10–50	10–50	0	2–10	2–10	50+	50+
Average project budget of the company (k€)	2–10	10–50	>300	100–300	N/A	10–50	10–50	100–300	10–50
Interview duration (min)	38	20	57	33	19	27	35	70	19
Ouptut (words/min)	151	96	132	94	80	146	98	92	102

3. Treatment

The recorded interviews were integrally transcribed, enabling thematic analysis of the data (Braun and Clarke, 2006). The analysis was performed using MaxQDA.[7] Thematic analysis is a widely used method for identifying, analyzing, and reporting patterns (themes) within qualitative data. The unit of extraction is called a segment and represents the shortest text extract which self-contains a meaning. Patterns can be identified in two primary ways: inductive/bottom up (Frith and Gleeson, 2004) or in a theoretical or deductive way (Boyatzis, 1998). In the inductive approach, the identified themes constituting the coding system are strongly related to the data themselves. Inductive analysis is therefore a process of coding the data without trying to fit it into a pre-existing coding system. This type of coding is called data-driven. Conversely, a 'theoretical' thematic analysis would tend to be driven by the researcher's theoretical framework, and is thus more explicitly analyst-driven. This form of analysis tends to provide less of a rich description of the data overall, and more of a detailed analysis of some aspects of the data, related to the dimensions of the chosen framework, as described by Braun and Clarke (2006). Relevant examples of such type of qualitative analysis can be found in Toerien and Wilkinson (2004) and Kitzinger and Wilmott (2002).

In this work, a hybrid treatment method based on these two approaches was applied: the initial guide was designed based on the questionnaire responses, and included questions linked to practical acceptability, particularly to obtain descriptions of real projects and concrete practical difficulties. This guide was then enriched from interview to interview, as described in Sec. III C 1: for instance, unexpected subcategories of the difficulties were created, that were used in the subsequent interviews, and providing a broader view to the interviewer. At the end, it contained nine themes and 25 sub-themes. As an example, one category was *Collaboration*, and included the following sub-themes: *Teaching Acoustics*, *Communication*, *Convincing*, and *Relation with the client*. All the other themes are not reported, as the analysis is performed at a subsequent stage, as explained below.

For each interview, a coding step was carried out, consisting in the assignment of a theme or sub-theme to chosen extracts of the transcribed interview. The length of theses extracts was not constant, being selected as soon as they provided a meaning, from a couple of words to whole or even two sentences to recall the context. The final step was to analyze each of these themes and the data contained in it, and to assign it to a dimension of the practical acceptability, for a clearer and more concise analysis.

IV. RESULTS

This section presents the quantitative results from the questionnaire as well as interview excerpts to better qualify and interpret the data. For the sake of clarification, global percentages correspond to questionnaire results, while X/N represents the number of interviewees sharing an opinion. Similarly, the term *Respondent* designates the respondents of the questionnaire while *Interviewee* corresponds to the interviewed participants.

In the following, results are presented as follows:

(1) *Projects*, including *Questionnaire* and *Interviews*, in Sec. IV B.
(2) *Tools used*, including *Method of Creation*, *Sound rendering system* and *Coupling with visual/VR*, in Sec. IV C.
(3) *Practical acceptability*, including *Usefulness*, *Usability*, *Cost*, *Compatiblity* and *Reliability* in Sec. IV D (dimensions definitions are given in Sec. II).

For each topic, the quantitative results of the questionnaire are presented first, followed by a grouping analysis (described below) when available. Each topic then concludes with pertinent interview quotations and subsequent interpretations. Such quotations are preceded by the associated subject's ID. In quantitative analysis, the number of interviewees sharing an opinion is a useful metric to quantify the importance of appearing themes (Braun and Clarke, 2006).

A. Grouping statistical analysis

A grouping analysis was performed on questionnaire responses to investigate potentially impacting factors related to the use of the technology, including: *Age*, *Years of Experience*, *Budget*, *Number of employees*, *Number of projects*, and *Field of Activity*. For each dimension of analysis, these factors were used with various thresholds to separate the population in two groups, producing two distributions of responses (for instance, for an Age threshold of 50 years, the two groups were respectively younger and strictly older than 50 years). These distributions were subsequently compared using a two-sample Kolmogorov-Smirnov (KS) test to evaluate the statistical difference between them (threshold $p = 0.05$). Whereas these tests often resulted in non-significant differences, we argue that the trend of the distribution remains interesting to discuss, and analyzing the actual p-value can provide an indication of the impact of the filtering factor.

B. Projects with auralizations

Most respondents (59%) had used auralizations in $<= 10$ projects, 20% in 11 to 50 projects, and 18% more intensive users on > 50 projects. By analyzing the number of projects with regards to project budgets, the two distributions show that higher budgets enable acousticians to conduct more auralizations, as seen in the distributions' shapes in Fig. 2, using a budget threshold of €50 000. A KS test evaluating the difference between the two distributions resulted in a p-value of 0.055, very close to the 0.05 threshold.

All interviewees had projects in architectural acoustics, and all except two (S7 and S9) also had environmental acoustics projects.

C. Tools used

This section focuses on the tools that are used to create, render, and listen to the auralizations. Participants were asked how they create their acoustical models and which

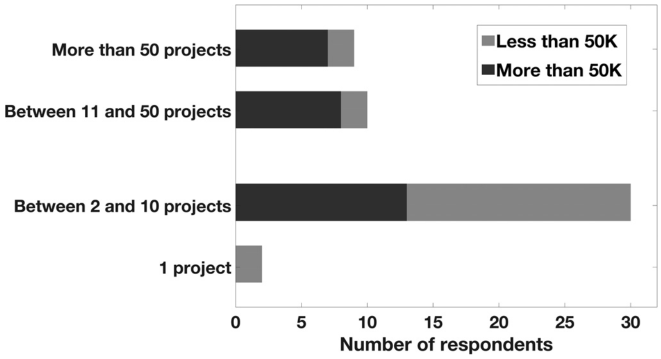

FIG. 2. Number of projects in which auralizations have been used, filtered by Budget (Auralization users only, Grey: ≤ €50 000, Black: > €50 000).

method/software they use to manage their auralizations, if these are real-time simulated, if they merge them with visual models, and finally if they use virtual reality (VR) interfaces.

1. Method of creation

Regarding the creation of acoustical models, a majority of 80% of the respondents create their own models, whereas ≈20% use already built models (generally received from the architect).

To create these models, they preferably used commercially available software, sometimes in-house developed algorithms, and rarely software coming from a research laboratory, as summarized in Fig. 3.

A majority of respondents did not use real-time auralizations (40% never, 70% rarely, with only 5% always using real time simulated auralizations).

Interviewees mentioned ten different softwares for the creation of models (between the nine interviewees), showing the variety of tools available, including AutoCAD, CATT-Acoustics, Grasshooper, Mithrason, Odeon, Price (noise), Rhino, Sketchup, and Trane (noise).

Regarding audio source material, a few interviewees (3/9) reported working with proper material (S3: "we sampled an instrument in an anechoic room with six microphones" and S4: "we recorded in free field,…we've got a Soundfield ST350") while others reported a lack of available quality material (S4: "what I remember was that there wasn't sufficient anechoic material" and S3: "I've done a simulation where I sampled traffic noise"), showing the variety of auralization renderings quality.

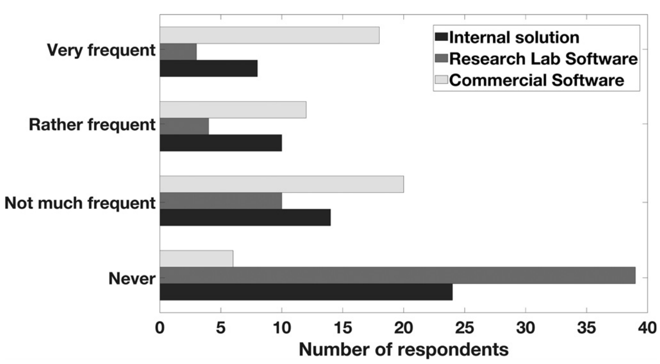

FIG. 3. Method of creation of acoustical models used by respondents to the questionnaire (Light Grey: commercial software, Dark Grey: research laboratory software; Black: internally developed algorithms).

2. Sound rendering system

The most used sound rendering system was headphones: more than 30% for both simple stereo or binaural rendering, and 10% for headtracked headphones. Speaker-based systems were also reported, though less prominently used, such as Ambisonics (12%), multi-channel (5.1, 7.1, *etc.*, 11%), and to a lesser extent WFS or VBAP (3% and 2% resp.).

Grouping analysis suggest through the two distribution shapes (no significant difference though between distributions, $p \gg 0.05$) that more experienced acousticians (> ten years of experience) would be more willing to exploit advanced techniques such as VBAP, WFS, or Transaural, likely since it requires more technical skills to use them properly.

Interviews revealed that some companies have dedicated listening rooms with Ambisonic systems (reported by two of nine interviewees), with S4 stating: "we can have two people here in our Ambisonic listening room or can even build a room to the client," with S9: "for a couple of wealthy clients, we've actually built for them").

3. Coupling auralizations with visual/VR

In architectural acoustics projects, it often happens that a visual model is built first by the architect, before the intervention of the acoustician. As such, the resulting auralization from the acoustical model can be coupled with this visual model (usually rendered on a desktop screen or a larger screen), resulting in an audio-visual experience of the space. To improve the immersion, this coupling can also be rendered using different VR interfaces (Thery *et al.*, 2017).

A majority of the respondents did not couple auralizations with visual models, and even less with VR models (more than 80% have never used VR), as shown in Fig. 4. This result is moderated by 25% of respondents who couple auralizations with visual models in more than 75% of their projects (likely using Desktop or TV screens). For the few VR users (overall less than 30%), they preferred, in decreasing order: Head-Mounted Displays (HMD), in-house installations, and more rarely smartphone based systems (e.g., Google Cardboard) or larger projection installations CAVEs (Poirier-Quinot *et al.*, 2016; Thery *et al.*, 2017).

Grouping analysis suggest that visual models are more used larger companies of more than 50 employees (though not significantly with $p = 0.227$, see Fig. 5), and less prominantly by acousticians younger than 50 years (still not significantly with $p = 0.227$, see Fig. 6). The size of the company may have a larger impact, if considering that the infrastructure costs can be distributed over more projects, making the investments less critical.

Interviews suggested that coupling with visual models helps to attract the attention of clients and engage them: S2: "coupling with visual models enables to engage more people since they are more sensible to it, compared to written reports."

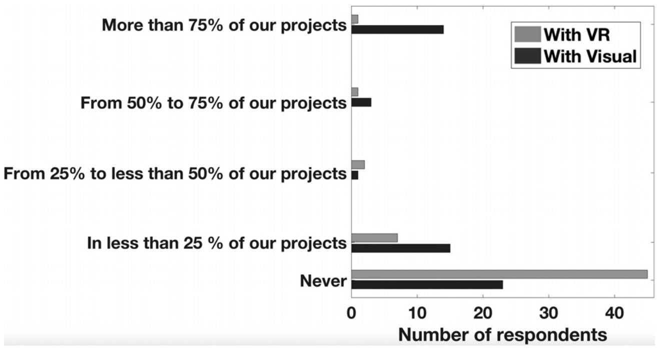

FIG. 4. Frequency at which auralizations are coupled with visuals (Black) or VR (Grey) models.

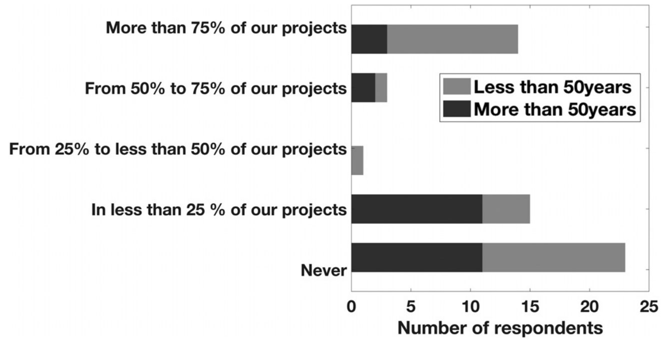

FIG. 6. Frequency at which auralizations are coupled with visual models, filtered by *Age* (Grey: ≤ 50 years old, Black: > 50 years old).

D. Practical acceptability

This section presents an analysis of auralizations for each dimension of practical acceptability from the Nielsen (1994) model (see Fig. 1), including (1) utility (what the technology is used for), (2) usability, (3) cost, (4) compatibility with the activities of acoustical consultants, and (5) reliability.

1. Utility

The majority of questionnaire respondents had projects using auralizations in architectural acoustics or environmental acoustics (95 and 76%, respectively), and to a somewhat lesser extent in electro-acoustics, sound quality, and vibro-acoustics (57, 50, and 54% respectively).

Five main uses of auralizations were identified in the questionnaire:

(1) To present to clients (30%).
(2) To test ideas (19%).
(3) To use as a verification tool (15%).
(4) To use as a marketing tool (12%).
(5) To improve internal company discussions (9%).
(6) Other (to present in competition, for public demonstrations, as a data collection tool, to convince stakeholders, in research).

Respondents agreed that auralizations help to improve internal/external collaboration, as well as improve project's actors' motivation (see Table III). Grouping analysis did not reveal any particular effects.

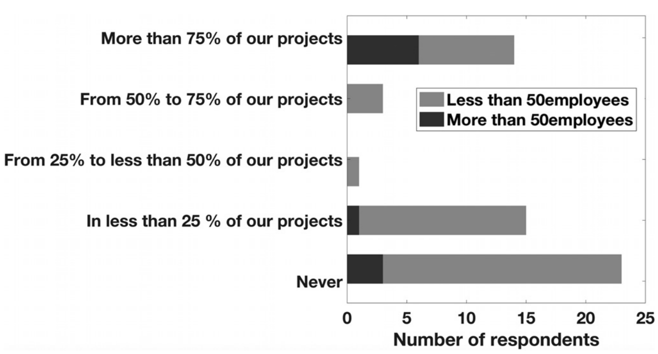

FIG. 5. Frequency at which auralizations are coupled with visual models, filtered by *Number of employees* (Grey: ≤ 50 employees, Black: > 50 employees).

Interviews were particularly fruitful regarding the description of auralizations uses, highlighting the following points:

(1) The diversity of the type of projects in which auralizations are used.
(2) The variety of project actors involved.
(3) Auralizations are mainly used to collaborate.
(4) They are used in a pedagogical way.
(5) They help in engaging and convincing clients.
(6) They help compensate for the lack of descriptive vocabulary in acoustics for some perceptions.
(7) They help make confident design choices.

In more detail, auralizations were reported as being used in various types of projects which can be classified as (A) public spaces (4/9): museums, building development, commercial galleries, residential, sport centers, congress center, and churches; (B) performance oriented spaces (7/9): concert halls, theaters, operas, and auditoriums); and (C) environmental noise (3/9): roundabouts, aircraft, train, and turbine noises as well as roads or city planning.

A variety of project "actors" are involved, including most often architects, but also chief executive officers, building users, urbanists, city technical services, musicians, or other discipline consultants such as lighting, landscape, or kitchen. As a consequence, this diversity leads the acoustical consultant to adapt their approach and how they use auralizations. It was commented that each project is unique (4/9), as illustrated by S9: "each auralization is a little bit different" or S7: "it kind of depends on what you sell", and S2: "every architect you're dealing with is completely different."

What clearly stood out was that auralizations were used mainly for collaboration. This was indeed the most coded theme in the *Auralizations uses* category (50%). In this collaboration theme, auralizations are primarily used for explaining acoustical phenomena to other project actors (5/9) because they usually do not understand objective acoustical parameters. They may not even be familiar with sound levels, as highlighted by S6: "it is very pedagogical. Each time, using auralization is pedagogical" and S2: "it's a tool to educate people and let them make sensible decisions." Along those same lines, it was agreed that auralization is a tool which facilitates communications with non-acousticians, as they lack the vocabulary to talk about acoustics (6/9) with S2 stating: "as a communication tool, it's unbeatable" and S9: "it is true that auralizations enable to communicate rapidly."

Still regarding collaboration, interviews revealed that auralizations were often used to convince decision makers, as an argument of negotiation, by letting them make informed design decisions and increasing their confidence (6/9), with for instance S3: "it helps I guess sell something" and S8: "likewise I can manage to convince a client to have a room of more than 20 m large to obtain a more diffuse sound." It was also reported to be used to inform the community.

Interviews revealed the diversity of tasks achieved with auralizations: (1) present results, (2) test ideas (comparing different scenarios, prediction, sound system or reflector design), (3) validate choices, (4) as a marketing tool, and (5) to improve collaboration and involve the community.

Finally, several interviewees considered simple sound scene simulations as auralizations (4/9): they mentioned the use of simply filtered sample sounds or the addition of audio effects such as artificial reverberation to provide their clients with a basic idea of what is going on, and let them understand their recommendations.

2. Usability

As described in Sec. III, the questionnaire assessed the dimensions of practical acceptability of the technology (see their definitions in Sec. II). Responses were collected using a 5-point Likert Scale. Table II summarizes the results on the scale of 0 to 4. The technology was rated as "rather efficient," "pleasant to use," and "compatible with activities within acoustical design offices" (median = 3). However, it was rated as being "rather difficult to learn" how to use it, and "rather difficult" to create auralizations. It is difficult to form any conclusions on other dimensions (Utility, Memorability, Errors, Reliability), as these were rated close to neutral (median = 2). However, these dimensions are still discussed with regards to interview data in Sec. IV D 2.

Learnability, Memorability: Respondents rated the technology as "rather difficult to learn" (the lowest rating with a mean = 1.7) and "rather difficult to create" auralizations. No effects were observed from the grouping analysis. Several interviewees mentioned difficulties, particularly that using auralizations properly requires a certain level of knowledge and experience (3/9), with for instance S6: "today, we haven't mastered it yet to be able to use it" explaining why they do not use auralizations, and S3: "it takes time then to "understand all the nuts and bolts of acoustical simulations."

Efficiency: Auralizations were rated as "rather improving the performance" (see Table II). Grouping analysis revealed that younger acousticians (<50 years, $p = 0.79$), larger companies (>50 employees, $p = 0.15$) and respondents who have conducted more projects with auralizations (> 10 projects, $p = 0.024$) rated auralizations as improving their performance, hence having a significant difference for the number of projects, suggesting that once the technology is adopted, it is a clear gain in productivity for the company.

Errors: This attribute was rated quite low by the respondents (the second lowest rated, with a mean = 1.7). Two thirds of interviewees (6/9) noted that using it properly requires a certain level of experience, potentially leading to errors, with S9: "So over the years sure, there's been some difficulties, you know, software bugs, or you know, just getting to a robust understanding of strength and weaknesses associated with the assumptions that these modeling programs make," and S3: "there are so many people who are using this software and are misusing it." Other sources of error come from the limitation of the validity of ray-tracing algorithms at low frequencies or the poor quality of raw material to be convolved (3/9). However, it was also mentioned that auralizations enable one to identify pathologies or acoustic defects that cannot be discovered otherwise (2/9).

Satisfaction: When asked about their general impression of the technology, respondents answered rather positively (23% have a very positive impression, 21% a positive, while 40% a neutral opinion, the rest having a negative impression). Even non-users responded that they would like to use it, suggesting that the technology is attractive to them. In addition, they take pleasure using it (mean/median = 2.9/3). The grouping analysis revealed that younger interviewees had more positive impressions.

TABLE II. Dimensions of the practical acceptability: 5-point Likert scale **(0–4)** mean and median attribute ratings. There is a trend only for **bold** values, meaning results were not judged neutral on the Likert Scale.

Dimension	Mean	Med	Std
Utility	2.3	2	1.1
Learnability (Ease of learning)	1.7	2	1.2
Ease of creation	1.8	2	1.3
Memorability (Ease of remembering how to use)	2	2	1.1
Errors (Enables to limit errors in projects)	1.7	2	0.9
Satisfaction (Taking pleasure using auralizations)	**2.9**	**3**	**1.1**
Reliability (Subjective fidelity of the renderings compared to the reality at the end of the project)	1.7	2	1.1
Compatibility (with acoustical design offices activities)	**2.5**	**3**	**1.1**
Efficiency (Performance improvement)	**2.5**	**3**	**1.1**

3. Cost

This factor was probably the most inhibiting with regards to the use of auralizations, in terms of economic cost as well as time cost. When asked how limiting the given factors of Table IV were regarding the use of auralizations, cost and time were rated very limiting (mean/median = 1.8/2 and 2.3/2, respectively, on a 0–3 Likert scale). Two thirds of interviewees (6/9) also repeatedly mentioned costs (money and/or time) as being a major obstacle to include auralizations in their projects, as S6 put it: "clearly, when we do it, it's at a loss," and S8: "we don't have time in our team to make auralizations, here there is not the money." It is interesting to note that the three interviewees not mentioning these difficulties were S2, S4, and S8, all being part of the largest companies (50–250 employees and more than 5000 for S4) and having conducted already more than 50 projects with auralizations.

4. Compatibility

Users: Respondents rated auralizations as "rather compatible" with their activities (this attribute was one of the highest rated attribute, see Table II).

Non-users: Among the respondents, 33% had never used auralizations in their projects. When asked for their intentions of use regarding auralizations, the majority of respondents did not intend to use it in the near future (more than 80%), even if they would like to use it (60% of respondents), meaning they have a rather good impression of the technology. The stated reasons for this "non-use" were mainly that projects do not actually require auralizations (23%), the cost (time, budget for 20% of the respondents), and the lack of utility (18%). Only 8% stated that their lack of use comes from a lack of compatibility, and around 5% from a lack of experience or skills, or because the technology is too complex to use. Additional spontaneous responses included: difficulties delivering auralizations to the client, getting it accepted in the project proposal, a lack of interest or demand by decision-makers, or the fact that simple written documents are sufficient. The grouping analysis revealed that compatibility with acoustical consulting activities was rated higher by younger acousticians (less than 50 years old), though not significantly different with $p = 0.096$ from the KS test.

During interviews, two main points appeared. The first was that traditional methods, such as written reports with standardized acoustical parameters, or bringing the client in person directly to different real rooms to evaluate what their needs would be, can be sufficient (4/9). This could explain why they have not seen the need for auralizations, with S9: "sometimes it is better to use your experience, I won't embark myself in an auralization," indicating that it takes time and unnecessary effort. The second point concerned the practical aspect of using auralizations, namely bringing an auralization to a client without having a suitable and reliable sound playback system or having to adapt to the acoustics of the meeting room (2/9). For instance, S6: "the entire playback system, from the initial signal to the headphones," is concerned or S3: "and if you have to email the presentation to them, you're really gambling with how they listen to it right."

5. Reliability

Subjective quality of auralization renderings was globally evaluated as neutral, though improving the quality of the rendering was judged as beneficial and encouraging the use of auralizations (see Table III). This is notable with regards to advances in the achievable quality of auralizations (Postma *et al.*, 2017; Postma and Katz, 2016), meaning that more work is needed to further improve the realism and overall quality of auralizations. No effects were observed from the grouping analysis.

TABLE III. Likert scale values **(0–3)** for attributes of factors encouraging the use of auralizations. There is a trend only for **bold** values, meaning results were not judged neutral on the Likert Scale.

Dimension	Mean	Med	Std
Improving internal collaboration	1.4	2	0.9
Improving external collaboration	**2.1**	**2**	**0.7**
Improving actors motivation	**1.9**	**2**	**0.8**

TABLE IV. Likert scale values **(0–3)** for attributes of difficulties linked to auralizations. There is a trend only for **bold** values, meaning it is not judged neutral on the Likert Scale.

Dimension	Mean	Med	Std
Misconception of the technology	1.5	1	0.8
Lack of skills by the user	1.7	2	0.8
Habits and methods of work	1.7	2	0.8
Time invested	**2.3**	**2**	**0.8**
Computing power	1.2	1	0.9
Results reliability	**1.8**	**2**	**0.8**
Cost	**1.8**	**2**	**0.9**

Extensive users of auralization (S2, S4, and S8) agreed that there is always a gap between the model and the reality. They also commented that improving the realism of the auralization brings benefits, as S8 puts it: "we found that the better it sounds, the more realistic the experience is, the more people are willing to trust it." For environmental noise projects, one stated that the idea is just to give a rough idea, whereas others stated that the auralization should be correct at least in terms of level/amplitude and frequency content (2/9), as S4 said: "in terms of level or amplitude yes, in terms of spatial realism or accuracy, very little consequence." On the other hand, 3/9 reported that the level of detail is not important, giving an estimate being the point in their activity, for example S7: "what the acoustical consultant knows, the clients generally don't care," and "it's just an estimate."

One element that stood out from the interviews was that since *sound* is very subjective, from the client's point of view, they generally do not perceive subtle differences, and the spatial accuracy is often not important (3/9). On the other hand, when presented to musicians or attentive listeners, auralizations have to be as accurate as possible. As it can be subjective, it can sometimes be a matter of taste (3/9), with for instance S7 (having worked on a lot of concert halls projects): "everybody will never agree, there's always some kind of controversy." As indicated in Sec. IV D 2: *Errors*, since properly using auralizations requires a certain level of expertise, the technology can be misused, leading to incorrect renderings and potential mistakes in the conception (2/9). See Table IV.

V. DISCUSSION

This survey study employed a questionnaire which was fully answered by 74 acoustical consultants, in France and around the world, in addition to nine semi-directed interviews. While not providing an exhaustive view, these results provide meaningful insights into the practices of the acoustical consulting community with regards to auralizations. Furthermore, data saturation is not reached and the number of interviews could beneficially be further extended (Guest, 2006). This study observed the diverse types of uses concerning how auralizations are applied to different types of projects, from the evaluation of the impact of an airport on the environment to the conception/renovation of classrooms or concert halls. The use of auralizations was seen being both project and client-dependent, as mentioned in Azevedo and Sacks (2014). As a consequence, acoustical consultants are required to adapt their use of the technology, depending on the project, but also the clients, who are potentially very different from one project to another. For instance, in environmental acoustics, it was reported that sound levels and frequency content are the parameters that matter, whereas for the conception of performance spaces, directivity and spatial components are also of importance, as recalled by Bradley (1994) in his perceptual study.

Regarding actual uses, this study showed that auralizations are primarily a tool facilitating collaboration between acousticians and other project actors, bridging the communication gap because of the technicity of acoustical slang. Auralizations are used for a variety of tasks: as a marketing tool (for fund-raising or for involving/informing the communities), to test different room configurations, to identify acoustic defects, to teach acoustics, and to design sound systems or reflectors.

The evaluation of the *practical acceptability* revealed several factors impeding a wider adoption of auralizations. The main factor was the associated cost, meaning that doing auralizations is not profitable, particularly for small acoustical practices. Another reason was the lack of experience and technical skills to be able to produce reliable auralizations, as the technology has been rated as relatively complex to learn and use.

Reliability of the results remains important: the better the renderings, the more immersive the simulation, the more people engage themselves in the project, as reported by an interviewee. There are still known factors impacting the reliability of the results such as having proper anechoic material, partially linked to the precision of the associated acoustical measurements, dependent on the recording engineer/researcher, microphones quality, or signal-to-noise ratios (Lundeby *et al.*, 1995; Pätynen *et al.*, 2008; Vorländer, 2013). The variability of simulation algorithms may have an impact on the confidence acoustical consultants have in the results of auralizations, compared to traditional methods using objective parameters synthetically presented in written reports. Real-time simulations have the advantage for the acousticians to be responsive, letting them better adapt to the situation. This may explain the growing enthusiasm for true real-time auralization engines such as Noisternig *et al.* (2008) or Schröder and Vorländer (2011), rather than real-time convolution with pre-calculated impulse responses, with these potentially being more used in the future in architectural acoustics projects. However, the reliability of these simplified acoustic algorithms to provide the full room response has yet to be validated for complex geometries.

All these various limitations may explain the relatively low level of adoption of auralizations in the design community. Despite their attraction, the technology is not yet integrated into the regular practices of acousticians, with 40% of respondents identified as non-users and a non-negligible part as only occasional users. Only a few consulting practices (generally large companies which have the needed resources) have fully adopted auralizations, using them extensively. These are the same firms which use auralizations in immersive environments coupled with visual models. The use of VR on the other hand remains rare, but the rapid evolution of these technologies may have an impact on both auralizations and VR uses in the near future, as studied by Portman *et al.* (2015) and Atkins (2017).

A deeper study investigating the use of reliable auralizations, coupled with visuals, in the context of concrete architectural projects is needed and is one of our future goals. While analyzing different viewpoints from the different actors, the idea would be to investigate the benefits of this kind of simulation as compared to current practices of an acoustical design office, or to true real-time simulations.

VI. CONCLUSION

This paper presented the results of a survey study concerning the use of auralizations by the acoustical design and consulting community, comprising a questionnaire and a series of interviews. To conduct this survey, we based our analysis on the theory of *technology acceptability* to design a questionnaire and conduct semi-structured interviews which enabled the assessment of the technology along the dimensions of Nielsen's model: *Utility*, *Usability*, *Cost*, *Compatibility*, and *Reliability*.

Results highlighted the diversity of projects in which auralizations are currently being used as well as the diversity of the tasks that are accomplished with this technology.

Despite the positive impression that consultants have of auralization technology, the level of adoption by the community remains relatively low, with a third of respondents to the questionnaire being non-users. Smaller acoustical consulting practices appear often unable to afford the use of auralizations in their projects, primarily due to a lack of resources (time, money, and also skills needed to produce reliable auralizations). In contrast, several (generally bigger) companies with higher budgets have clearly adopted the technology and use it extensively, producing high quality auralizations, in addition to (immersive) visualizations of the modeled spaces. These firms also reported improvements in collaboration and communication with other project actors, with the technology being a productivity catalyst. While real-time auralizations are not widely used at the moment in the consulting community, this may increase in the near future with the improvement and reliability of such algorithms.

Further investigations studying the use of auralizations in actual projects will contribute to understanding the benefits this technology can bring to architectural projects, and to reflect on how to better integrate it in the practices of acoustical consultants. Studying the uses from the point of view of the architect and other project actors also represents an interesting perspective, investigating how auralizations are received by non-experts in acoustics.

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[1]For more information, see www.catt.se
[2]For more information, see https://ease.afmg.eu/

[3]For more information, see www.odeon.dk.
[4]For more information, see www.sketchup.com/.
[5]For more information, see cycling74.com/products/max/.
[6]For more information, see drive.google.com/file/d/1EJOXrGannTAR9PVpxZwkEjySXn75sch7/view?usp=sharing.
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