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COMPLEX HUMAN AUDITORY PERCEPTION AND SIMULATED SOUND PERFORMANCE PREDICTION

A case study for investigating methods of sound performance evaluations and corresponding relationship

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Abstract. This paper reports an investigation into the degree of consistency between three different methods of sound performance evaluation through studying the performance of a built project as a case study. The non-controlled office environment with natural human speech as a source was selected for the subjective experiment and ODEON room acoustics modelling software was applied for digital simulation. The results indicate that although each participant may interpret and perceive sound in a particular way, the simulation can predict this complexity to some extent to help architects in designing acoustically better spaces. Also the results imply that architects can make valid comparative evaluations of their designs in an architecturally intuitive way, using architectural language. The research acknowledges that complicated engineering approaches to subjective analysis and to controlling the test environment and participants is difficult for architects to comprehend and implement.

Keywords. Human sound perception; acoustic simulation; experiment and measurement.

1. Introduction

The mechanism of receiving signals from the source to the human ear is only the beginning of the sound perception process. Eggermont (2001) elaborated the hierarchal systems which occur between receiving and perceiving the sound. What makes auditory sensation a complicated phenomenon to fully understand is the interpretation phase in the brain, which is unique for each person. If this is exceptional and complicated process in each person, can architects predict human sound perception at the design stage with the aid of digital simulation? And if so, are the results consistent with post occupancy experimental outcomes? One problem is that acoustics, as a branch of engineering is challenging for architects and is more focused on quantitative rather than subjective analysis. This study aims to provide architects with a better understanding of how to evaluate the sound performance of their design before and after the design fabrication in terms of human perception of the sound.

In recent decades where landscaped plans in offices prevail, sound performance has become a key in architecture design. The database significantly indicates complaints about speech privacy rather than noise level in open plan offices (Jensen and Arens, 2005). Although objective measurement is useful, the human perception of the sound is a determinant of the speech privacy rating in the space. Cavanaugh (1962) found in his experimental research that each subject had his own personal criterion for defining speech privacy in a wide variation of 10 dB. While computer simulations have been widely applied to generate the spatial and temporal data describing the behaviour of sound in space (Stettner and Greenberg, 1989), the degree of compatibility of the simulation with the actual human perception of the sound is still in question.

In doing an experiment with human participants, it is hard to take all parameters into account unless the experiment is implemented in a laboratory, under controlled conditions. Upon doing so, the contradiction is that the environment itself has a great impact on the test participants due to failure to adequately represent the natural situation. Human perception of speech is highly dependent on the eavesdropper's brain interpretation of the sound and it varies from one individual and circumstance to another. An acoustical engineering approach to subjective experiment is well documented in the literature, all carried out in a very controlled conditions; while this methodology is appropriate for outlining the general conclusions and relationships, it may result in investigating impractical conditions (Haapakangas et al, 2014). This research is implemented from an architectural standpoint to test the human auditory performance in the realistic situation of an open plan office.

The significance of this study will be highlighted when it comes to the complicated geometry with articulated surfaces of small-scale spaces where the software is unable to process the data accurately. FabPod, a semi enclosed meeting room located in a large indoor open plan office at the Royal Melbourne Institute of Technology (RMIT) design hub, is an ideal case study of such a complex design. The space has non-rectangular overall geometry, non-parallel walls and the highly articulated interior surfaces. The aggregate structure, composed of hyperboloid cells with different types of material (Woven image Echopanel, Aluminium and Acrylic) were designed to provide an acoustically live space with better speech intelligibility and privacy (Burry et al, 2012; Williams et al, 2013), (Fig. 1, right).

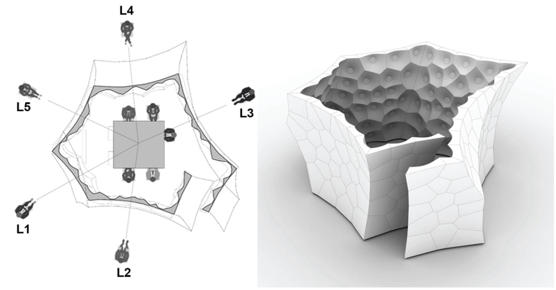

Figure 1. Experiment plan (left), 3D rendering of the FabPod (right).

2. Subjective experiment and objective measurement

The experiment was designed to assess the human auditory evaluation of the sound field, both inside and outside the FabPod, in a natural situation with controlling neither the environment nor the participants. The study frame can be considered an exploratory cross-sectional research and does not aim to test a statistically significant sample of participant experiences.

2.1. EXPERIMENT METHOD AND SETUP

Ten native English speakers, five males and five females, without any reported hearing deficit, participated in the research and were divided into two groups of five according to their age and position.

2.1.1. Procedure

The process started with a brief introduction to the experiment along with signing the consent forms. One group held a meeting inside the FabPod on a general topic of their own choice with their natural sound level, while the other group was listening to the conversation outside the FabPod in five different locations, specified before the test. ISO 3382-3 (2012) was applied to layout the listeners' locations approximately 1.5 m from the walls of the FabPod and all in the same distance of 4 m relative to the centre of the pod, where an omnidirectional microphone was installed (Figure 1, left).

The conversation inside the FabPod resembled a real meeting for 15 minutes and the eavesdroppers around the pod were advised to listen to the conversation as if they were supposed to work at that place. These eavesdroppers were each interviewed immediately afterwards to record their experience of listening. The groups then changed their positions as listeners and speakers and repeated the same procedure for the second round for another 15 minutes. All the participants were given full information about what they were doing.

2.1.2. Questionnaire and interview

The listeners around the FabPod in the open plan office were given a qualitative questionnaire focused on speech privacy and level of distraction after each round of experiment. Participants were asked to rate the speech privacy of the open plan office on a slider range from no privacy to confidential privacy and to identify the conversation topic if it was intelligible. The multiple-choice questions were composed of 5-point scales for describing the level of privacy and distraction, acoustic satisfaction, applicability and effectiveness of the design. The speakers inside the pod were interviewed after the test to share their auditory experiences of intelligibility and sense of privacy while having a meeting inside the pod. They rated the perception of the speech privacy while being inside in addition to intelligibility and clarity.

2.1.3. Data analysis

All participants sitting around the pod were able to distinguish the conversation tone and mood. Seven listeners could hear odd words of the sentences but couldn't make sense of them. Eavesdroppers in location L3, described speech privacy as normal with satisfactory acoustic comfort. Participants in location L2 perceived no privacy at all and could easily get distracted with clearly hearing every word. Locations L5, L4 and L1 stand in between these two respectively with little differences in defining speech privacy. Only one participant could identify the topic of the conversation in location L2.

Table 1. Participants' qualitative description summary

Gender Difference	*50% heard males pitch better*	*50% no difference in gender*
Degree of effectiveness	90% slightly to strongly effective	10% Neutral
Degree of applicability	90% helpful to extremely helpful design	10% slightly helpful, hard to notice
Speech privacy comparison	90% slightly to reasonable degree of privacy inside the pod	10% slight degree of privacy in open plan office

The average speech intelligibility and clarity subjective rating inside the FabPod was 0.90. And the average speech privacy rating outside the FabPod was 0.50. The difference between the speech privacy rating outside the pod and perception of privacy inside the pod is illustrated in Fig. 2 for participants in each location. These differences can be attributed to the visual sense of privacy inside the pod.

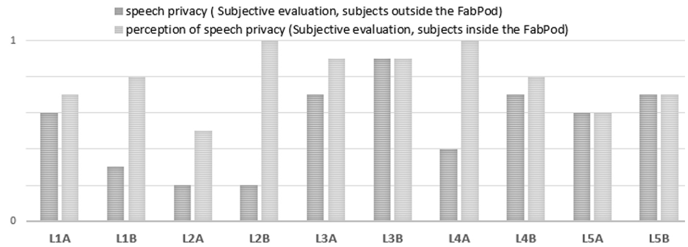

Figure 2. Difference in rating speech privacy inside and outside the pod.

2.2. OBJECTIVE MEASUREMENT

In the objective evaluation, both un-weighted and A-weighted, were measured. A-weighting is a sound filter which covers the full frequency range of human hearing between 20 Hz and 20 kHz and it has the most identical form to the reaction of the human ear.

The aim was to compare the outcome with the measurement which was implemented before, in a controlled condition with omnidirectional loudspeaker (Qui et al, 2013) instead of natural human conversation as a source. Also the results were compared with human subjective rating and computer simulation as a mean of speech privacy evaluation.

2.2.1. Measurement instrumentation and setup

The background noise was measured by the B&K system comprised of the Hand-held Analyser Type 2270 and microphone Type 4189 with Type ZC 0032 preamplifier. The Sound Pressure Level (SPL) was measured by four NTi systems consisted of an Audio Type XL2 Hands-held Audio and Acoustic Analyser and a Behringer ECM8000 ½'' microphone. The systems were calibrated with a B&K Type 4230 calibrator.

The background noise was measured at 1 position inside (L0) and five different positions outside (L1~L5) the Fabpod when there was no human activity in the open plan office. The measurement positions L0~L5 are shown in Fig. 1 (left), where the microphone is 1.2 m above the floor. The measurement for background noise lasted 60 seconds at each position, which was long enough according to the ISO 1996-1 (Chen et al, 2010).

The SPL was measured at 1 position inside (L0) and 3 different positions outside (L1~L3) the Fabpod simultaneously when the group held a meeting inside. Each round of the SPL measurement was lasting for 15 minutes in accordance to the subjective experiment, during which time the SPL was averaged every 10 seconds, which was long enough according to ISO 140-4 (1998). The SPL was measured in 1/3 octave band from 6.3 Hz to 20000 Hz.

2.2.2. Background noise

The un-weighted and A-weighted total SPLs of background noise inside the Fabpod at the center (L0) and outside around the pod at five different positions (L1 ~ L5) are shown in Table 2. The un-weighted and A-weighted total background noise level inside is about 2 dB and 4 dBA lower than the average value outside the FabPod respectively.

Table 2. A-weighted and un-weighted background noise pressure level in 6 locations

Positions	*L0*	*L1*	*L2*	*L3*	*L4*	*L5*	*Avg.*
L_n *(dB)*	48.3	49.8	51.1	47.2	49.1	52.7	50.4
L_{nA} *(dBA)*	34.2	36.7	40.6	36.6	38	39.7	38.6

2.2.3. Sound pressure level

For the first round of measurement, the SPLs inside are about 14 dB and 18 dB and for the second round 11 dB and 16 dB higher than that outside the FabPod in terms of the un-weighted and A-weighted total SPLs, respectively. The sound pressure level values are summarized in Table 3 and Fig. 3.

Table 3. A-weighted and un-weighted Sound Pressure Level (SPL) for two rounds of experiment in one location inside and 3 locations outside and A-weighted SPL Difference.

	Round A				*Round B*			
Positions	*L0*	*L1*	*L2*	*L3*	*L0*	*L1*	*L2*	*L3*
L_p (dB)	68.5	54.4	54.9	53	64.4	51.7	53.7	51.9
L_{pA} (dBA)	64.8	48	47.8	45.2	60.1	42.1	44.9	43.8
L_{pA} D (dBA)	--	16.8	17.0	19.6	--	18.0	15.2	16.3

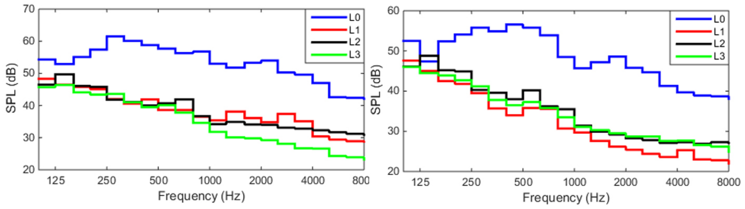

Figure 3. The sound pressure level in 1/3 octave band round A (left) round B (right).

3. Digital simulation

The main challenge in simulating the FabPod was the extreme irregularity in shape and material. Previous attempts to simulate the FabPod used approximation and simplification of the geometry and materials (Peters et al, 2013; Zhao et al, 2015), however noticing the fact that for making comparisons between human perception of the sound and measurement with digital simulation results comparable conditions were required, we needed to get as close as possible to the actual geometry and materials distribution and absorption coefficients to avoid any possible deviation causes by estimation. 3D visualisation of the simulated pod is shown in Fig. 4. Each hyperboloid was assigned the actual property without generalizing the material distribution, with high mesh resolution and small tolerance for water tightness.

Table 4. Absorption coefficients of the open plan office surfaces.

Frequency	*63*	*125*	*250*	*500*	*1000*	*2000*	*4000*	*8000*
Ceiling (α)	0.3	0.3	1.00	1.00	1.00	1.00	0.97	0.97
Wall (α)	0.1	0.1	0.05	0.06	0.07	0.09	0.08	0.08
Glass (α)	0.18	0.18	0.06	0.04	0.03	0.02	0.02	0.02
Floor (α)	0.02	0.02	0.05	0.05	0.1	0.05	0.02	0.02

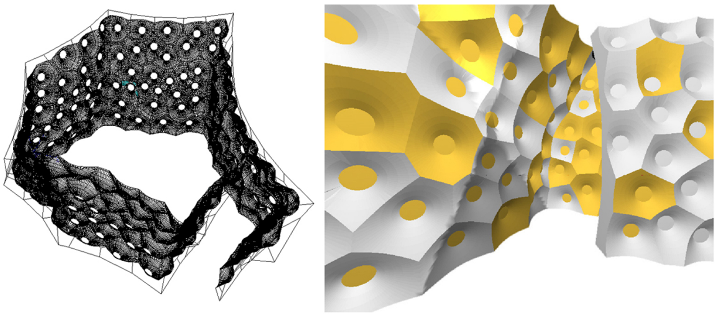

Figure 4. 3D of imported FabPod in ODEON (left), 3D openGL in ODEON (right).

3.2. SIMULATION ANALYSIS

For analysing the results two main parameters were selected according to the standard 3382-3:2012. ODEON calculated A-weighted sound pressure level (SPLA) and speech transmission index (STI) and the grid map in Fig. 5 indicates the STI for receivers in each 0.25 m^2 of the open plan office. STI is the quality of transferred speech from source to receiver (Svensson and Nilsson, 2008) and it is found to be one of the best descriptors for speech privacy and speech intelligibility. With the higher STI, the more intelligibility and consequently less privacy can be achieved in the space. According to ISO 3382-3:2012, the distraction distance starts when the STI falls below 0.5 and the privacy zone has the STI between 0 and 0.2.

The results show that location L3 has less STI (0.24) and more SPLA reduction which implies that this space can be considered more private and less distracting when there is a meeting in the pod. Location L5 would be the next with the STI of 0.28. STI decline at L5 relative to L3 is above the just noticeable difference (JND) range which is 0.03 (Bradley et al, 1999), indicates participants should perceive the difference between speech privacy in L3 and L5. The STI difference between Location L1 and L4 is below JND and it is 0.32 and 0.31 respectively. Therefore, these two locations would stand in the same position in terms of speech privacy. STI for L2 is 0.57.

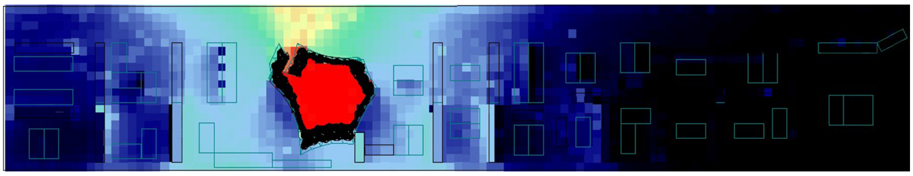

Figure 5. Calculated STI, grid map of the open plan office at 1.2 m height.

It is important to notice the limitation of the ODEON software in simulating complex geometry and considering the sound transmission through walls simultaneously. Since the presented simulation is regardless of transmitted sound through structure, currently we are not able to compare the simulated STI with standards, however it is not the focus of this study.

To investigate the effect of the sound transmission through pod's surfaces, we need to simplify the geometry and exclude the impact of the hyperboloids in simulation. The STI will then dramatically increase to 0.59 in L3 and correspondingly to all other locations. The suggested reason for improved speech privacy in spots 3 and 5 is the FabPod's overall geometry with sharp edges in the corners, which provides acoustic shadows at these two locations (Fig. 6).

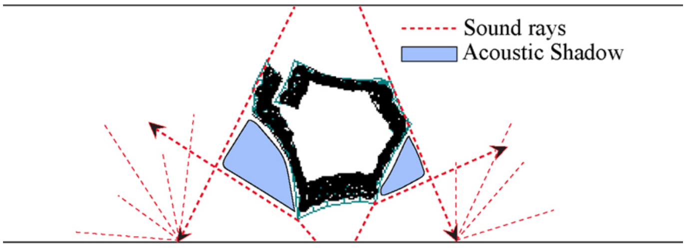

Figure 6. Acoustic shadows provided by FabPod sharp edges.

4. Results comparison

Theoretically for each location the sound level reduction in both rounds should be the same. One reason for discrepancy in measurement was uncontrolled natural environment of the open plan office. The SPL at each location was not only a transmitted sound from meeting in the FabPod, but also from occupants working at the open plan office at the same time. The second reason was inaccessibility to the multi-channel measurement system at RMIT Acoustic Lab. The measurement results of the four NTi systems might not be synchronized accurately due to manual operations. Also as a result of NTi system noise floor, any SPL measured by the NTi systems lower than 37.5 dBA is unaccountable. Despite these inaccuracies, the average measured sound level reduction is in line with the previous study (17 dBA), carried out in a very controlled situation (Qui et al, 2013). Furthermore, the reverberation time (T20) in simulation (0.27 s) is very close to the post occupancy objective measurement (0.26 s) implemented before (Zhao et al, 2015).

The remarkable consistency between subjective rating, measurement and simulation prediction shows that in all evaluations the best and worst locations in terms of speech privacy are the same. L3 is constantly the best spot in all analysis and L2 with the highest STI and lowest sound level reduction is the most distracting location. Some fluctuations can be seen in the ranking of the other locations due to the complex human perception of the sound and many variables involved in subjective rating, besides the non-controllable situation of the experiment.

5. Conclusion

This architectural approach to the research studied the consistency of the simulation prediction with post occupancy subjective judgement of the sound field and measurement in complex geometries. The importance of the results lies in the significance of how architects can predict sound performance regarding human perception and to what extent this prediction can approximates human interpretation of the speech privacy. We observed a high correlation between simulation prediction of speech privacy and human's perception of the privacy, which indicates that architects can predict the acoustic performance of their complex designs especially in small spaces using either simulation techniques before fabricating the full-scale prototype or arranging subjective experiments with scaled prototypes. Second, the consistency between objective measurement, digital simulation and architectural subjective study implies that architects can set up a simple subjective experiments for preliminary testing of sound performance of their design by knowing only the basics of architectural acoustics. This type of experiment is relatively different from an acoustic engineering approach. However, it can provide continuous feedback for the design before and after fabrication. The STI threshold of privacy and distraction needs further study, specifically for experiments in natural environments, since this research has demonstrated that occupants in the places with STI greater than 0.5 can still be acoustically comfortable doing work with no distraction even though this is above the acoustic threshold suggested in the literature and by the standards.

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