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AN EMPIRICAL EXAMINATION OF THE EVALUATIVE UTILITY OF DESIGN AURALIZATION

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ABSTRACT

This paper explores the degree to which subjective assessments of the acoustical properties of a real space can be reproduced by assessments that are based on computational auralization. Toward this end, three spaces with different functional and acoustical characteristics were selected. These spaces were evaluated by a group of test participants. A second group of test participants evaluated high-quality auralizations of the spaces. The results of the two groups were compared to empirically determine if auralizations can reliably represent real spaces for acoustical quality evaluation purposes.

INTRODUCTION

Scientific simulation of acoustical conditions in architectural spaces has been used in the past to generate numeric values of acoustical performance indicators. Such indicators include, for example, sound pressure level and reverberation time. Designers and consultants typically compare such numeric results with minimum or maximum requirements in relevant room acoustics and noise control standards to decide if a particular design meets mandated performance criteria. Recently, the possibility has emerged that such traditional numeric evaluation methods could be complemented by approaches that rely on scientific auralization tools, enabling the users to virtually experience and "directly" evaluate the acoustical quality of architectural spaces. In this context, an important research question arises: To which extent can subjective assessments of the acoustical properties of a real space be reproduced by assessments that are based on auralization (i.e. virtual acoustical replacements of real spaces)?

A review of the past research in room acoustics provides the starting point for the present study, but not the answer to the main question we are posing. Numerous research tools and commercial applications are available for the analysis of room acoustics in architectural spaces. Some of these tools allow for the auralization of designs (Henderson 2004). The study of the subjective assessments of acoustical conditions in rooms has a long tradition. For instance, Beranek (1962) used verbal reports of listeners' reactions to musical performances as well as interviews with musicians and music critics toward derivation of evaluative criteria for room acoustics. A common instrument for conducting studies on subjective evaluations of room acoustics makes use of semantic differentials (Hawkes and Douglas 1971, Wilkens and Kotterba 1978). For instance, Fasold and Winkler (1976) used a test protocol involving bi-polar 5-step semantic differentials to capture subjective acoustical evaluations. Attribute pairs used in such studies allow for the use of statistical methods to analyze and interpret the results (Rasch and Plomp 1982). As to the auralization tools, they are being increasingly applied to support the design and improvement of acoustically sensitive spaces (Ciao 2000, Brooks 2000). Nonetheless, to our knowledge, the corresponding literature has not explicitly addressed the specific research question that concerns the present contribution, namely the reproducibility of subjective acoustic evaluations of real spaces based on their virtual (auralized) counterparts. From the methodological point of view, however, comparable studies have been conducted in the visual domain (comparison of lighting evaluations of real spaces versus evaluations based on high-quality renderings of those spaces). Such a study (Mahdavi and Eissa 2002) provided the methodological basis for the present study, to be described in the following section.

RESEARCH DESIGN

The research design for the present study involved the following steps:

1. Based on the results of previous research (Fasold and Winkler 1976) and our own studies, we selected a metric that captures certain subjective dimensions of the acoustical experience of spaces (cp. Table 1). As an example, Figure 1 shows the 5-point scale for the perceived loudness.

Table 1
Evaluation axes and corresponding bi-polar scales with associated points (from -2 to +2) for the evaluation of the acoustical quality of space

Evaluation axis	Bi-polar terms
1 Reverberation	Reverberant (+2) – dry (-2)
2 Loudness	Loud (+2) – quiet (-2)
3 Clarity	Clear (+2) – blurry (-2)
4 Sharpness	Shrill (+2) – dull (-2)
5 Warmth	Warm (+2) – cool (-2)
6 Brightness	Bright (+2) – dark (-2)
7 General Impression	Pleasant (+2) – unpleasant (-2)
8 Speech intelligibility	Good (+2) – poor (-2)

2. Three rooms with differing acoustical attributes were selected for the study, including the ceremonial hall and a mid-size lecture room in the Vienna University of Technology as well as a small recording studio in Vienna (see Figures 2 to 4). Relevant geometric and semantic information (such as absorption coefficients of room surfaces) was collected. Reverberation time (see Figure 5), sound level distribution, and ambient sound level were measured in all three spaces. Data on assumed absorption coefficients of the main surfaces of these three rooms are provided in Table 2.

3. A digital recording of a sample of acoustical events was prepared including speech, music, and various sounds (see Table 3). The recording also included a reading of a set of logatoms (Fasold and Winkler 1976) for speech intelligibility test purposes.

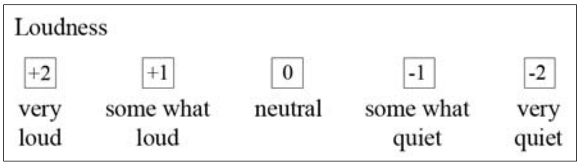

Figure 1
Example of a scale (loud-quiet) of the metric

Table 2
Absorption coefficient assumptions for the three rooms

Room	Surface	Frequency [Hz] 63	125	250	500	1000	20000	4000	8000
Ceremonial Hall	Walls	0.02	0.02	0.02	0.03	0.04	0.08	0.09	0.05
	Floor	0.15	0.15	0.11	0.1	0.09	0.08	0.08	0.08
	Ceiling	0.2	0.55	0.5	0.35	0.2	0.15	0.1	0.1
	Window	0.5	0.25	0.05	0.03	0.02	0.02	0.02	0.02
	Window seals	0.04	0.04	0.04	0.05	0.06	0.06	0.06	0.06
	Doors	0.14	0.14	0.1	0.06	0.08	0.1	0.1	0.1
Lecture room	Walls	0.02	0.02	0.02	0.03	0.04	0.05	0.05	0.05
	Floor	0.04	0.04	0.04	0.07	0.06	0.06	0.07	0.07
	Ceiling	0.3	0.2	0.1	0.07	0.05	0.05	0.05	0.05
	Window	0.5	0.5	0.2	0.05	0.03	0.03	0.03	0.03
	Seating	0.15	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Doors	0.14	0.14	0.1	0.06	0.08	0.1	0.1	0.1
Recording studio	Walls	0.21	0.35	0.51	0.91	0.7	0.39	0.35	0.35
	Floor	0.02	0.03	0.06	0.08	0.1	0.3	0.5	0.6
	Ceiling	0.4	0.4	0.3	0.15	0.1	0.07	0.12	0.12
	Window	0.2	0.12	0.1	0.05	0.04	0.04	0.02	0.02
	Doors	0.53	0.53	0.69	0.66	0.64	0.56	0.4	0.4

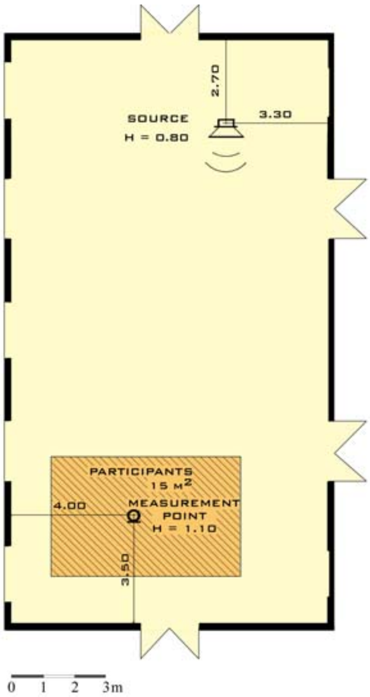

Figure 2
Schematic plan of the ceremonial hall of the Vienna University of Technology

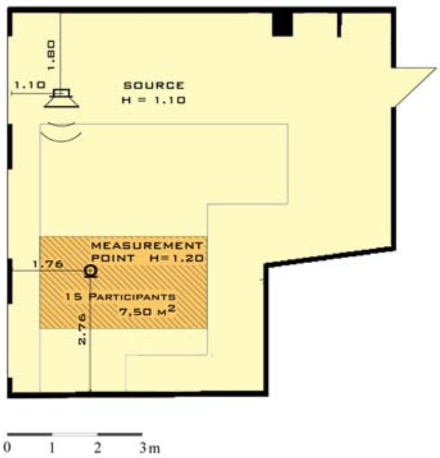

Figure 3
Schematic plan of a mid-size lecture room in tVienna University of Technology

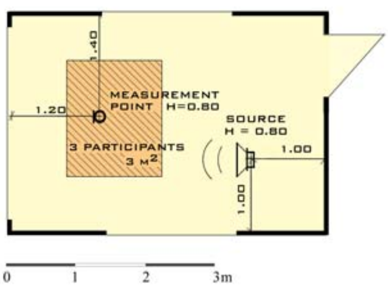

Figure 4
Schematic plan of a small recording studio in Vienna

Table 3
Pre-recorded sequence of acoustical events

Event	Duration [min]
Sound 1 (knocking, 3 times)	0.03
Dialog (in German)	0.17
Song (unaccompanied male voice)	0.08
Pop music	0.18
Sound 2 (coughing, twice)	0.02
Monolog (in English)	0.05
Sound 3 (breaking glass)	0.03
Sound 4 (gong)	0.05
Classical music	0.29
Logatoms	2.00

4. The acoustical properties of these rooms were evaluated by a group of test participants (30 architecture students) using the above mentioned metric (cp. Table 1), as the pre-recorded sequence of acoustical events (see Table 3) was being played in the rooms. Additionally, a speech intelligibility test was performed using a list of logatoms (Fasold and Winkler 1976). Moreover, the participants were asked to specify the location of the sound source by specifying the prevailing direction from which they believed the sound was coming (front, back, left, right, or indefinable). The circumstance that the sample consisted exclusively of architecture students was intentional, as the purpose of the study was to explore the reliability of auralization tools for design support purposes.

5. High-quality auralizations of the spaces were generated using the simulation tool ODEON 6.0 (Christensen 2002) and the aforementioned pre-recorded sequence of acoustical events. The location (position in the room) of the source and receiver in the virtual models matched the conditions that prevailed as the tests in the real spaces were conducted. The ambient sound (as recorded in the real spaces) was embodied in auralizations. The underlying simulation models were tested in view of their numeric reproduction of measured sound distribution pattern and reverberation times. Figure 5 shows, for comparison purposes, the measured and computed reverberation times in these rooms (empty conditions). For the computation of the reverberation times in the three rooms, the "ray-tracing" option in Odeon was selected.

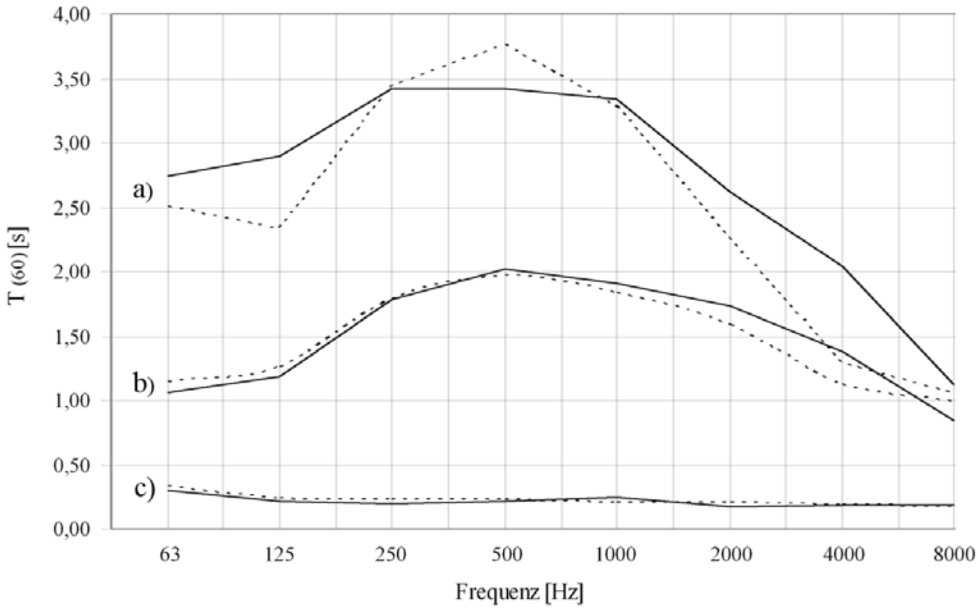

Figure 5
Measured (dashed lines) and computed (full lines) reverberation times in the three spaces: a) ceremonial hall, b) lecture room, c) recording studio

6. The auralizations of the three spaces were presented (via head phones attached to computers) to and evaluated by a second demographically similar group of test participants (75 architecture students), who again made use of aforementioned acoustical quality metric and also located the sound source. The volume of the output signal on the headphones was adjusted in way so as to match the sound level as experienced by the participants in the real rooms. During the test, a picture of the respective room (taken from the receiver view point) was projected onto the wall behind the computer. As with the real spaces, a speech intelligibility test was performed based on logatoms list as included in the sound sample recording.
7. The evaluation results of room acoustics in the real spaces were compared with those based on the virtual spaces. Common statistical methods were used to explore the degree of congruence between these two sets of evaluation results.

RESULTS

Figure 6 shows the results of the study in terms of evaluation means in the eight categories considered. Thereby, for each room the evaluations based on the experience of the real spaces are compared to those based on auralizations.

correlation between the evaluation means of the real spaces versus the evaluation means of the auralizations for the eight categories considered.

Figure 8 shows the same results, but this time with separate regression lines for each of the three spaces and without differentiating between the evaluation categories.

Table 4 includes the results of the speech intelligibility test with logatoms expressed as percentage of the logatoms correctly recognized by the test participants. The results are given both for real and auralized spaces.

Figure 9 presents the comparison of the perceived location of sound source in terms of the direction from which the two groups of test participants believed the sound was coming. Note that in this Figure the difference to 100% for each case is attributable to the test participants who could not specify the source location.

Table 4
Percentage of correctly recognized logatoms by the participants averaged over rooms and evaluation basis (real versus auralized spaces)

Room	Real spaces	Auralized spaces
Ceremonial hall	70	70
Lecture room	85	86
Recording studio	95	96

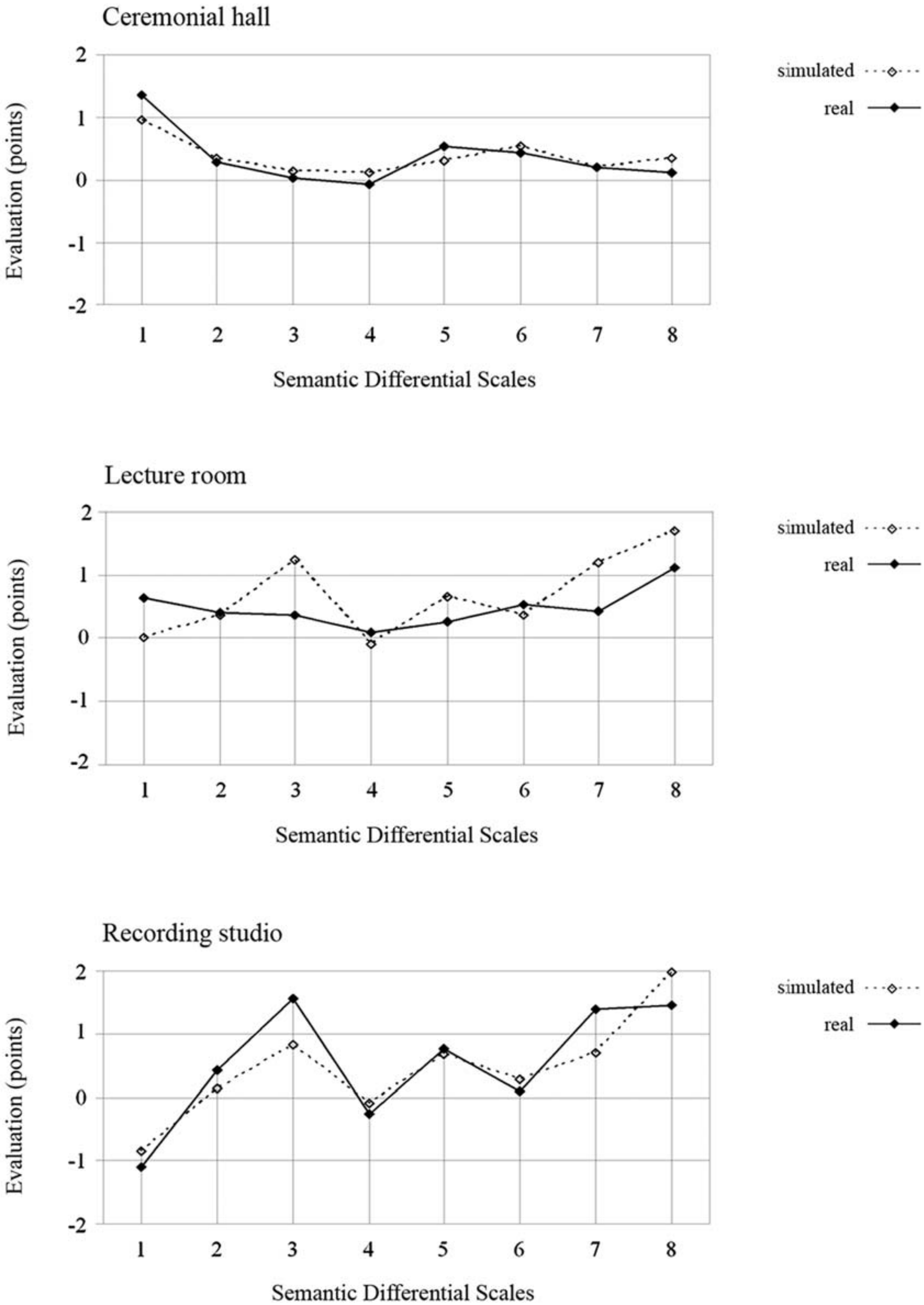

Figure 6

Evaluation means top: ceremonial hall, middle: lecture room, bottom: studio (1: Reverberation; 2: Loudness; 3: Clarity; 4: Sharpness; 5: Warmth; 6: Brightness; 7: General impression; 8: Speech intelligibility

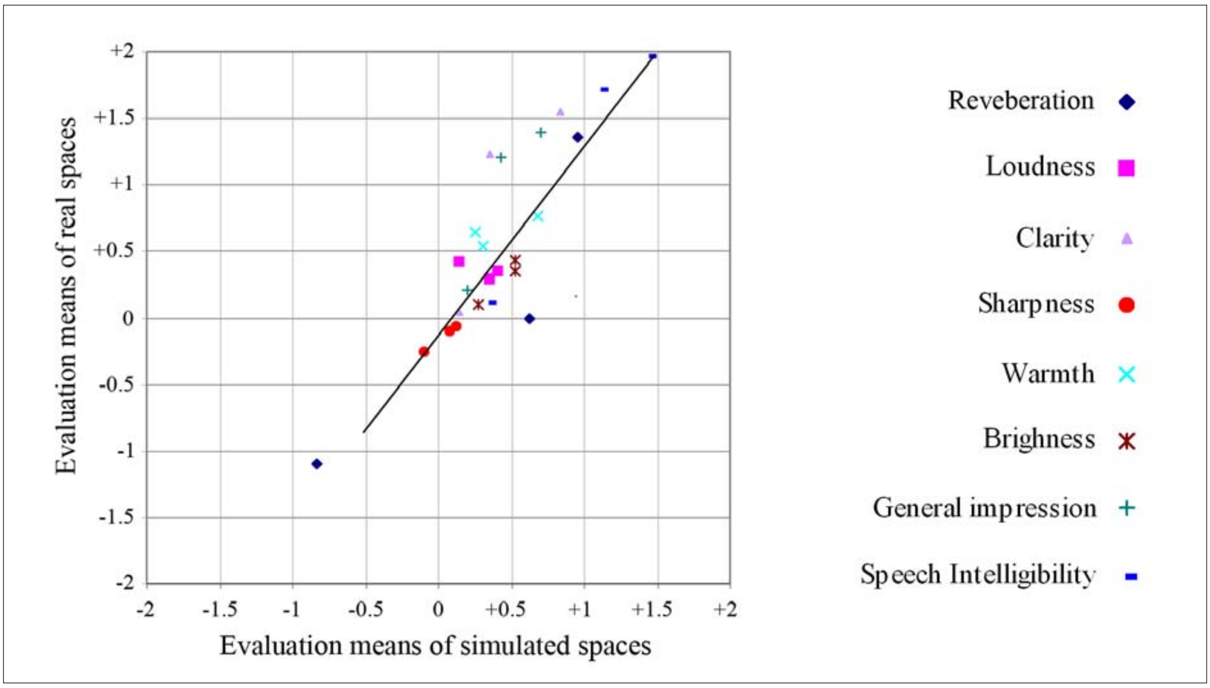

Figure 7 Regression Analysis across all spaces

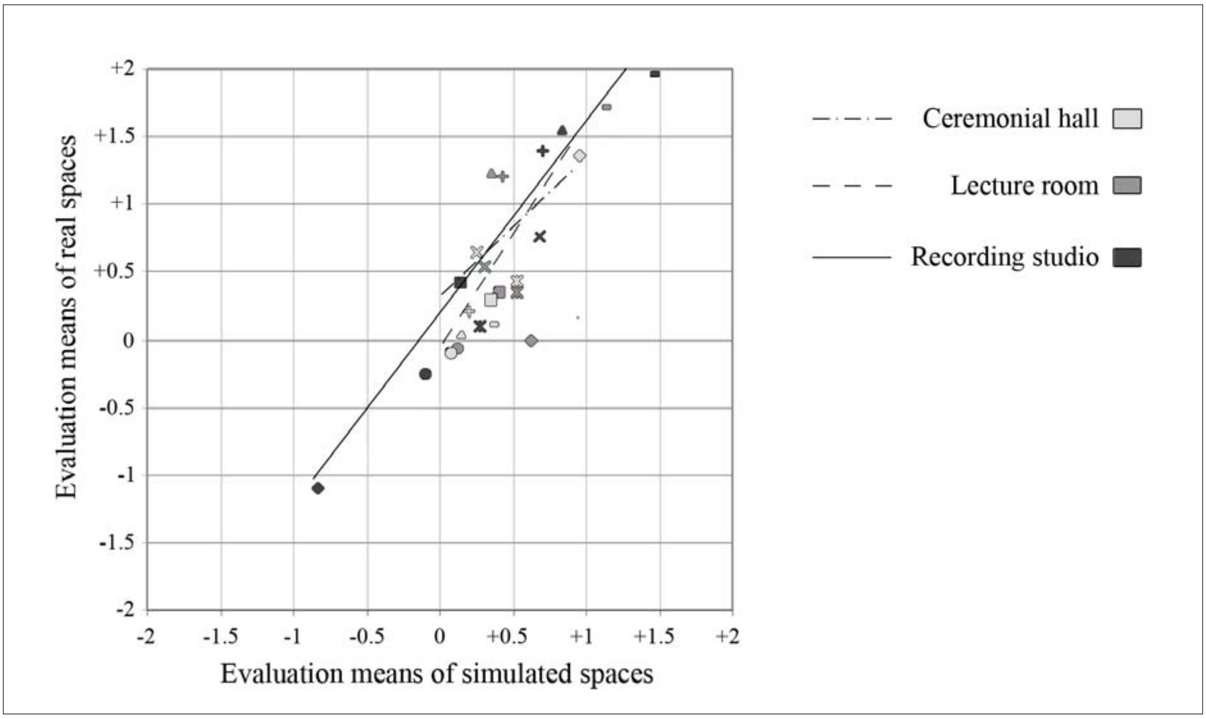

Figure 8 Regression Analysis across separate spaces

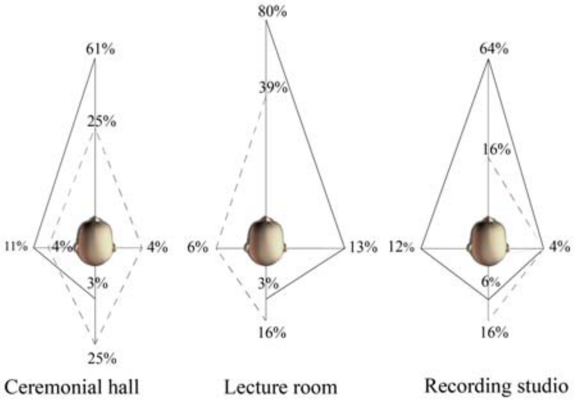

Figure 9
Comparison of the perceived location of the sound source by the test participants in the real spaces (full lines) versus those exposed to auralizations (dashed lines) in terms of the percentage of votes for a certain direction, i.e. front, back, left, right

DISCUSSIONE

A first visual inspection of the results in Figure 6 shows a general agreement between acoustical evaluations based on real and auralized rooms, particularly for the ceremonial hall and the recording studio. This impression is statistically reinforced, as the study of the correlation between the two evaluation groups demonstrates (see Figure 7). However, the degree of correlation is different from space to space. Table 5 includes the values of correlation coefficient for the entire set of results as well as for individual rooms. The table includes also for each case the probability levels with which the relationship between the two evaluations is not incidental (random). These probability terms were computed in terms of an r-test using the sample size and degrees of freedom as input.

Table 5
Correlation coefficients for evaluations made on the basis of real spaces versus those based on auralization together with corresponding non-randomness probabilities (p in %)

Room	r	p
All rooms	0.87	99.9
Ceremonial hall	0.97	99.9
Lecture room	0.56	95.0
Recording studio	0.94	99.9

These results imply a stronger congruence between the two evaluation methods in acoustically more "pronounced" cases. The ceremonial hall is rather large and reverberant, whereas the recording studio is very small and acoustically "dry". The lecture room, however, is moderate both in size and acoustical properties. This plausibly suggests that the computational reproduction of acoustical properties of real spaces is in view of evaluative utility (as expressed in terms of a quality metric) more effective in rooms with pronounced acoustical attributes.

A closer look at the individual scales of the quality metric reveals different levels of "expressiveness": whereas the numeric values of some scales change noticeably from spaces to space, others change only marginally (see Figure 7). In this sense, the scales for reverberation, clarity, speech intelligibility, and general impression may be said to be more expressive. The following scales, however, are less expressive: sharpness, warmth, and brightness.

The present study suggests that auralization provides an effective means to predict the speech intelligibility in spaces. The results of auralization-based test were strikingly close to the test results of the real spaces. However, auralization did not provide a reliable reproduction of the perceived direction of the incoming sound. This latter failure is probably due to the difficulties inherent in the evocation of spatial acoustical orientation via headphones.

CONCLUSION

Computational auralization clearly has the potential to provide a useful means for supporting the design of acoustically critical spaces. A study of three acoustically distinct spaces showed that people's acoustical evaluation of real spaces (as captured via a metric consisting of bi-polar 5-step scales) can be approximated by auralization-based evaluations. The approximation works better for spaces with pronounced acoustical properties and scales of higher expressiveness (reverberation, clarity, speech intelligibility, and general impression). Speech intelligibility indices in the three spaces could be accurately reproduced using auralization.

Future research must attempt to probe the validity of these results in a more comprehensive manner. A larger number of spaces, different demographic samples, other computational auralization tools, additional (and alternative) evaluation scales and tone sequence samples must be considered. Moreover, consistent (possibly standardized) criteria and processes are needed in view of the digital quality of tone samples, the properties of computers' sound cards and the headphones, and calibration of sound levels supplied by headphones.

REFERENCES

Beranek, L. L., 1962. Music, acoustic and architecture. New York: Wiley, USA.

Brooks, B. M., 2000. Acoustical Modeling and Auralization as a Design Tool for a University Concert Hall Renovation. Paper 3aAA4 - 139th Meeting of the Acoustical Society of Amerika. Atlanta, USA.

Ciao, Q., 2000. Hearing Architectural Design: Simulation and Auralization for Generating Better Acoustics Space. http://www. generativeart.com/2000/CIAO.HTM

Christensen, C. L. 2002. ODEON Room Acoustics Program. Version 6.0, Industrial, Auditorium and combined Editions. Technical University of Denmark Lyngby.

Fasold, W., Veres, E. 2003. Schallschutz und Raumakustik in der Praxis. Berlin. Huss-Medien GmbH Verlag Bauwesen. Deutschland.

Fasold, W. , Winkler, H. 1976. Bauphysikalische Entwurfslehre. Band 5 Raumakustik. 1.Auflage. Berlin. VEB Verlag für Bauwesen. Deutschland.

Hawkes, R. J., Douglas, I1. 1971. Subjective acoustic experience in concert auditoria. Acustica, Number 24, pp.135-150.

Henderson, P. et al. 2004. High-resolution Spatial Auralization Techniques for Room Acoustics Design. http://scitation.aip.org/confst/ASA/data/2/1pAA4.pdf

Mahdavi, A., Eissa, H. 2002. Subjective evaluation of architectural lighting via computationally rendered images. Journal of illuminating engineering society. Volume 31. Number 2. pp. 11 - 20.

Rasch, R. A., Plomp, R. 1982. The listener and the acoustic environment. The psychology of music. http://www.zainea.com/raschlistener.htm

Wilkens, H. Kotterba, B. 1978. Vergleich der Beurteilung verschiedener raumakustischer Situationen bei Anregung eines Raumes mit einem Orchester oder Lautsprechern. Acustica. Number 40. pp 291-297.