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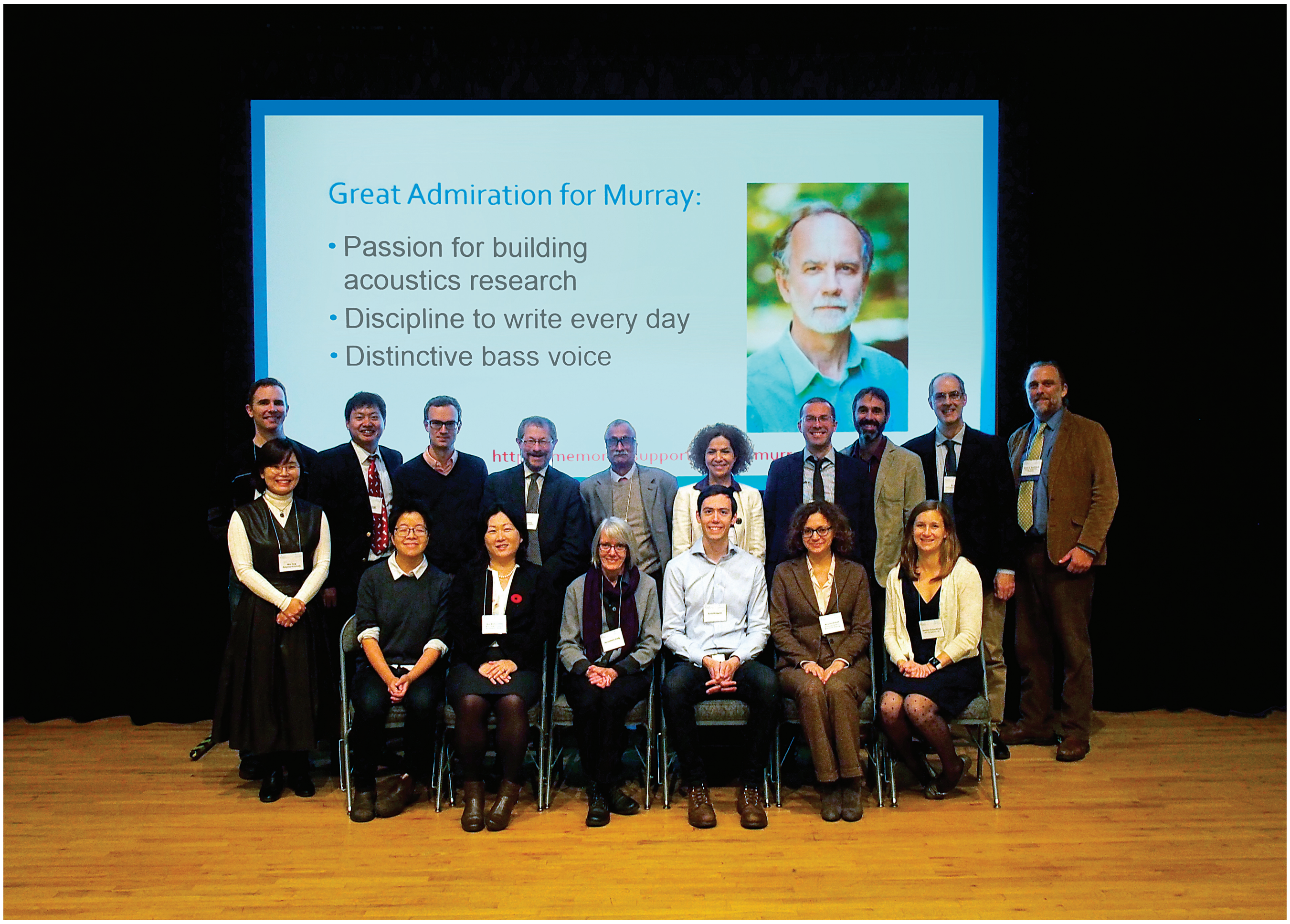

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L'Acoustique Canadienne publie des articles arbitrés et des informations sur tous les aspects de l'acoustique et des vibrations. Les informations portent sur la recherche, les ouvrages sous forme de revues, les nouvelles, l'emploi, les nouveaux produits, les activités, etc. Des articles concernant des résultats inédits ou des applications ainsi que les articles de synthèse ou d'initiation, en français ou en anglais, sont les bienvenus.

Acoustique canadienne est publié quantre fois par an, en mars, juin, septembre et décembre. Cette revue trimestrielle est envoyée gratuitement aux membres individuels de l'Association canadienne d'acoustique (ACA) et aux abonnés institutionnels. L'Acoustique canadienne publie des articles arbitrés et des rubriques sur tous les aspects de l'acoustique et des vibrations. Ceci comprend la recherche, les recensions des travaux, les nouvelles, les offres d'emploi, les nouveaux produits, les activités, etc. Les articles concernant les résultats inédits ou les applications de l'acoustique ainsi que les articles de synthèse, les tutoriels et les exposées techniques, en français ou en anglais, sont les bienvenus.L'Association canadienne d'acoustique a sélectionné Paypal comme solution pratique pour le paiement en ligne de vos frais d'abonnement. Paypal prend en charge un large éventail de méthodes de paiement (Visa, Mastercard, Amex, compte bancaire, etc) et ne nécessite pas que vous ayez déjà un compte avec eux. Si vous désirez procéder à un paiement par chèque de votre abonnement, merci d'utiliser le formulaire d'adhésion du site de l'ACA et de retourner ce dernier avec votre chèque ou mandat au secrétaire de l'association (voir adresse ci-dessus). - Canadian Acoustical Association/Association Canadienne d'Acoustiquec/o JASCO Applied Sciences2305–4464 Markham StreetVictoria, BC V8Z 7X8 Canada - - - secretary@caa-aca.ca - Dr. Roberto Racca

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WE CAN MAKE WHATEVER YOU MAKE
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Editor's note: Murray Hodgson's legacy
Éditorial : L'héritage de Murray Hodgson


Murray Hodgson's legacy: how acousticians can improve the world

Dear reader, it is with great pleasure that we present this special issue in memory of the distinguished fellow acoustician, previous editor-in-chief, colleague and friend Prof. Murray Hodgson. The 12 papers here enclosed have been collected and processed after the namesake special session held in Victoria, BC, Canada on 9 November 2018 at the joint ASA – CAA meeting.

The session lasted one day and had some 17 distinguished speakers from North-America, Europe and Asia to witness the many connections that prof. Hodgson had established during his career. The contributions presented at the Conference covered a breadth of topics that ranged from the room acoustical foundations of diffuse field theory, to studies in classroom acoustics and to diverse applications in noise control and acoustics for sustainable constructions. Indeed, the session was a faithful representation of the many areas in acoustics that prof. Hodgson had researched, and of his interest in the multidisciplinary approach to problems involving acoustics.

In addition to the outlook of his scientific achievements, also the outstanding qualities of prof. Hodgson as a mentor and as a servant for CAA and for this journal were recalled. Some of his graduate and Ph.D. students depicted a vivid image of an extraordinary mix of science, competence and warmth which were the traits of his activity.

In this respect the introductory speech given by John O'Keefe, that you will find transcribed in the opening of this special issue, was a moving testimony and it was very effective in describing what good science can do to solve practical problems, an art where the mastery of prof. Hodgson is undisputed. This special issue has thus the aim of fixing both the memory of the scientist and of the man. From many of the papers here enclosed dealing with sound diffusion or with classroom acoustics just to mention two of the most covered topics, it clearly appears that he was able to leave a mark that others could later take over.

L'héritage de Murray Hodgson: comment les acousticiens peuvent-ils améliorer le monde

Chère lectrice, cher lecteur, c'est avec grand plaisir que nous vous présentons ce numéro spécial à la mémoire de l'éminent acousticien, ancien rédacteur en chef, collègue et ami, le professeur Murray Hodgson. Les 12 articles ci-joints ont été rassemblés et traités après la session extraordinaire tenue à Victoria, Colombie-Britannique, Canada, le 9 novembre 2018, lors de la conférence conjointe ASA - CAA.

La session a duré un jour et a rassemblé 17 éminents conférenciers provenant d'Amérique du Nord, d'Europe et d'Asie, témoins des nombreux liens que le Prof. Hodgson avait établi au cours de sa carrière. Les contributions présentées à la conférence couvraient un large éventail de sujets allant des fondements de la théorie des champs diffus en acoustique des salles à l'acoustique des salles de classe et à diverses applications dans le contrôle du bruit et l'acoustique dans les constructions durables. En effet, cette session était une représentation fidèle des nombreux domaines de l'acoustique étudiés par le Prof. Hodgson et de son intérêt pour une approche multidisciplinaire des problèmes liés à l'acoustique.

Outre les perspectives de ses réalisations scientifiques, les qualités exceptionnelles du Prof. Hodgson en tant que mentor et serviteur de l'ACA et de ce journal ont été rappelées. Certains de ses étudiants de deuxième et troisième cycle ont décrit une image éclatante d'un mélange extraordinaire de science, de compétence et de chaleur qui caractérisait son activité.

À cet égard, le discours d'introduction de John O'Keefe, que vous trouverez transcrit au début de ce numéro spécial, était un témoignage émouvant, décrivant efficacement ce qu'une « bonne science » peut faire pour résoudre des problèmes pratiques, un art que maitrisait le Prof. Hodgson de façon incontestée. Ce numéro spécial a donc pour but d'honorer la mémoire du scientifique et de l'homme. À partir des nombreux articles inclus dans ce numéro, traitant de la diffusion ou de l'acoustique des salles de classe, pour ne citer que deux des sujets les plus abordés, il apparaît clairement qu'il a pu laisser une empreinte dont d'autres ont pu s'inspirer.

This is a rare but an essential quality that helps our discipline to progress step by step, and from one generation to the next.

Another legacy of prof. Hodgson that you will find across the papers of this issue is the convincement that the openness of acoustics to meet other disciplines should be fully exploited. In fact, a more comprehensive and useful view of many practical problems could be accomplished from such contaminations.

In conclusion we hope that this special issue will provide a picture, albeit partial and incomplete, of the relevant and lasting contributions in science and style that an exemplary career in acoustics such as that of prof. Murray Hodgson has left to us.

We wish you a pleasant reading of this issue.

Umberto Berardi and Nicola Prodi
Editors for this special issue.

C’est une qualité rare mais essentielle qui permet à notre discipline de progresser pas à pas, et d’une génération à l’autre.

Un autre héritage du Prof. Hodgson, que vous trouverez à travers les articles de ce numéro, est la conviction que l’ouverture de l’acoustique à d’autres disciplines devrait être pleinement exploitée. En fait, une telle contamination peut donner une vue plus complète et utile à de nombreux problèmes pratiques.

En conclusion, nous espérons que ce numéro spécial brossera un tableau, bien que partiel et incomplet, des contributions pertinentes et durables à la science et au style que l’exemplaire carrière en acoustique du Prof. Murray Hodgson nous a laissé.

Nous vous souhaitons une bonne lecture.

Umberto Berardi and Nicola Prodi
Éditeurs pour ce numéro spécial.

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- Calculation of the sound power level based on technical parameters such as rotational speed or power

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MURRAY HODGSON:
AN APPRECIATION FROM A PRACTICING ACOUSTICAL CONSULTANT

John O'Keefe[*]
O'Keefe Acoustics, Toronto, Ontario, Canada

Résumé

Une grande partie de ce que nous savons sur le comportement du son dans les salles provient d'études effectuées dans des salles de réverbération et des salles de concert. Une géométrie architecturale peu commune au quotidien. L'auteur a rencontré Murray Hodgson pour la première fois à Cambridge lorsque le Dr. Hodgson était en train de faire ses premières études de modèles sur des usines. Du point de vue géométrique et acoustique, les usines ressemblent beaucoup plus à l'environnement bâti dans lequel nous habitons au quotidien. La géométrie d'une usine est généralement longue, large et très plate avec des éléments dispersants, généralement au sol. Murray appliqua ensuite son travail sur les usines à d'autres salles longues, basses et larges. Notre compréhension de l'acoustique des bureaux à aire ouverte, des établissements de soins de santé et, bien sûr, des salles de classe peut être attribuée à ses travaux postdoctoraux à Cambridge. Il est impressionnant que ses travaux sur l'acoustique en usine aient été transposés à une grande partie des pièces dans lesquelles nous vivons. Plus impressionnant encore fut sa capacité à traiter des questions auxquelles personne ne souhaitaient répondre. Des questions souvent posées aux consultants en acoustique et qui n'ont toujours pas de réponse, comme par exemple, celles concernant le contrôle du bruit dans les bâtiments à ventilation naturelle. Ses travaux sont devenus un fondement pour le genre naissant de l'écoconstruction.

Mots clefs : acoustique architectural, réverbération, intelligibilité de la parole, lutte contre le bruit

Abstract

So much of what we know about the behaviour of sound in rooms comes from studies in reverberation rooms and concert halls. Hardly everyday architectural geometry. The author first met Murray Hodgson in Cambridge when Dr. Hodgson was doing his early scale model studies on factories. Geometrically and acoustically, factories are much more akin to the day to day built environment that we inhabit. The geometry of a factory is typically long, wide and very flat with scattering elements, typically on the floor. Murray would go on to apply his work on factories to other long, low and wide rooms. Our understanding of the acoustics of open plan offices, health care facilities and, of course, classrooms can be traced back to his post-doctoral work in Cambridge. One is impressed how the work on factory acoustics grew to cover so much of the rooms we live in. More impressive was his ability to tackle questions that others wouldn't. Questions that acoustical consultants are often asked and really don't have an answer for yet. Noise control in naturally-ventilated buildings for example. His legacy will show this work as seminal in the nascent green building type genre.

Keywords: architectural acoustics, reverberation, speech intelligibility, noise abatement

1 Preamble

The following comes from the tribute session for Murray Hodgson, convened at the joint meeting of the Canadian Acoustical Association/Association Canadienne d'Acoustique and the Acoustical Society of America, held in Victoria BC on 8 November 2018. In the spirit of a testimonial to a friend, the author has suggested, and the editor and reviewers have kindly accepted, a proposal to reproduce this paper as presented. Which is to say that the following prose is more about stand up and deliver as opposed to sit down and read. This also explains its less formal conversational, first person nature, for which the author apologises for in advance.

2 Introduction

J'ai pensé que je pourrais commencer mes quelques mots sur notre ami Murray en Français. Parce que quand je pense à Murray j'entends l'homme criant à l'arrière de la salle lors d'une réunion de la ACA en criant à l'orateur : «En Français !». Donc, Murray, j'essaie d'apporter ma petite contribution, «en Français».

For our American friends, and I dare say one or two Canadians, I was just saying that one of my enduring memories of Murray was the voice from the back of a CAA General Meeting shouting to the poor fellow at the front of the room: "En Français !". And now you've just heard my feeble attempt.

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[*] john@okeefeacoustics.com

3 Early years

I first met Murray some 35 years ago. He'd just finished his Ph.D. [1] at Southampton's Institute of Sound and Vibration Research (ISVR) the same year that I started my Master's. That was 1983. I don't recall meeting him at ISVR though. We met in Cambridge where he was doing his post-doc work on factories and I was doing my thesis on British theatres.

There was quite a team of acousticians there, though we didn't think much of it at the time. There was Raf Orlowski, who would go on to do some important things. Mike Barron, who had already done important work and would continue to do so. Murray, doing his early scale model work on factories. And for better or (probably) worse, me!

I would go on, later, to do quite a bit of work in scale modelling. So, when I was invited to give this talk, I originally thought that I would focus on Murray's models. Something I knew a little bit about. But, after some thought and a bit of review, I realised I could talk on something I know a little bit more about – acoustical consulting.

4 Contributions

Because Murray's work has made a significant contribution to the tool-kit of the average work-a-day acoustician. People like many of us here today. And it all started with scale models of factories.

There was a fantastic scale modelling facility up in Cambridge, cobbled together originally by Mike Barron to study, among other things, the then new Barbican Concert Hall. Raf Orlowski tells me [2] that Mike recruited both Murray and himself. Their first grant was for the concert hall kind of work that Mike was doing. But when the 2nd and 3rd grants came along, the powers-that-be suggested: "Hey, wouldn't it be nice if you included some factories?" You know, real people! So they followed the money. Murray, of course, had done his Ph.D. on scale model factories. And that was a fortunate thing for all of us.

Here's a thought that occurred to me. Most of what we know about the behaviour of sound in a room comes from reverberation rooms and concert hall research. Neither of which share a geometry with the great bulk of the built environment. Concert halls and reverberation rooms are, proportionally, tall and often narrow. Factories, on the other hand, are often very wide with, proportionally, very low ceilings. And so are open plan offices, classrooms and hospital wards. All areas of study that Murray would go on to explore. Not to mention roadside noise barriers. The sort of thing that the average work-a-day acoustician might confront. As I have with, at the time, little guidance from the literature. Something Murray would help to take care of. There are a lot more highways and open plan offices being built these days than concert halls. There always have been and there always will be.

Our world of acoustics is, I suggest, a little too occupied with the success of its first science – Reverberation Time. For any type of building that we humans might occupy, be it an office, factory, a classroom or, yes, even a concert hall… the thing that we respond to most is not reverberant decay, but Loudness. Go home and look at your stereo. The biggest knob doesn't control Reverberation. It controls Loudness!

Perhaps I should be more formal in this forum. To be more accurate, I'm referring to the Signal to Noise Ratio. Something, I note, that is documented in burgeoning field of classroom acoustics research [3, 4] but is not quite as well appreciated in concert hall research.

Murray was particularly well positioned to comment and inform us on the reverberation calculations that are often found at the foundations of so much of what we do. That's because, unlike many others, he has measured all manner of rooms. Rooms that vary vastly in geometry and, in particular, the distribution of surface types. If you hang around with people like me – and many of you do – you'll find a lot of measurements in theatres and concert halls. Rooms where most of the acoustic absorption is found on a single surface. The floor. Come to think of it, when we use a reverberation room, we measure the absorption of a material laid out on the floor. Hardly the uniform distribution that either Sabine or Eyring had in mind.

So it's disconcerting that Murray should find – quite conclusively – that, although both Sabine and Eyring quite accurately predict reverberant decay, they do not do so for reverberant level [5]. This, at least in my opinion, comes from one of his more important pieces of work.

He identifies a problem that we all needed to be aware of. And now we are. Enigmatically though, he poses no solution to the problem. But there is, and there was, a solution [6]. He was aware of it. He chose not to mention it. But that's a story for another time.

Still, Murray's work gave us lowly consultants another wonderful tool for our toolkits. The knowledge of when our basic assumptions work and, just as importantly, when they don't. Both Sabine and Eyring predict reverberant decay quite reliably. Neither of them can reliably predict reverberant level [7].

5 Scale models

I won't say that we ever did or ever will suffer from a surfeit of concert hall scale model studies. But Murray started out with physical scale models of factories and would return to scale models when he could throughout his career. And thank goodness he did.

Thank goodness for two reasons. Almost all computer models these days are energy based, as are our Sabine and Eyring reverberation calculations. For most of us, there are no wave effects in our computer models. Parenthetically, I should add that wave based computer simulations are quickly catching up and may, someday, be useful in normal sized rooms. Most current computer models, however, are based on specular reflections, the physics of which amounts to the assumption that the reflecting surface is infinite in size and perfectly flat. No curves allowed. So, in short, if you want to believe your modern energy based computer model you have to pretend that sound is not a wave and that you are a paid up, card carrying member of the flat earth society!

Current computer models only pretend to include diffusion effects. They do so with a physically inaccurate, mathematical sleight of hand. Diffusion is a wave effect and right now, for a large room, that can only be modelled reliably in a scale model.

One of Murray's more important studies was a quantification of the acoustic effects of fixtures on a factory floor [8]. Something he couldn't have done without physical scale models. And, I'll hasten to point out, the acoustic effects of factory floor fittings are not unlike a row of desks in a classroom or open plan office. Ever seen a reliable absorption coefficient for a desk in an open plan office, occupied or unoccupied? You may have. But I haven't.

So, that was Thank Goodness #1. That he was working on scale models.

Thank Goodness #2? That he was working on factories. Because, as I've mentioned, the geometry of a factory is much closer to the majority our built environment. Much closer than it might seem at first glance. As, I pointed out, it was a short step from factories to classrooms, offices and hospital wards.

6 Sustainable acoustics

Murray points out – quite rightly – that providing unsatisfactory acoustics in sustainable buildings is… well… unsustainable! [9] Someone is eventually going to change things. So much for sustainability.

But there is, or was, a dearth of data on green buildings as consultants like me so often found as we tried to apply our nascent science of acoustics to the real world.

Some years ago, I did a green office building for Manitoba Hydro in Winnipeg. A city known affectionately to the Canadians in this room as "Winterpeg". Situated at the centre of the continent, it suffers a continental climate of extremes. Freezing cold in the winter and boiling hot in the summer. If ever there was a challenge for sustainable design, this was the place. The building more than met those challenges and won a number of awards. None of them, I'm sure you've guessed, were for the acoustics!

Murray was one of the first to publish cold hard facts about the acoustics of green buildings [10, 11]. Unfortunately for me, that was in the early 2,000s, a few years after we had completed the design. With calculations that I don't mind telling you were, at the time, no more than acoustical stabs in the dark. It's nice to know that we now have documented data to verify what we're trying to predict. And Murray, more than any other I might suggest, got that ball rolling.

7 Multi-disciplinary

Murray's work so often crossed so many disciplines. Factory workers, architects, school teachers and so many more. Murray worked with them all.

Having recently donned a pair of hearing aids, [12] I've taken a latter day interest in audiology. My wife, who actually is an audiologist, never tires of telling me that acousticians really don't know all that much about hearing. But that didn't faze our friend Murray.

Get this for a multi-disciplinary study: ship building, workers' health and safety and the very wide chasm between acoustics and audiology. And believe me, there is a chasm. I've lived the last 35 years of my life learning how just much I don't know about audiology! I'm speaking, of course, of Murray's work with our friend Chantal LaRoche [13], oh about fifteen years ago.

The resulting papers, many of which were presented here in Victoria at our meeting in 1999 were published later in Canadian Acoustics/Acoustique Canadienne [14]. These papers are a tour de force in the application of multi-disciplinary research.

8 Editor

Finally, I would be remiss if I did not mention Murray's time as our editor of Canadian Acoustics/Acoustique Canadienne. From 1990 to 1998.

He said that one of his proudest achievements in that office was the publication the late Raymond Hétu's controversial comments on Occupational Hearing [15]. Which wasn't easy. The illustrious likes of Edgar Shaw, for example, refused to review it. Murray was even threatened with legal action. But you didn't mess with our Murray, especially when he cared about something. Thanks to his persistence, the debate that Hétu initiated was given a voice.

9 Conclusion

Factories, offices, classrooms, hospitals and, yes, even ships on the ocean. He's done them all and done them well.

He enjoyed the admiration and affection of his students. That affection was well earned. I was told last night that he was still helping his students from his hospital bed.

He commanded the respect of all of us in the Canadian Acoustical Association and, of course, acousticians throughout the world. And I thank so many of you for coming here today. He died too soon. But few of us will soon forget him.

In our little corner of science called acoustics, the description of our built environment is a better place for the work of our friend Murray Hodgson. I can think of no better tribute for the work or for the man.

Au revoir mon ami.

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MODELING NON-DIFFUSE SOUND FIELDS IN ROOM ACOUSTICS: FROM MURRAY HODGSON'S EARLY WORKS TO THE DIFFUSION EQUATION MODEL

Vincent Valeau[1*], Cédric Foy[†2] and Judicaël Picaut[‡3]
[1]Institut PPRIME UPR 3346, CNRS – Université de Poitiers – ENSMA, Poitiers, France
[2]CEREMA, IFSTTAR, UMRAE, Strasbourg, France
[3]IFSTTAR, CEREMA, UMRAE, Bouguenais, France

Résumé

Le concept de champ diffus en acoustique des salles est l'hypothèse de base de la théorie classique de la réverbération. Cette hypothèse est pourtant fausse dans de nombreuses situations pratiques pour lesquelles le champ sonore réverbéré présente d'importantes variations spatiales dans la pièce. Murray Hodgson a consacré une partie importante de ses activités de recherche à l'étude des champs non diffus, par des études combinant souvent des aspects expérimentaux et de modélisation. Certaines des premières contributions de Hodgson en lien avec ce sujet sont d'abord présentées. Dans une deuxième partie, le papier présente des développements concernant un modèle statistique pour les champs non diffus basé sur un processus de diffusion. Le papier se concentre en particulier sur la modélisation des réflexions diffuses au sein de ce modèle de diffusion, l'application de ce modèle aux locaux industriels, et la modélisation des flux d'énergie en utilisant la loi de Fick. Tous ces développements constituent une suite naturelle des travaux d'Hodgson, concernant de multiples problématiques qu'il a soulevées sur le sujet des champs non diffus.

Mots clefs : acoustique des salles, réverbération, diffusivité du champ sonore, équation de diffusion

Abstract

The concept of diffuse sound field in room acoustics is the basic assumption of the classical theory of reverberation. This assumption is however false in many practical situations where the reverberant sound field undergoes significant spatial variations in the room. Murray Hodgson has dedicated an important part of his research activities to the study of such non-diffuse sound fields, through studies combining generally both experimental and modeling aspects. Some of Hodgson's early contributions in link with this topic are first presented. In a second part, the paper presents some developments concerning a statistical model of non-diffuse sound fields based on a diffusion process. The paper focuses in particular on the modeling of mixed reflections within this diffusion model, the application of this model to industrial workrooms, and the modeling of energy flows by using the Fick's law. All these developments are a natural continuation of Hodgson's works, concerning numerous issues that he raised on the modeling of non-diffuse sound fields.

Keywords: room acoustics, reverberation, sound field diffuseness, diffusion equation

Foreword

The first author of this paper visited Murray Hodgson at the University of British Columbia for the first time in 2005. This visit has been followed by several others, which led to a very friendly relationship, and to numerous and fruitful exchanges, thanks to Murray's great expertise in many fields of acoustics. A collaboration on the development of a statistical model for room acoustics was carried out in the years 2005-2008, and the paper is a review of these works, highlighting the fact that they can be seen as a natural continuation of Murray's earlier works on the modeling of non-diffuse sound fields.

1 Introduction

It is well known that the reverberant sound field in a room can be accurately described by statistical models at medium and high frequencies, provided that there is sufficient modal overlap. In practice, it is considered that such models are valid for frequencies above the so-called "Schroeder frequency" [1]. The classical statistical theory of reverberation is a powerful tool for predicting sound pressure levels and reverberation times based on little information about the room. It is based on the concept of "diffuse sound field", according to which the reverberant sound field at any location in a room is due to uncorrelated waves traveling with equiprobable directions and intensity [2]. Widely used by practitioners for obtaining acoustic predictions within "engineering accuracy" [3], the diffuse field concept is nevertheless limited to restricted practical situations, and is by nature unable to predict spatial variations of the reverberant field in a room. Sound fields

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[*] vincent.valeau@univ-poitiers.fr
[†] cedric.foy@cerema.fr
[‡] judicael.picaut@ifsttar.fr

for which such spatial variations are significant will be called “non-diffuse” sound fields in the rest this paper.

Murray Hodgson, since his PhD works in the early 80s on the sound field in industrial workrooms [4], has dedicated a significant part of his research activities to the study of non-diffuse sound fields, through studies combining generally both experimental and modeling aspects. In the years 2000s, Murray Hodgson has been collaborating with the authors of the present paper on the modeling of non-diffuse sound fields, by using a specific statistical model based on a diffusion equation [5]. The objective of this paper is to underline some aspects of Hodgson’s research on non-diffuse sound fields, to establish the link with the research activities on the diffusion model, and to make a summary of the collaborative activities between Murray Hodgson and the authors of this paper.

In this purpose, in Section 2, some aspects of Hodgson’s research concerning non-diffuse sound fields and the sound field in industrial workrooms are presented. In Section 3, the diffusion model for room acoustics is briefly presented, and the different aspects in which Murray Hodgson has been involved are synthesized, before a brief set of conclusions and perspectives in Section 4.

2 Some aspects of Hodgson’s research on non-diffuse sound fields and industrial workrooms

Murray Hodgson has devoted an important part of his research to the study of sound field diffuseness in room acoustics. Several of his papers have had a significant impact on the scientific community working in the field of room acoustics. In his 1996 famous paper, “When is diffuse sound field theory applicable?” [3], Hodgson pointed out that, based on his experience (“*from having measured sound fields in hundred of rooms of any type*”), this theory is generally accurate for describing the reverberation time in real rooms. On the contrary, the prediction of steady-state sound pressure level (SPL) should be limited to rooms with cubic shape and uniform absorption coefficient. If the room shape departs from a cubic geometry, the diffuse sound field theory will be more accurate if the walls have specular reflections [6]. Indeed, Figure 1 shows the reasonable agreement of the diffuse sound field theory with the measured SPL for a squash court (a nearly-cubic room with flat surfaces, i.e., specular reflections), but also demonstrates (along with other examples given in [3]) a general trend of this theory to under-estimate the spatial decay of the SPL for rooms with common aspect ratios. Reference [3] is definitely a paper that has been greatly useful to practitioners, giving accurate guidelines for applying (or not) the well-known diffuse sound field theory. This study definitely demonstrated the need for modeling non-diffuse sound fields with a satisfactory precision.

From the 80’s, Hodgson’s research has been indeed largely dedicated to the characterization and the prediction on non-diffuse reverberant sound fields, especially by using simulations tools based on ray-tracing, image-source, radiosity models etc. (eg., [6-9]). Hodgson’s most cited paper (according to the Scopus database), published in 1991, focused in particular on the influence of the walls’ reflection law on the reverberant sound field [8]; in this context, a mixed reflection is defined as a mix of diffuse and specular reflection. The key-parameter is the non-dimensional scattering coefficient (noted down *d* in the following) defining the proportion of specular and diffuse reflections (ranging from 0 for purely specular reflections to 1 for purely diffuse reflections). The need of incorporating the scattering coefficient in ray-tracing simulations was demonstrated experimentally, as illustrated in Figure 2. In the case of a proportionate room (left column in Figure 2), it is shown that the scattering coefficient *d* has no influence on the predicted SPL; whatever its value, the simulation shows a generally satisfactory agreement with the measurement data. On the other hand, in the case of a flat room (an empty factory, right column), the spatial decay of the SPL is very sensitive to the scattering coefficient, and increases with the amount of diffuse reflections. It was concluded that it is generally possible to obtain a best-fit agreement with experiment for a particular value of *d* between the two extremes. This conclusion is now common knowledge among practitioners, and most simulation tools incorporate the scattering coefficient value [10, 11].

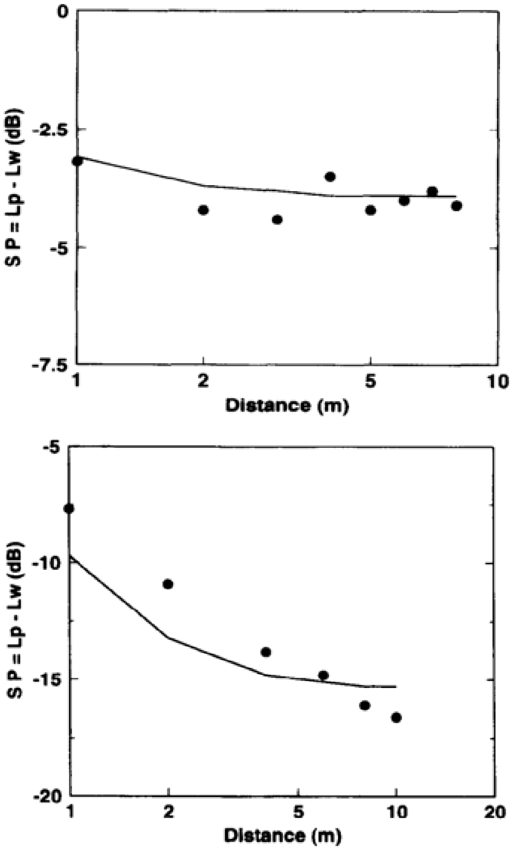

Figure 1 (from [3])**:** Plain line: diffuse sound field theory, (●) measured sound level decay in the 1000 Hz-Octave band, as a function of the distance to the sound source, for: Top: a room with homogeneous dimensions (a squash court , dimensions 10 x 6 x 5 m^3), Bottom: an elongated room (a classroom, dimensions 14 x 8 x 3.5 m^3).

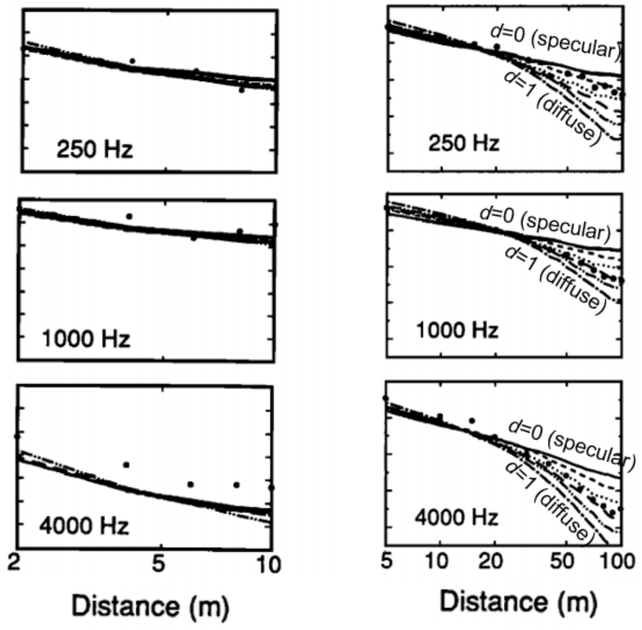

Figure 2 (adapted from [8]): SPL predictions in dB by using the ray-tracing technique, in several octave bands, for different values of the scattering coefficient *d* between 0 and 1, for: a proportionate room (a gymnasium, left column), a flat room (an empty factory, right column). (●) measurement data.

Another important interest of Murray Hodgson was the prediction of the reverberant field in industrial workshops [4]. The presence of "fittings" in the room (which can be called a "fitted room") can potentially enhance the diffuseness of the reverberant field, due to the acoustic scattering by the obstacles. The fittings are generally modeled by a statistical parameter called the fitting density (analogous to a mean free path [12]), and by their absorption coefficient. Many models, often empirical, exist for predicting the reverberation in such rooms, and Hodgson's research in this field has been dedicated to accurate evaluations of such models (e.g., [13-15]), or to assess the correct values for the fitting characteristics (e.g., [16]) by using extensive comparisons between predictions and experiments. Hodgson's publications on the topic of the acoustics of industrial workshops illustrates well how providing reliable tools to practitioners has been a constant goal in Hodgson's research.

3 The diffusion model for room acoustics

Hodgson's works on non-diffuse sound fields truly justifies the need for a model able to describe common practical situations involving non-diffuse sound fields, mixed reflection and scattering by fittings. A solution was proposed with the development of the so-called diffusion model for room acoustics.

The idea of describing the reverberant field in a room by a diffusion process is initially due to Ollendorff in 1969 [17], but the concept was really applied and validated by Picaut et al. in 1997 [5]. The model is based on the sound particle concept [18], *ie.*, on the analogy of the acoustic energy density with a density of "sound particles" propagating at the speed of sound *c* along straight lines. Many geometrical models (like the ray-tracing technique and its variants) consist in emitting a great number of particles (high enough for reaching the statistical convergence) and following their individual trajectories (the rays).

Conversely, the diffusion model starts from the transport theory developed in statistical physics [19], using the distribution function of the particles in the phase space for modeling the particle dynamics in a global way. Under a set of assumptions, in particular, i) the walls of the room are analogous to a cloud of spherical scatterers located within the room volume, and ii) the phenomena are nearly isotropic, a diffusion equation governing the sound energy density can be obtained [5]. The key-parameter of the diffusion process is the so-called "diffusion coefficient" D (unit m^2/s), and is, in theory, equal to $\lambda c/3$, λ being here the room mean free path, and c the sound speed. In this expression, the classical mean free path of an empty room $\lambda_r=4V/S$ (V and S are respectively the room volume and the area of the room surfaces) is used, which is valid in the case of purely diffuse reflections [2].

This diffusion equation is then associated with an appropriate boundary condition requiring the introduction of an exchange coefficient depending on the absorption coefficient of the walls [20-23]. The advantage of the diffusion model is that it can be rather easily solved numerically [21], and can handle complex cases (eg., complex networks of coupled rooms [24,25]) with a low computational cost compared to geometrical techniques.

The diffusion equation was shown to be an extension of the classical reverberation theory to non-diffuse sound fields [21], and is perfectly adapted for predicting spatial sound decays in rooms such as the ones reported in Figure 1 by Hodgson [3]. In the years 2005-2008, Murray Hodgson was involved in several contributions concerning the development of the diffusion model for room acoustics [21, 26-28], that are reminded in this section.

3.1. Adaptation to mixed reflections

In the validation cases proposed in reference [21], some comparisons were provided by using a ray-tracing code with a value of the scattering coefficient *d* of 1 (purely diffuse reflections). It was obvious, considering Hodgson's early works (see last section), that the model could only be applied practically if it could handle situations with mixed reflections (*d* between 0 and 1).

The observation of the effect of the diffusion coefficient value on the simulation results brought a first answer to this problem [26]. In the case of a room with homogeneous dimensions, it was found that the diffusion coefficient value has no effect on the predicted levels; let us remind, from Hodgson's former results in Figure 2, that similarly, the reflection law (through the scattering coefficient *d*) has no effect on the predicted levels. Let us now define a correction factor K ($K \geq 1$), so that the value of the diffusion coefficient is set to $K \times D$.

As initially observed by Hodgson (Figure 2 [8]), the sound decay in a flat room, predicted by using the ray-tracing technique, is greatly affected by the amount of specular reflections (i.e., the value of the coefficient *d*), as shown in Figure 3. It was then observed, as demonstrated in Figure 3b, that it is always possible to find a correction factor *K* so that a good match can be obtained between the diffusion model predictions and the levels predicted by the ray-tracing technique for different value of the scattering coefficient *d*. It was then concluded that there is an analogous behavior between the effect of the scattering coefficient *d* on the ray-tracing results, and the effect on the diffusion coefficient value $K \times D$ on the diffusion result.

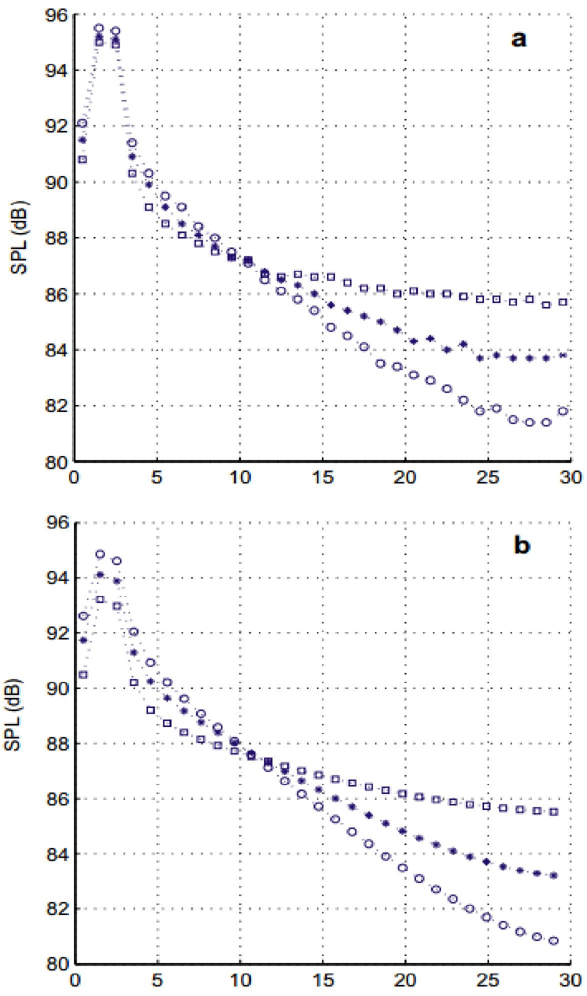

Figure 3 (from [26]): SPL decay in a room of dimensions 30 x 8 x 3.85 m^3 (source at x=2); (a) Ray-tracing model: (◦) d = 1 (diffuse reflections); (∗) d = 0.5; (□) d = 0 (specular reflections); (b) Diffusion model: (◦) K = 1 (theoretical model); (∗) K = 1.8; (□) K = 5.

As it will be explained in section 3.3, the coefficient *D* sets the relation between the energy density and the acoustic energy flow through the room (*i.e.*, the intensity). For an elongated room or a flat room, a lower diffusion coefficient means that the diffuse reflections involve a higher resistance to energy flow than specular reflection, likely due to back-scattering.

Some further research was carried out in order to find a general empirical law for the correction factor *K*, which would allow the diffusion model to be applied for a wide range of mixed reflection laws and room aspect ratios [29]. A more satisfying solution was finally derived some years later by working out a theoretical expression of the diffusion coefficient, starting from the transport theory [30]. A new expression for the diffusion coefficient *D* was obtained:

$$D = \frac{\lambda c}{3}\frac{1}{\alpha+(1-\alpha)d} \qquad (1)$$

Where α is the absorption coefficient of the room's walls. The dependence to the scattering coefficient *d* appears in the expression, and in the case of purely diffuse reflections (d=1), the expression of Eq. (1) logically matches the original value, $\lambda c/3$.

More surprisingly, a dependence of the diffusion coefficient *D* to the absorption coefficient α also appears in Eq. (1). At low absorption coefficient ($\alpha \ll 1$), the value of *D* significantly increases when the amount of specular reflections increases (*ie.*,when *d* decreases), while *D* remains approximately equal to $\lambda c/3$ whatever the value of *d* at high absorption (α close to 1) [30]. The dependence of *D* to the absorption was also observed numerically in the case of elongated rooms [31].

3.2. Predicting the reverberant field in fitted rooms

As mentioned in Section 2, modeling the acoustics of fitted rooms have been a constant goal in Hodgson's research. Fitted rooms are characterized by the presence of a large number of obstacles with different shapes and orientations, and a statistical approach can accurately describe the effect of the fittings, as initially proposed by Kuttruff [12]. The statistical parameter for describing the fittings is the mean free path λ_f of a random spatial distribution of scatterers in the room volume (the fitting density is then defined as $1/\lambda_f$ [6, 32]).

The idea of describing the fittings effect by a diffusion process had been proposed by Kurze in 1985 [33], associated to an image source model for the ceiling and floor. In 2007, a unified model [26] was proposed in order to combine the diffusion by the fittings and by the walls of the room, considering the classical mean free path λ_r of an empty room. The propagation of sound in a fitted room was supposed analogous to the propagation of sound particles through a medium of scatterers accounting for both walls and fittings. In such a medium, the mean free path λ (in meter) of the sound particles is:

$$\lambda = \frac{\lambda_r \lambda_f}{\lambda_r + \lambda_f} \qquad (2)$$

So that a diffusion process describing the propagation of sound particles in the fitted room can be defined and solved numerically by adding appropriate boundary conditions [26].

The example of Figure 4 [26] illustrates the efficiency of such a model, by considering the case of a parallelepiped room with specular reflections and half-fitted following two configurations [32] (the absorption coefficient of the fittings is 0.3). In both cases, the diffusion process matches both ray-tracing predictions and measurement data.

3.3. Predicting energy flows

A diffusion process involves a linear relationship between the gradient of the acoustic energy density ∇w, and the energy flow $\boldsymbol{J}$ (a vector interpreted in acoustics as the acoustic intensity with dimension W/m^2):

$$\boldsymbol{J} = -D\,\nabla w \tag{3}$$

This law is generally called the Fick's law. From 2008, several studies started using the Fick's law in order to investigate energy flows in single [28] or coupled rooms [34]. Ray-tracing or particle-tracing codes can also be used to evaluate the reverberant energy flow vector, by associating each ray (or sound particle) with an elementary intensity vector; by summing the contributions of the set of rays or particles crossing a given receiving volume, the net intensity vector can be obtained [28, 31].

The energy flow vector is an interesting quantity for investigating the diffuseness of a reverberant sound field. A purely diffuse sound field is composed of many uncorrelated sound waves coming from uniformly distributed directions. By nature, the energy flow should be zero. By considering numerical simulations of the reverberant sound field, it was found that the geometry that can meet rigorously this property is a sphere with uniform absorption [31, 18]. A cubical with homogeneous absorption is known as a favorable configuration for generating a diffuse sound field [3]. Looking closely at the energy flow in a cube, it nevertheless appears that the reverberant intensity vectors describe an organized pattern with significant intensity [31]. Figure 5 displays the intensity vector pattern in the vicinity of the corner of a cubical room, oriented from the source toward the edges of the room, the norm of the reverberant intensity being larger close to the room boundaries. This pattern explains that some significant variations of the sound intensity level close to the walls of the rooms can be observed, whereas the SPL of the reverberant field appears to be rather constant throughout the room [31]. This example demonstrates that the energy flow pattern is an appropriate tool for investigating the diffuseness of a sound field.

The Fick's law is a quite unusual behavior in acoustics (the intensity is proportional to ∇w); indeed for propagating waves, the intensity is proportional to the acoustics energy density w.

The simulation results of Figure 5 tend to indicate that the Fick's law is relevant for a reverberant field in room acoustics, because the particle-tracing results reveal the same intensity pattern as the Fick's law. The Fick's law has been further confirmed in the case of elongated rooms, in particular by using an experimental approach based on a scale model and pressure-velocity probes (for measuring the intensity vector) [35]. The use of the energy flow vector calculated from the Fick's law has also been shown to be very useful for understanding multiple decay phenomena in monumental spaces such as mosques [36].

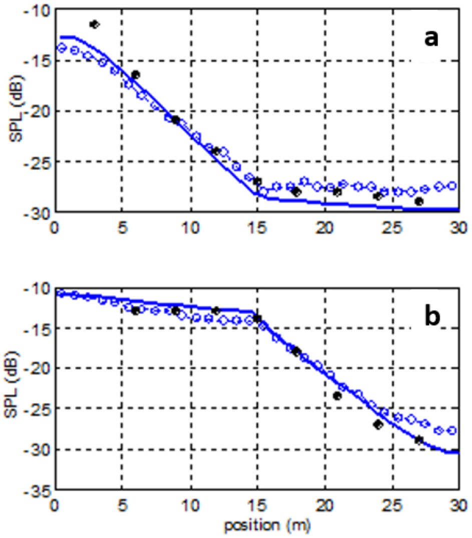

Figure 4 (from [26]**):** SPL decay in a room of dimensions 30 x 8 x 3.85 m^3 (source at x=1.5); (a) room fitted (λ_f = 3.9 m) for x<15 m, empty for x>15 m; (b) room empty for x<15 m, fitted (λ_f = 3.9 m) for x>15 m. Solid line: diffusion model; (o) ray-tracing prediction; (●) measurement data [32].

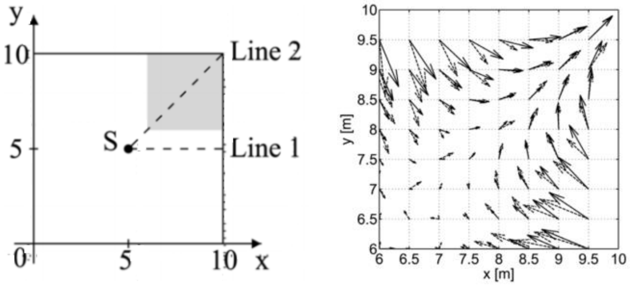

Figure 5 (adapted from [31]): Left: top view of the cubical room (10 x 10 x 10 m^3, source in the room center, purely diffuse reflections); the grey zone indicates the domain in which the energy flow vectors are plotted. Right: energy flow vectors obtained by particle tracing simulations (solid arrows) and the Fick's law (dashed arrows).

4 Concluding remarks

Some remarkable contributions of Murray Hodgson's research on reverberation modeling, and on the effect of scattering objects and wall reflection law have been first presented in this paper. The research works carried out on the development of a diffusion model for room acoustics can be seen as a continuation of Hodgson's work concerning numerous issues that he raised, generally, on the modeling of non-diffuse sound fields. The diffusion model for room acoustics is now applicable to a wide range of practical situations.

However, some aspects still need improvements and developments. In particular, the diffusion coefficient, which is the main parameter of the model, is now known to be varying along the room [31, 35], and this variation would need to be taken into account to accurately model complex situations like flat or elongated rooms with large aspect ratios. In some cases of networks of coupled rooms (with different aspect ratios or coupled by large apertures), the diffusion model gives some interesting results for physical interpretations, but the quantitative results still need to be improved, possibly because the change of the diffusion coefficient between coupled volumes requires further improvement to accurately model the energy transfers. The question to be answered will be if diffusion, which is an approximation of a more general transport process, has reached its limits, or if some further modeling of the diffusion coefficient is still possible in those cases.

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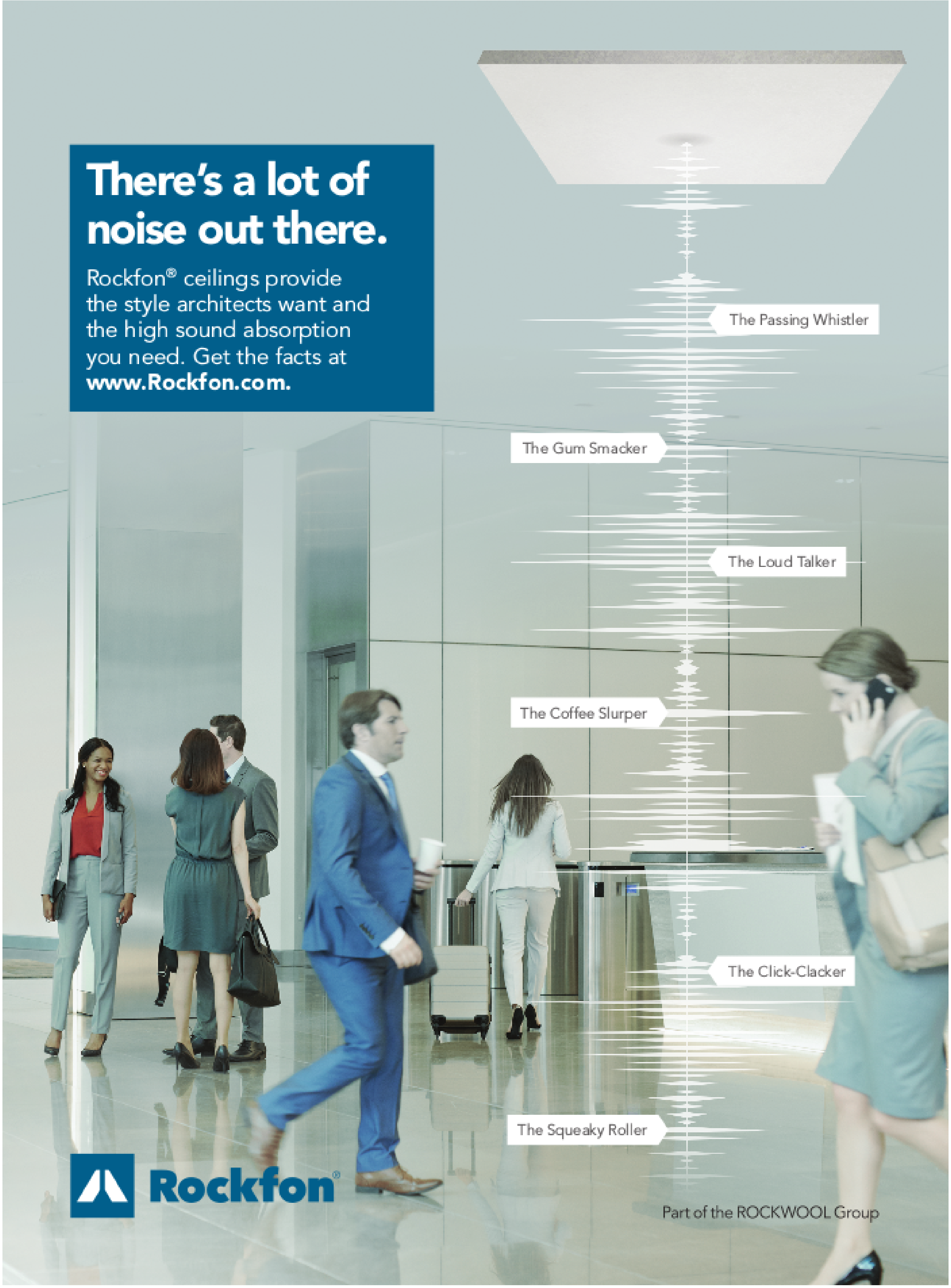


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DO WE STILL NEED DIFFUSE FIELD THEORY?

Francesco Martellotta[*]
DICAR – Politecnico di Bari, Bari, Italy

Résumé

Plus de vingt ans après l'article de Murray Hodgson intitulé "When is diffuse field theory applicable?", nous avons rassemblé de plus en plus de preuves selon lesquelles la théorie des champs diffus est essentiellement une chimère. Si nous considérons les deux implications les plus importantes du modèle de champ diffus, à savoir la distribution uniforme du niveau de pression acoustique et l'invariance du temps de réverbération, il est assez facile de dire que de telles conditions ne sont pratiquement jamais retrouvées, sur la base de mesures réelles dans plusieurs espaces différents. La diffusion sonore idéale nécessite des conditions ergodiques et de mixage, qui ne se produisent pas nécessairement, notamment lorsque l'absorption acoustique est répartie de manière inégale ou lorsque les pièces ne sont pas proportionnées. Ainsi, apparemment, la théorie des champs diffus pourrait être écartée au profit d'approches plus précises capables de prendre en compte la nature spécifique de chaque espace. De nos jours, nous disposons de plusieurs instruments allant des nombreuses variations de l'algorithme de lancer de rayons à la solution numérique de l'équation d'onde. Cependant, ces méthodes reposent sur la mesure ou l'estimation d'autres coefficients qui, s'ils ne sont pas correctement calculés, peuvent introduire des inexactitudes encore plus grandes. Une analyse critique est présentée ici, principalement basée sur l'expérience de recherche de l'auteur, montrant que la théorie des champs diffus représente toujours un moyen important de comprendre la propagation du son dans des espaces clos.

Mots clefs:champ sonore diffus, modèles de prédiction, Murray Hodgson

Abstract

More than twenty years after Murray Hodgson's "When is diffuse field theory applicable?" paper we have gathered more and more evidence that diffuse field theory is mostly a chimera. If we consider the two most important implications of the diffuse field model, i.e. uniform distribution of sound pressure level and reverberation time invariance, it is quite easy to say that such conditions are hardly ever found, based on actual measurements in a number of different spaces. Ideal sound diffusion requires ergodic and mixing conditions, which do not necessarily occur, particularly when sound absorption is unevenly distributed or rooms are not proportionate. Thus, apparently, diffuse field theory might be dismissed in favour of more accurate approaches capable of taking into account the specific nature of each space. Nowadays we have several instruments spanning from the many variations of the ray-tracing algorithm to the numerical solution of the wave equation. However, such methods rely on the measurement or estimation of other coefficients that, if not properly made, may introduce even greater inaccuracies. A critical analysis is presented here, mostly based on the author's research experience, showing that diffuse field theory still represents an important way to understand sound propagation in enclosed spaces.

Keywords:diffuse sound field, prediction models, Murray Hodgson

1 Introduction

As a young researcher in acoustics, needing advice from those who had already mastered the discipline, it was an obvious choice to rely on my advisors and tutors, who were there in person, but, in addition, a handful of "sacred texts" were constantly on the desk, ready to be consulted for a prompt reply (it was quite uncommon to "google" everything at the time). Among that pile of books, there were also some papers, and Murray Hodgson's "When is diffuse field theory applicable?" [1] was one of the most crumpled (and covered in notes) due to frequent use. In fact, in its concise and schematic clarity, the paper always provided guidance as to which classical formula for diffuse field had to be used or which were the conditions that allowed the safe use of either one formula or another in order to predict reverberation time or sound pressure level. The paper relied on the in depth study Hodgson had conducted on this topic, also involving the role of scattering elements in rooms [2,3], and the reliability of the Eyring and Sabine equations when non-low absorption conditions were met [4], as well as discussing them in the perspective of "engineering accuracy" which he assumed to be ±2 dB for sound pressure level, and ±10% for reverberation time. In times in which the only alternative to classical formulas were the costly and not yet fast or friendly ray tracing tools, such guidance was of the greatest importance in order to understand when diffuse field theory could be applied.

When discussing whether real rooms might be considered to fulfill wide ranging requirements, Hodgson stated that "Generally, sound-decay curves are quite linear, and diffuse-field reverberation-time prediction is quite accurate in most real rooms. Consequently, average surface

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[*] francesco.martellotta@poliba.it

absorption coefficients derived from measured room reverberation times using diffuse-field theory have considerable applicability. However, diffuse-field steady-state sound pressure level prediction is seldom accurate in real rooms and can, in fact, be highly inaccurate."[1] The fact that sound pressure level (and other more sensitive energy-based parameters) were not responding to the diffuse field theory predictions had previously been discussed (and brilliantly resolved) by Barron and Lee [5] with reference to auditoria. They assumed that total sound was made up of direct sound and a linearly decaying reflected component (depending on source-receiver distance). Apparently, only the simplest rooms, with very little sound absorption, behaved as expected.

According to the theory, propagation of sound inside an enclosure can be described as a twofold process. First a deterministic process is followed, since the single or multiple contributions (within a limited order) stemming from reflections on room boundaries can be easily spotted. Secondly, due to the increasing number of contributions, the process becomes purely stochastic. In particular, these latter conditions are satisfied when the room is ergodic and mixing [6]. The first term refers to the sound trajectories, where the time spent close to a point is the same for all points in the enclosure. The second term implies that two trajectories initially close to each other shall have a vanishing correlation as time goes to infinity (in other words there should be no memory of the initial state after a certain time). When both conditions are satisfied the result is an ideally diffuse sound field, meaning that the sound energy is uniformly distributed in the space. It should be emphasized that a mixing room is a necessary, but not sufficient, condition to obtain diffusion. In fact, non-uniform surface absorption, or disproportionate rooms, may significantly compromise the diffuseness of a sound field.

Therefore, it seems that the sound field in an enclosed room is, more often than desired, far from being ideally diffuse. Nonetheless, formulas based on diffuse field theory have been used for a long time. At the end of his paper [1], Hodgson concluded that "practitioners using diffuse-field theory should be aware that the assumption of a diffuse sound field may seriously limit the accuracy of prediction, particularly of steady-state sound pressure level." Then he recommended: "Models, such as the method of images and ray tracing, which are accurate in the case of non-diffuse sound fields, are available."

Nowadays we have even more powerful instruments to model the sound field in a room. They span from the many variations of geometrical acoustic (GA) methods [7], including ray-tracing, cone-tracing, beam-tracing, image source methods, radiosity, to diffusion equations [8,9], up to the numerical solutions of the wave equation (based on finite elements, boundary elements, finite difference time domain, etc.) [10]. All these methods rely on the proper description of the surface properties, which is not just limited to diffuse field absorption coefficients and scattering coefficients, but may now include angle-dependent behavior and complex impedance. However, even limiting the choice to absorption coefficients, which are certainly (and dangerously) the easiest values to find, there are several issues which undermine the quality and the reliability of the final result. The first aspect is that Sabine's absorption coefficients, which suffer from large measurement uncertainties depending on the test room [11], differ from diffuse field absorption coefficients to be used in geometrical acoustic tools. Solutions to overcome this problem have been proposed and will be discussed in detail later, but they are mostly circumscribed to research environments. Similarly, normal incidence absorption coefficients measured in a standing wave tube cannot be used "as is" in geometrical acoustic tools as this would normally underestimate the absorption [12]. Thus, a practitioner aiming to use one of the many widely available commercial tools based on geometrical acoustics, should be equally aware of the "traps" along the way.

Among the emerging methods (diffusion equation, finite-difference-time-domain, etc.) the treatment of the boundary surfaces is not a straightforward issue. When using diffusion methods, proper adaptation of absorption coefficients is needed [13]. For wave-based methods things get even more complex because of several factors, including the difficulty to model frequency dependent absorption, the surface discretization (staircasing), the need to know angle-dependent impedances rather than just diffuse field absorption coefficients, just to mention the most critical. Nevertheless, convenient solutions have been provided to address most of these issues [14], so the spread of such methods is to be expected. However, for the purpose of comparison with diffuse field theory, as wave-based methods are typically effective in a frequency range where the diffuse-field theory cannot be applied at all, they will not be considered in the following presentation.

In the subsequent sections, the paper discusses in more detail the problems related to the application of the diffuse field theory in real rooms, both in terms of energy distribution and reverberation time, mostly taking advantage of the author's own experience. Then, the current alternatives to the theory are also outlined, discussing some accuracy issues pertaining to input parameters and calculation algorithms. Finally, an attempt is made to respond to the initial question.

2 Diffuse field theory and real rooms

2.1 Sound energy distribution

As anticipated, one of the most evident deviations from diffuse field theory predictions is the non-uniform distribution of acoustic energy in enclosed spaces. When the relative sound pressure level is considered (i.e. the sound strength *G*) the theory states that [5]:

$$G(r) = L(r) - L_{10} = 10\,log(100/r^2 + 31200\,T/V) \qquad (1)$$

Where T is the reverberation time, V is the room volume, and r is the source-receiver distance. So, according to the formula, when the distance from the source is greater than the critical distance, G is reduced to 44.9+10log(T/V). Taking advantage of a large set of measurements carried out by the author in churches [15] it was possible to show that, when considering average values, the agreement between theory and experimental values was good (Figure 1).

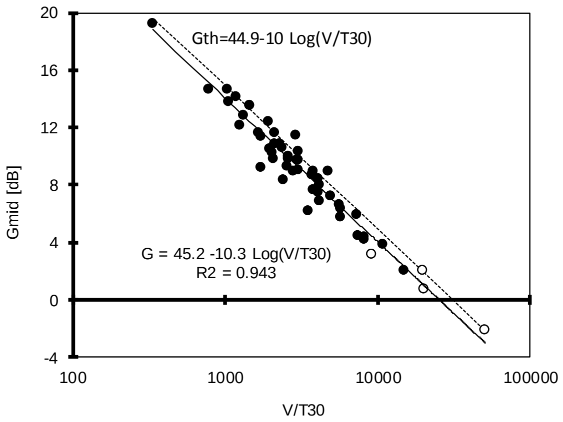

Figure 1: Plot of the of sound strength (averaged at 500 and 1000 kHz) as a function of the V/T30 ratio.

However, this apparently reassuring observation had to be revised after checking the actual dependence as a function of distance. In this case the results showed a much-varied condition (Figure 2). In all the cases, and particularly for the largest spaces, such as the church of the Holy name of Jesus in Rome [16] (Fig. 2a) and St. Peter's Basilica in Rome (Fig. 2b), the level kept on decreasing well beyond the critical distance. In the first case, the overall room volume was approximately 40000 m^3, and in the second it was about 500000 m^3. Both churches had quite long naves (but St. Peters' was twice as long as the first one) and large transepts with central domes. Thus, the observed behavior was likely to depend on a subtraction of acoustic energy from such subspaces, which consequently weakened the early reflections, particularly at the farthest receivers. The analysis of the energy decay plots clearly confirmed such behavior.

According to measurements carried out by the author in theatres [18], smaller and more compact than churches, the variations were less dramatic than in the previous cases, but they were present nonetheless. In such cases some of the farthest receivers were located in boxes or close to curved walls around the stalls, clearly contributing to provide strong early reflection.

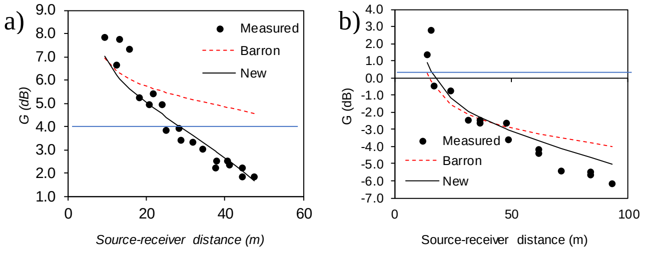

Figure 2: Plot of the distribution of sound strength (averaged at 500 and 1000 kHz) as a function of distance in: a) Church of "Gesù" in Rome, b) St. Peter's basilica in Rome. The blue line represents the diffuse field value neglecting the direct sound contribution

Therefore, the reduced rate of variation was not a matter of better compliance to diffuse field theory.

In all the cases a comparison with semi-empirical models like Barron and Lee [5] and its variation specifically adapted by the author to churches [19], showed that the first model fitted data measured in theatres very well, while the accuracy tended to decrease in churches (particularly at the furthest points). The second model managed to better match the observed values by reshaping the energy decay curve as the superposition of two exponentially decaying processes (one affecting the early reflections and one representing the ideal diffuse field). In addition, it proved also to be suitable for other spaces, such as churches acoustically treated as auditoria, if the input parameters were properly chosen [20]. Whatever the model used to "revise" the theory, the limitations of the "diffuse field" model were mostly located in the early part of the decay, suggesting that the late part of the decay behaved as expected, at least when rooms were proportionate and mixing.

The empirical observation that any decay process could be schematized as the combination of multiple exponential decays suggested that, as already demonstrated by Anderson and Bratos-Anderson [21] for St. Paul's Cathedral in London, the acoustics of complex spaces might be described as the sound propagation in a system of coupled volumes. According to this approach the diffuse field theory still retains its validity, but it is applied to a system of subspaces mutually connected. Therefore, the variation in the early energy part results from the acoustic energy flow from one volume to the others, depending on coupling apertures and sub-volumes. As explained in detail in Ref. 17, the resulting energy balance equation is:

$$V_i(dE_i/dt) = -cA_iE_i/4 + \sum_j cS_{ij}(E_j - E_i)/4 \qquad (2)$$

where c is the sound speed, E_i denotes the average sound energy density in the i-th subspace, V_i is the volume of the i-th subspace and A_i is the equivalent absorption area of the i-th subspace calculated as $S_i\overline{\alpha_i} + 4mV_i$, where S_i and $\overline{\alpha_i}$ are respectively the total surface area and the geometrically averaged absorption coefficient of the i-th subspace, and $4mV_i$ is the propagation loss due to air. The coupling area between subspace i and adjacent subspace j is denoted $S_{i,j}$.

Application of this model, as refined by Summers *et al.* [22], was successfully tested by the author in Roman basilicas [15,17], while Chu and Mak [23] also proposed an improvement based on the use of a delayed coupled volume model which was tested in two Chinese churches. The application to St. Peters' Basilica (Figure 3), as well as to other Roman basilicas, proved capable of accounting not only for sound level variations but also for other energy-based parameters like center time, as well as for early decay time. Thus, after all, a proper application of diffuse field theory managed to explain the acoustic behavior of very complex spaces.

Uneven level distribution is also a typical problem in many spaces in which the reverberation time shows no significant spatial variation. However, there are a number of cases in which this parameter also needs to be carefully taken into account.

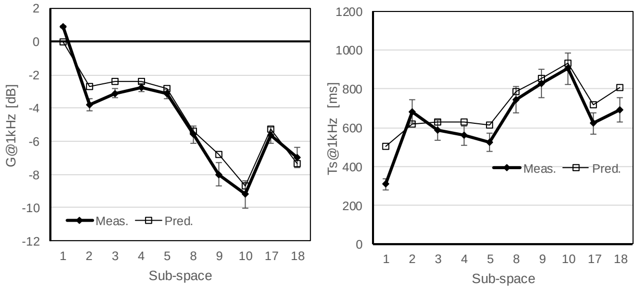

Figure 3: Plot of the distribution of sound strength and center time (at 1 kHz octave band) in St. Peter's Basilica in Rome, measured and predicted using a statistical acoustic model of coupled volumes.

2.2 Reverberation time related issues

When dealing with reverberation time, it is common experience, as Hodgson had anticipated [1], that "generally, sound-decay curves are quite linear, and diffuse-field reverberation-time prediction is quite accurate in most real rooms". In fact, most of the effects that have been discussed above affect the early part of the decay and, consequently, have a lesser influence on the late decay. So, as reverberation time is always calculated by excluding the first 5 dB of the decay, the adverse effects are certainly limited [24]. However, it is not unusual to find exceptions due to particularly evident influences of early reflections (e.g. in very large spaces where even T20 or T30 may show dependence on source receiver distance), or due to coupled volume phenomena. In both cases, the use of Bayesian estimation [25] may reliably contribute to identifying the different components of the decay process. The real problems arise when it is the late part of the decay to show large variations, which normally takes place when the fundamental assumptions of the theory are, in some way, not satisfied. Thus, disproportionate rooms, and non-uniform distribution of absorption are the typical causes for such behavior, but the appearance of modal effects may equally contribute to abnormal distribution of reverberation times, particularly in smaller rooms.

A singular example of such odd behavior which was investigated by the author and colleagues is the crypt of the Cathedral of Cadiz [26], where the reverberation time measured in the "rotunda" dramatically changed by simply moving the source along the axis. Without going too deeply into the details of the complex phenomena occurring in this space, the problem could be summarized by stating that the shape of the space clearly contributed to originating flutter echoes between the floor and the dome, which became more evident when the source position moved off the border. The flutter echoes involved all the receivers in the rotunda, as shown by the "staircase effect" in the decay curve in Figure 4. A detailed analysis demonstrated that they were caused by a complex 3D path, and resulted in a much longer reverberation time. The same decay process also appeared, although with a reduced magnitude, in the side chapels as a consequence of the weak coupling between them.

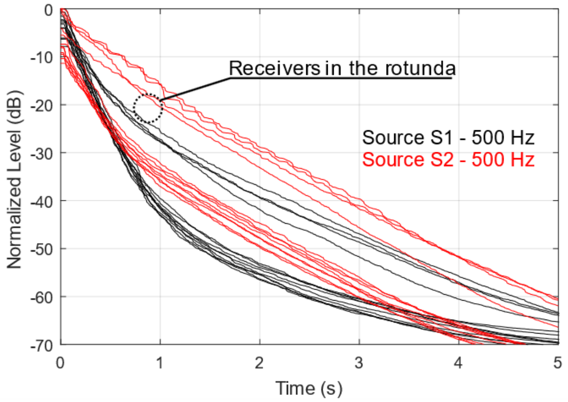

Figure 4: Normalized backward integrated decay curves in the 500 Hz octave band, as a function of source and receiver position. Normalization is obtained in each case by taking the receiver with the highest relative level as a reference.

Non-uniform distribution of reverberation times (or strong dependence on the source position) may become real problems if the room is used to test sound absorption coefficients, as this may cause different results depending on the measurement set-up, or on the particular set of sources and receivers chosen for the measurements. From this point of view ISO standard 354:2003 [27] poses no limitations to large T30 variances. In fact, the only qualification test that the room must pass refers to diffuser installation which must ensure that the measured absorption coefficient is maximized. Conversely, ASTM C423-17 [28] requires the relative values of the variation of decay rates with microphone position (to be moved in at least five positions) to be smaller than a maximum limit, when the room is empty. The relative variation is expressed as the ratio of the standard deviation between decay rate measurements (s_M) and their mean value (d_M).

To give an idea of the sensitivity to change of any of the possible variables, assuming ASTM limits as a reference, a set of measurements were carried out by the author in a 200 m^3 reverberant room complying with ISO standard 354, with six diffusers (covering an overall surface of 10.2 m^2) installed to comply with Annex A requirements. Figure 5 shows the set of measured reverberation times and the corresponding relative variations under normal use, with sources at the corners (Fig. 5a), with source and receivers moved to different positions and some diffusers removed (Fig. 5b), and with the room filled with a 10.8 m^2 sample of 2 cm polyester fiber mat (Fig. 5c).

In the first case, in which both source positions were in the corners and the receivers were kept at 1 m from walls but along the peripheral area of the room, the standard variations were within the limits in nearly all the frequency bands (with the only exception at 200 Hz, where the limit was slightly exceeded). In the second case, one of the sources was moved far from the corner and one of the receivers was moved towards the center of the room, causing significant variations, particularly in the low frequency range. The large variation of about 6 s depended on the significant differences appearing in measured reverberation times when the source was in the corner and receiver in the center (resulting in the lowest measured values), and the combination with source far from walls and receivers at the opposite position of the room (resulting in the longest measured values). Finally, it was interesting to observe (Fig. 5c) what happened when the room was filled with a large sample of a material to be tested (2 cm thick fiber mat). This test was not requested by any standard but showed the dramatic variations also appearing at medium-high frequencies as a consequence of a clear violation of the diffuse field conditions. Similar results were obtained for different materials.

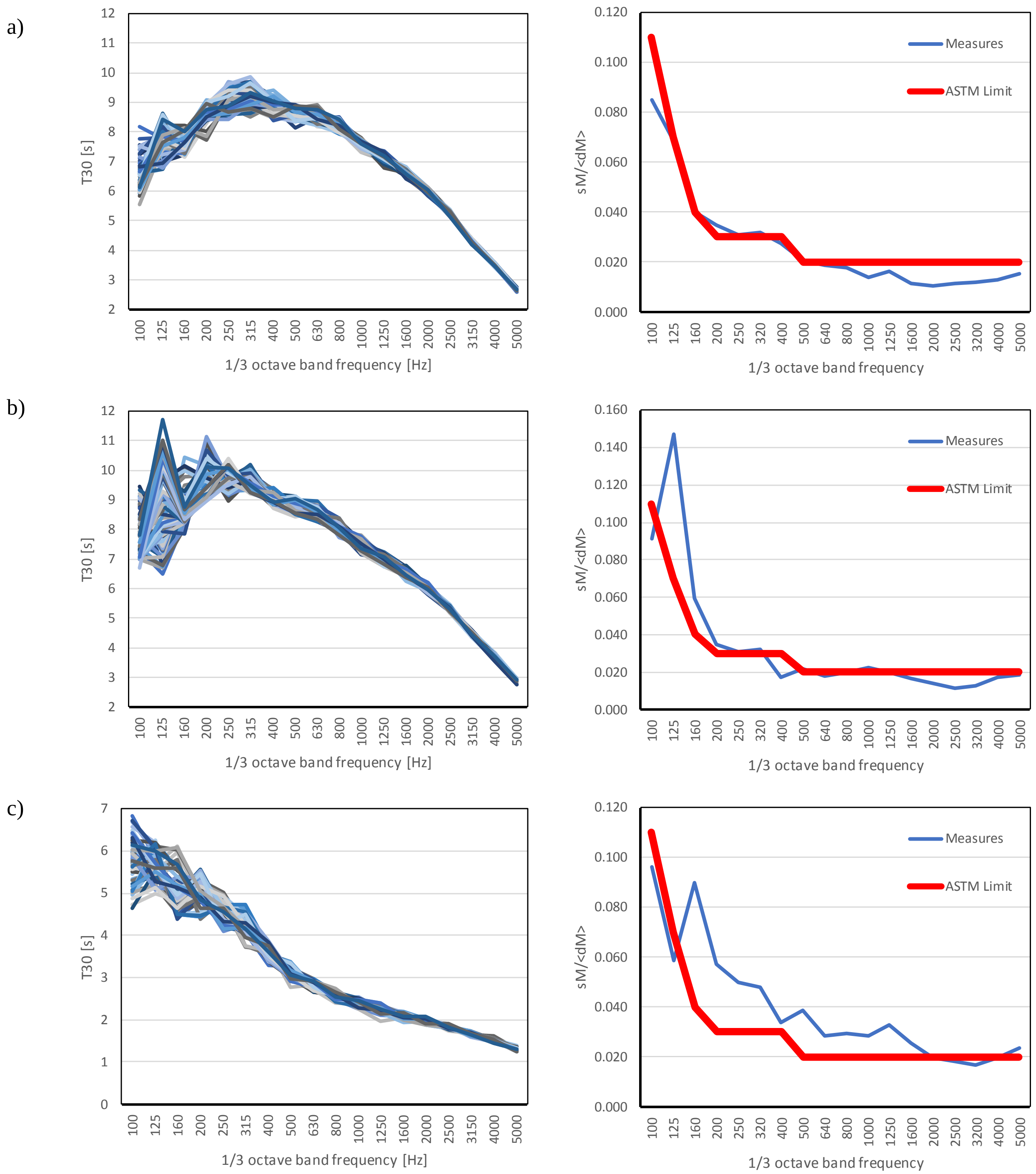

Figure 5. Plot of measured reverberation times as a function of frequency and relative variations of decay rate with microphone position compared with ASTM C423 limits. a) Reverberant chamber with sources in the corners; b) Reverberant chamber with one source in the corner and one far from the walls; c) Reverberant chamber with sources in the corner and a 10.8 m^2 absorbing sample.

The above observations showed that reverberation time varied more than expected, particularly in the lower frequencies, but this does not imply that the resulting absorption coefficients should be less accurate. In fact, a comparison of the absorption coefficients measured using both of the previously mentioned configurations (Figure 6) showed very small variations in the medium and low frequency range (where the standard requirements were not met), while some slightly greater differences appeared at the highest frequencies (with nonetheless negligible variations, never exceeding 7%). Thus, the relative variation of the reverberation time in the room was apparently not, by itself, a measure of the reliability of a measurement. The differences in the high frequency range were probably due to the removal of some of the diffusers, which had a limited effect on the s_M/d_M parameter when the room was empty, but made a difference with the sample in place. Thus, in the presence of a long reverberation time, increasing the number of measurement positions might be a safer choice than just choosing a set of combinations that minimize the change.

Nonetheless, it is a matter of fact that changes in the room configuration and, more obviously, changes within the room, may induce significant variations in measured absorption coefficients [29]. The shape of the room and the position (and type) of the diffusers may play a major role in directing sound reflections towards the sample under test. If diffusers (or dampers) are not properly located, persistent reflection paths may move above the sample with limited interactions with it (at least at high frequencies), resulting in a lower absorption. Overall, observed variations can be quite large, with standard deviations which may exceed ±0.1 in many cases, particularly if highly absorbing samples are tested. Such inaccuracies in absorption coefficient measurements also pose serious problems when using numerical tools but this will be discussed in more detail in the next section.

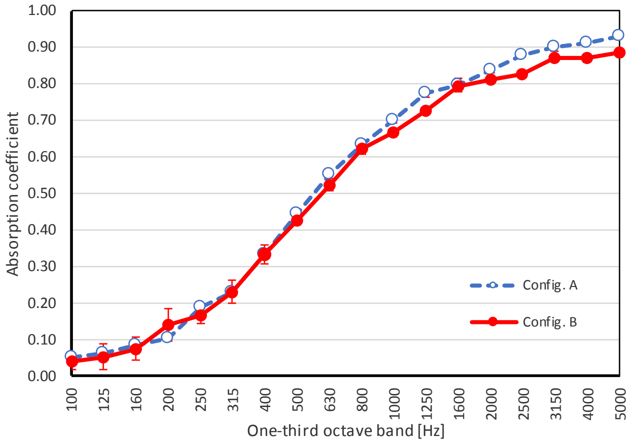

Figure 6. Plot of absorption coefficients of a 2 cm polyester mat under the two configurations analyzed in Fig. 5

3 Computational methods

It is clear from the previous discussion that the cases in which diffuse field theory is strictly valid are very limited and, consequently, the use of classical formulas to predict acoustical parameters or derive, indirectly, the absorption coefficients, may lead to more or less significant inaccuracies. Therefore, as Hodgson suggested in his 1996 paper, other methods based on geometrical acoustics should be considered as alternatives. However, since then GA tools have become so widespread that they are now available both as specialized acoustic tools but also as plugins of 3D modeling tools, and are therefore accessible to a much wider (and not sufficiently aware) audience. Meanwhile, increased computation power made several alternatives available, including the use of diffusion equation which was largely studied by Hodgson himself, as well as solutions of the wave equation based on finite elements, boundary elements, or finite-difference-time-domain (FDTD) approaches, which now allow to complement GA methods in the low frequency range. Anyway, at the moment the latter are still circumscribed to a more selected audience of researchers, which should, in principle, imply that they are used with criterion.

The description of the available computational methods goes well beyond the scope of this paper and has been addressed by several scientific papers and reviews [7,10]. However, in order to understand if such tools may be reliably used by the acoustic practitioner it is important to point out the main causes of uncertainties in acoustic modelling. Vorländer[30] in his comprehensive analysis of the problem subdivided the uncertainties in two groups: systematic and stochastic. Systematic uncertainties include those related to the level of detail of the geometric model, to the presence of curved surfaces, to the effect of diffraction, and, finally, to spherical wave impedance. Stochastic uncertainties are related to the number of rays, and to the choice of absorption and scattering coefficients. The main conclusion of the paper is that by using absorption coefficients measured according to ISO 354 [27] (i.e. those typically listed in textbooks and in the same datasets provided by commercial tools), it is impossible to obtain simulated results with an uncertainty below one just noticeable difference. In fact, by propagating uncertainty it is shown that the uncertainty of T30 follows that of the absorption coefficients pertaining to materials with the highest absorption, which may well be characterized by variations of ±0.1 (and things may get worse if seats and audience are considered).

However, even though, ideally, one should be able to get a perfectly suitable acoustic model of a space by simply using literature data, anyone ever involved in the acoustic simulation of an existing space knows that in order to get the best possible agreement between measurements and predictions a calibration step is needed. Calibration typically consists in changing absorption coefficient values until a better match is obtained between measured and predicted reverberation times (with the maximum error being assumed as 5%, or one just noticeable difference).This is one of the most “subjective” (and hence questionable) tasks which may be carried out and, consequently, many authors tried to propose more objective approaches [31], or possibly use completely automated systems based on least-mean-squares optimization [32]. However, if performed under the right conditions, that is when there is one surface with markedly different characteristics or, like in a reverberant chamber test, a sample that is added to the space, this procedure may provide very interesting results with the advantage of returning absorption coefficients which can reliably used. This procedure was first proposed by Benedetto and Spagnolo [33] and subsequently applied by Summers [34] to characterize seat blocks, and by the author and colleagues [35, 36], to define absorption of seats, audiences, and tapestries in churches.

The main advantage of this method is that, if properly carried out, it may account for the surface behavior as a whole (thus including both absorption and scattering), with reference to the chosen level of detail of the modelled surface which, in this case may be relatively low. All the effects due to irregular shape will simply be accounted by absorption and scattering coefficients. This might contribute to significantly remove, or limit, the uncertainties due to the geometric model discretization.

The level of detail of the geometric model has been a long debated issue. In fact, a high level of detail in the model certainly lengthens computation time because of the need of a proportionally higher number of rays in order to hit the smallest surfaces. In addition, evidences supporting an improved reliability of the acoustic results are still not convincing. So, it is common practice to avoid including smaller details (relative to the scale of the room) to find a balance between geometrical accuracy and computation time. Replacing complex and detailed surfaces by means of simplified blocks implies that their absorption and scattering coefficients need to properly take into account the original features of the surface. The computation will consequently be much faster, but the adaptation of the coefficients, if not carried out according to one of the objective procedures described above, needs an experienced user to avoid problems.

As an example, it can be instructive to recall the case of St. Peter’s Basilica in Rome [17], which, despite its volume of 500000 m^3 was modelled by the author by using only 1500 planes. The absorption coefficients of the surfaces were assigned, where possible, by comparison with other buildings where those surfaces where found (and their presence directly influenced the reverberation time), then by iteratively changing the coefficient for the largest surfaces (about 40% of the total) largely covered by decorations. Although made of marble, the absorption coefficients varied between 0.04 at low frequencies and 0.08 at high frequencies. Specific tests with scaled down models of similar decorations proved that, compared to the flat version of the same surface, the presence of the decorations increased the absorption from 50% to 110%. Scattering coefficients were accordingly changed as a function of the decoration dimension compared to the wavelength. The resulting accuracy in parameters prediction was very good, with point by point differences well within the just-noticeable-difference in nearly all the cases (Figure 7).

In the previous discussion absorption and scattering were considered together, but it is worth specifying that if absorption is affected by measurement uncertainties and, particularly for existing spaces, by the problem of finding “equivalent” surfaces, scattering coefficients present even bigger problems. In fact, tables with measured data are still too few [37, 38], and many surface treatments which are sold as “diffusers” do not even have scattering data although a standard procedure has been defined since several years [39]. There are some computational tools which allow calculation of the scattering coefficients based on the specific design, but they work in 2D and for mostly repetitive patterns. In addition, GA tools often treat scattering differently (some by assigning a reference value and deriving the relevant octave band values, some by directly assigning them in octave bands). So, the risk is that an inexperienced user may neglect this coefficient, or just assume default values, but this may lead to significant variations in the final results.

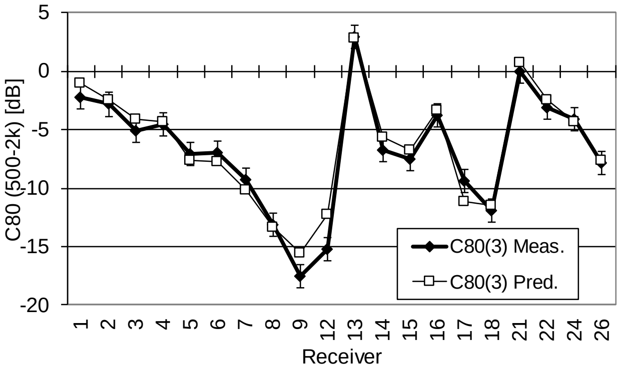

Figure 7: Plot of multi octave average of clarity (C80) as a function of receiver positions measured and predicted (using GA model) in St. Peter's basilica in Rome

4 Conclusions

At the end of this brief digression on the state of the “diffuse field theory” it is clear that, despite the many limitations and boundary conditions that need to be satisfied in order to strictly apply the theory, we cannot definitely dump it as it still proves to be robust enough to offer useful predictions without significant effort. In addition, despite the widespread availability of alternative tools based on geometrical acoustics and other computational models, without a clear understanding of the theory and of the fact that models rely on measurements which depend on the theory, obtainable results may be characterized by uncertainties which remain quite high for the time being. Actually, any good acoustician will be likely to use both theory and computational tools, to find her/his way through acoustical problems. Hence, when one considers the acoustics of a space, used for listening or evaluating the absorption coefficient of materials, the answers Murray Hodgson gave to the question “When is diffuse field theory applicable?” remain a safe guide.

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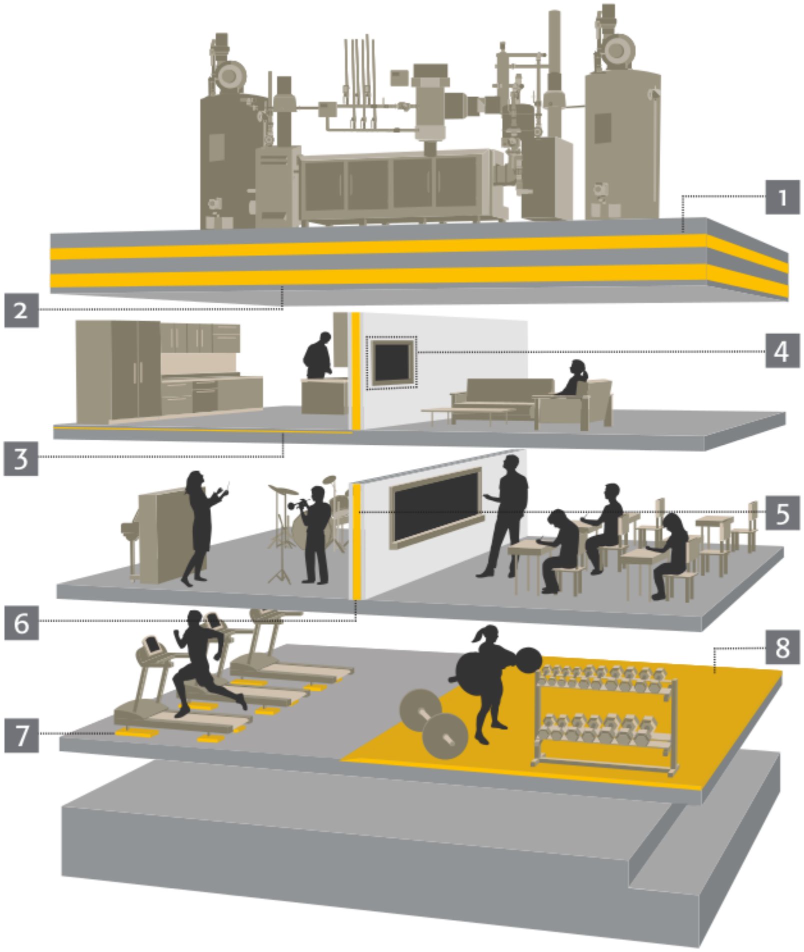
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CONCAVE SURFACES AND ACOUSTICS OF PERFORMANCE SPACES PART I – HYBRID RAY-IMAGE ANALYSIS

Eva M. Johnston-Iafelice[*] **and Ramani Ramakrishnan**[†]
Department of Architectural Science, Ryerson University, Toronto, Ontario, Canada

Résumé

Les pratiques acoustiques actuelles considèrent que les surfaces concaves ne fournissent pas de bonnes performances acoustiques. Cependant, les anciennes cathédrales, églises et lieux de spectacle aux intérieurs concaves semblent d'avoir une bonne performance acoustique. La partie I de cette recherche analyse les performances acoustiques des espaces à surfaces courbés. L'objectif principal est de rechercher l'uniformité du champ acoustique produit par les surfaces courbes en analysant la distribution des niveaux de pression acoustique dans l'espace du public. Cela à permit d'étudier l'impact du plan focal sur la distribution générale du son dans un espace clos. Pour analyser l'effet des surfaces courbes à différentes fréquences, trois lieux fermées aux surfaces courbes ont été utilisées pour mesurer les niveaux de pression acoustique dans l'espace du public : la galerie Paul Cocker à l'Université Ryerson à Toronto; l'église Anglicane St. Martin-in-the-Field à Toronto; et le Wigmore Hall au Royaume-Uni. Les évaluations ont été réalisées avec des méthodes expérimentales et des simulations informatiques utilisant des méthodes d'image hybride-rayon. Les simulations sur ordinateur ont été validées par les mesures initiales aux sites à Toronto. Après que ces analyses étaient effectués, les résultats ont montrés que dans ces conditions, les surfaces incurvées avaient un impact négatif minimal tel que perçu par le public. Les résultats de cette étude seront présentés dans cet article.

Mots clefs: Surfaces concaves; focalization; théorie de lancer de rayons; répartition des niveaux de pression sonore; simulation acoustique

Abstract

Current acoustic practices deem that concave surfaces do not provide good acoustical performance. However, old cathedrals, churches, and enclosed performance spaces with concave interiors seem to perform well. Part I of the current investigation analyzes the acoustical performance of spaces with curved surfaces. The main focus of the current investigation was to research the uniformity of the sound field produced by curved surfaces by analyzing sound pressure level distribution throughout the audience space. It studied the impact of the focal plane on the overall sound distribution within an enclosed space. To analyze the effect of curved surfaces at different frequencies, three enclosed rooms with curved surfaces were used to measure the sound pressure levels throughout an audience space: the Paul Cocker Gallery in the Ryerson Architecture Building, Toronto; St. Martin-in-the-fields Anglican Church, Toronto; and Wigmore Hall, United Kingdom. The evaluations were achieved with both experimental methods, and computer simulations using hybrid-ray-image methods. Computer simulations were validated by the initial on-site measurements in the Toronto locations. After these evaluations were performed, results showed that in these conditions, the curved surfaces had minimal negative impact as perceived by the audience. The results of the investigation will be presented in this paper.

Keywords: Concave surfaces; focussing; ray-image theory; sound pressure level distribution; acoustic simulation

1 Introduction

Conventional wisdom states that having concave surfaces as the envelope of any occupied space does not produce good sound [1]. It is well known that the focussing effect produced by concave surfaces can be problematic. Focussing can cause high sound pressure levels, coloration, and echoes [2]. However, throughout history there have been many enclosed rooms with large curved surfaces as envelopes that seem to produce good acoustics. Many churches, opera theatres, auditoriums, and concert halls alike were designed with curved features.

The main aspect investigated in the two papers is to find out if curved surfaces in performance spaces generate unsatisfactory acoustic results. In Part I, analysis was conducted applying hybrid image-ray acoustics. The results are highlighted below. Full details of the investigations can be gleaned from the research report by Johnston-Iafelice [3].

2 Background

The rationale for the current investigation was initiated by the anecdotal observation by O'Keefe during a performance in Toronto's Runnymede United Church, shown in Figure 1. He noted a strong and positive subjective response to a bass note of the 'G String (37 Hz)' even though he was sitting far away from the focal plane of the barrel vault ceiling. He

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[*] johnstoniafeliceeva@gmail.com
[†] rramakri@ryerson.ca

wondered about the reasons for his clear perception of the note played by the bass. What happens to the sound beyond the focal plane, he mused. Some of his thoughts resulted in a conference paper [4]. The current investigation was undertaken to answer the truisms accorded to curved surfaces in performance spaces and are highlighted in the following sections.

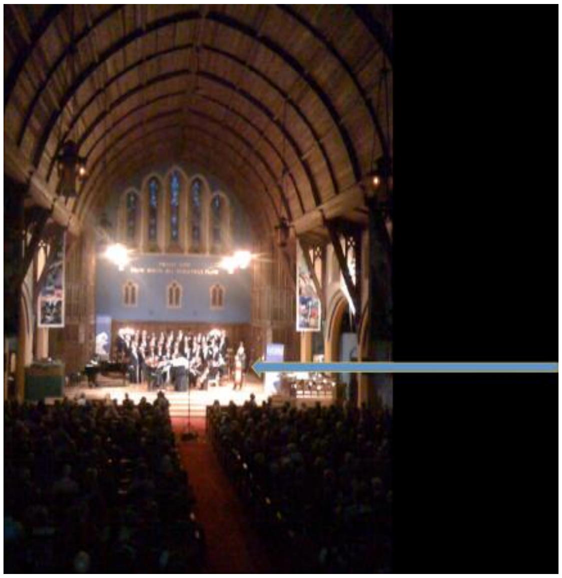


Figure 1: Runnymeade United Church with Curved Ceiling (Photo Credit: John O'Keefe).

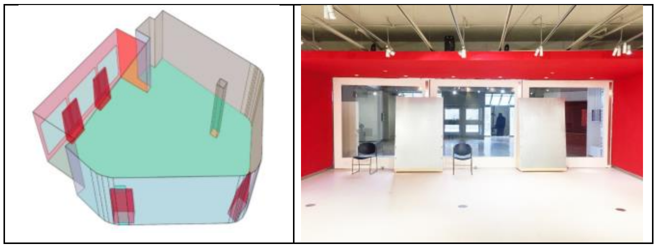


Figure 2: Paul Cocker Gallery, Ryerson University, Toronto

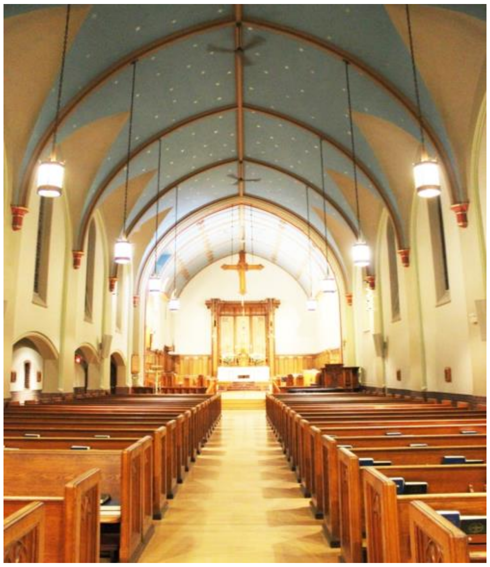


Figure 3: St. Martin in the Fields Anglican Church, Toronto.

3 Case study spaces

Three spaces were chosen for the investigation. They, as shown in Figures 2, 3, and 4, are: a) Paul Cocker Gallery (the Gallery) situated within the Architectural Science Bulding, Ryerson University, Toronto; 2) St. Martin-in-the-Fields Anglican Church (the Church), Toronto; and 3) Wigmore Hall in London England.

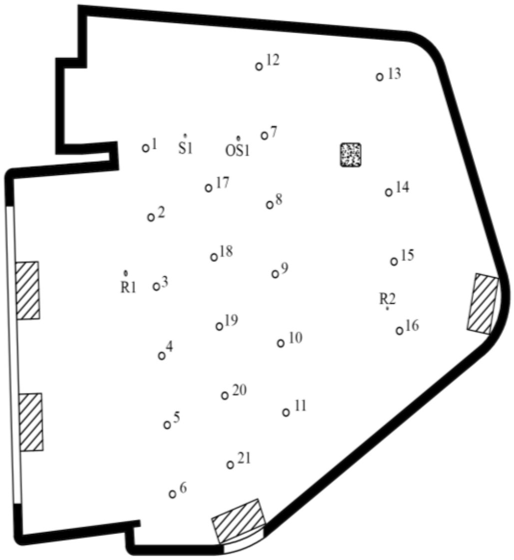
Paul Cocker Gallery was used as a test case to conduct both simulations as well as site measurements. It had no strong curved surfaces. However, three different concave surfaces were created and placed within the gallery to investigate the effects of curved surfaces. On the other hand, Wigmore Hall and the Anglican Church had strong concave surfaces as seen in Figures 3 and 4.

Figure 4: Wigmore Hall, Lonmdon, England.

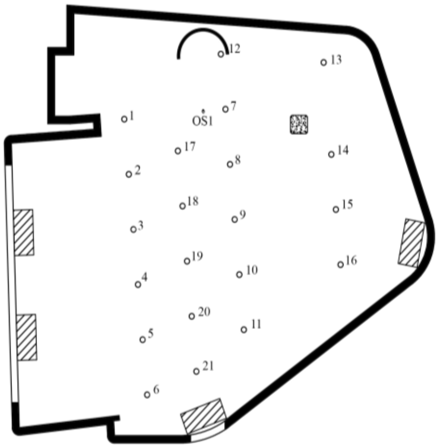
4 Measurements and analysis

Measurements were conducted in the Gallery and the Church by using a sine-sweep signal to calculate the impulse response. Some of the basic acoustic metrics such as reverberation time, clarity, centre time etc were evaluated. In addition, sound pressure level measurements were conducted at a number of locations in the Gallery by generating a pink noise signal through a dodecahedron speaker system. Measurement locations for the sound pressure level distribution, in the Gallery, with and without the curved surface are shown in Figure 5 below.

In addition, field measurements, and simulation of the three performance spaces were conducted. The site measurements of reverberation time, evaluated in the Gallery and the Church, were used to calibrate the simulations. Measurements of Barron were used to calibrate the Wigmore Hall simulations [5]. The commercially available software, ODEON, was used for the simulations, by applying a hybrid method using image-ray theory [6]. Vorlander [7] and Vercammen [8, 9] have discussed the uncertainties associated with the application of commercial software's simulating curved surfaces. However, Vercammne clearly indicates that geometric acoustics can be successfully applied in determining the sound levels beyond the focal plane of the concave surfaces. In addition, Wulfrank and Orlowski have successfully used ODEON in determining the properties of Wigmore Hall with concave surfaces [10]. The application of geometrical acoustics to determine the sound levels in the three spaces, under investigation, is, therefore, valid.



(a) Bare Room



(b) Horizontal Plane at 50 Hz

Figure 5: SPL Measurement Locations in the Gallery.

5 Results and discussion

Measurement results of the Sound Pressure Level (SPL) distribution around the Gallery are shown in Figures 6 and 7 with the source, OS1 located as shown in Figure 5. A pink noise was generated through a dodecahedron speaker system at OS1. The results are shown for four frequency bands at 63 Hz, 125 Hz, 200 Hz and 500 Hz. The SPL variation is also shown with and without the curve surface placed at location shown in Figure 5b.

The results at 63 Hz and 125 Hz do not show much difference with and without the curved surface placed in the Gallery. The SPL, for the two low frequencies, at Location 12 was not modified becasue the source wavelength was larger than the size of the curved surface. The only major change with the curved surface was seen at Location 12 for the 200 Hz and 500 Hz bands. Location 12 is within the curved surface and hence additional reflection at higher frequency of 200 Hz and 500 Hz was evident (Refer to Figure 7).

Finally, the SPL variation at Location 8 is shown in Figure 8 for the two conditions of bare room and the room with the curved surface. Once again, the curved surface is seen to have minimal impact on the SPL distribution.

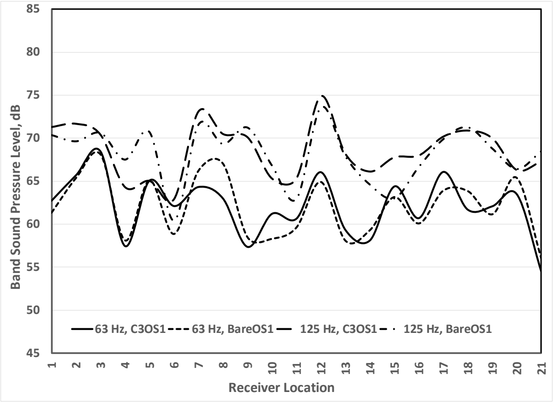


Figure 6: SPL distribution in the Gallery at 63 Hz and 125 Hz third-octave band frequencies.

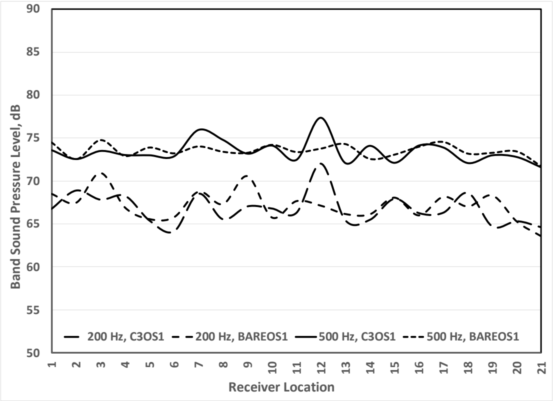


Figure 7: SPL distribution in the Gallery at 200 Hz and 500 Hz third-octave band frequencies.

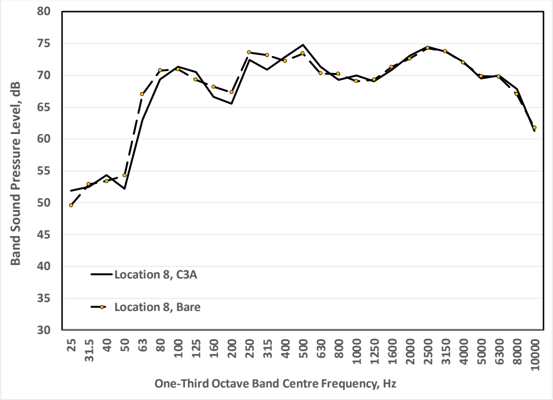


Figure 8: SPL distribution in the Gallery at Location 8.

Next, the simulations results for the three performance spaces are presented below. Simulations were first calibrated with site measurements. Simulations were then undertaken for different source locations within the three spaces. Results for the Gallery are discussed first. The results for the Gallery are presented in Table 1 below.

Table 1: SPL variation across the Gallery space, dB

Band Frequency, Hz	125	500	2 K
Source Location OS1	4.7	3.9	4.5
Source Location LA	4.8	4.4	5
Source Location LB	4.8	3.8	5
Source Location LC	4.8	3.8	5

The four source locations are highlighted in Figure 9 below. The table shows the difference between the minimum and maximum SPL in the gallery with the source placed in four different locations within the room. The maximum deviation is 5 dB and the minimum deviation is 3.9 dB.

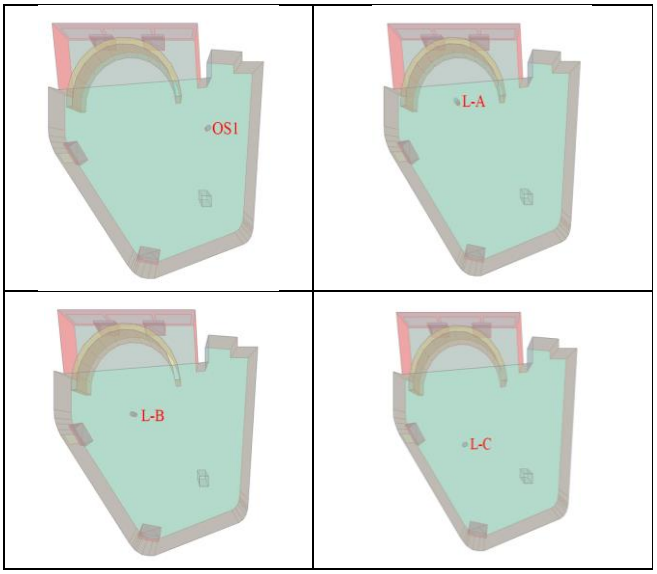


Figure 9: Source locations for the Gallery simulations.

A sample SPL distribution at 500 Hz for source location L-B is shown Figure 10 below. The lowest sound level is behind the large curve surface and if the shadow region is not included, the deviation will be smaller. Similar behaviour was observed for the different source location and other frequencies.

The results for the Church are presented in Table 2 below. The three source locations are highlighted in Figure 11 below.

The table shows the difference between the minimum and maximum SPL in the Church with the source placed in three different locations within the Church. The maximum deviation is 4.8 dB and the minimum deviation is 3.4 dB. A sample SPL distribution at 500 Hz for source location S-B is shown Figure 12 below. The lowest sound level is near the back of the Church. Similar behaviour was observed for the different source location and other frequencies.

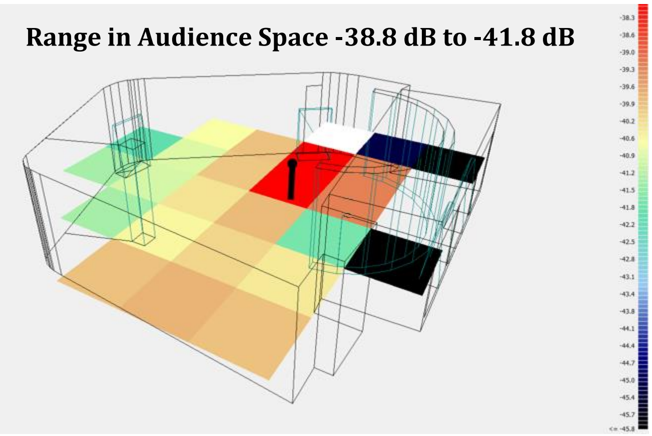


Figure 10: Simulation of SPL variation at 500 Hz in the Gallery.

Table 2: SPL variation across the Anglican Church, dB

Band Frequency, Hz	125	500	2 K
Source – A (Fig.11)	4	4	4
Source – B (Fig.11)	4.2	3.8	3.8
Source- C (Fig.11)	3.4	4.8	3.4

Figure 11: Source locations for the Church simulations.

The results of Table 2 and Figure 12 showed that the curved ceiling of the Church had minimal impact on SPL variation in the audience area except the fact the SPL decayed from front to the back. The reasons are outlined below. It is, conventionally, believed that the sound in enclosed spaces becomes diffused after a short distance away from the source of sound.

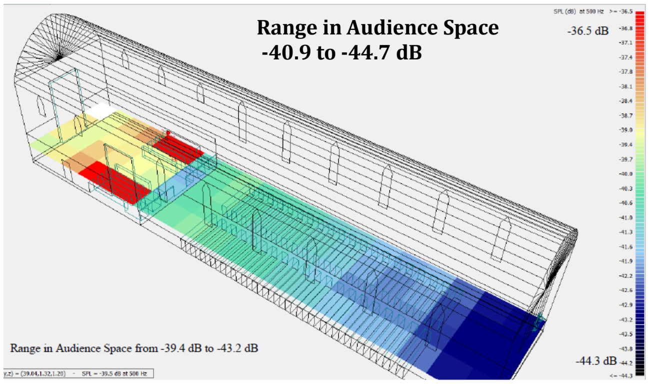


Figure 12: Simulation of SPL variation at 500 Hz in the Church.

But Gade's study on the room acoustics of Danish concert halls hinted at the notion that reflected sound pressure levels in concert spaces decreased as the receiver moved further away from the source [11]. The 'revised theory' of sound level in rooms was derived from early research of Barron [5, 12]. The revised theory states that reflected sound is not constant throughout an audience space, but decreases as a function of source-receiver distance.

Finally, the results for Wigmore Hall are presented in Table 3 below. The table shows the difference between the minimum and maximum SPL in the audience area with the source placed in five different locations within Wigmore Hall. The maximum deviation is 4.4 dB and the minimum deviation is 2.6 dB.

A sample SPL distribution at 500 Hz for source located inder the dome on the stage is shown Figure 13 below. The lowest sound level is near the back of the hall. Similar behaviour was observed for the different source location and other frequencies.

The results of Table 3 and Figure 13 showed that the curved ceiling and domed stage of Wigmore Hall had minimal impact on SPL variation in the audience area except the fact the SPL decayed from front to the back. The reasons for the SPL variation were discussed already.

Table 3: SPL variation across Wigmore Hall, dB

Band Frequency, Hz	**125**	**500**	**2 K**
Source-back of stage under dome	2.8	2.6	3.5
Source at middle of stage	3.8	3.5	3.6
Source-at front of stage	4.2	3.9	3.8
Source-5 on stage (Unoccupied)	4.0	3.3	2.7
Source-5 on stage (Occupied)	4.4	2.5	2.8

6 Conclusions

Impact of curved spaces was investigated in the two-part papers. Three interior spaces with curved surfaces were selected as test cases for the investigation. Part I of the two-part papers applied a Hybrid-Image-Ray analysis to evaluate the impact in mid-to-high-frequencies.

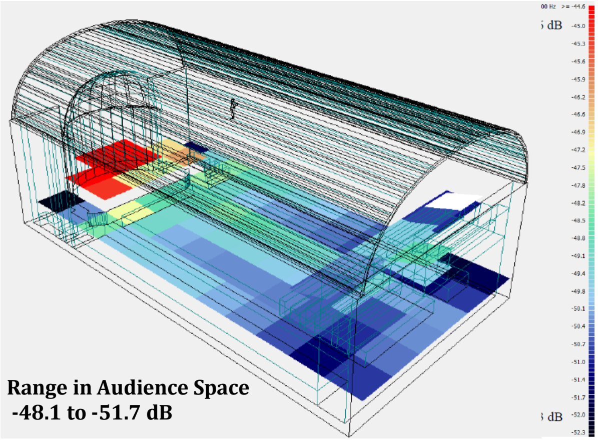


Figure 13: Simulation of SPL variation at 500 Hz in Wigmore Hall.

The results presented in Section 4 clearly indicated that concave surfaces have no negative impact on SPL distribution throughout the audience space. Beyond the focal plane, curved envelopes diffuse SPL equally throughout the enclosed spaces. The results also confirmed the 'revised theory' that SPL reduces as a function of source-receiver distance even in closed spaces.

Acknowledgements

We would like to acknowledge the contribution made by John O'Keefe, a senior acoustic consultant of Toronto as well as his permission to use the image shown in Figure 1.

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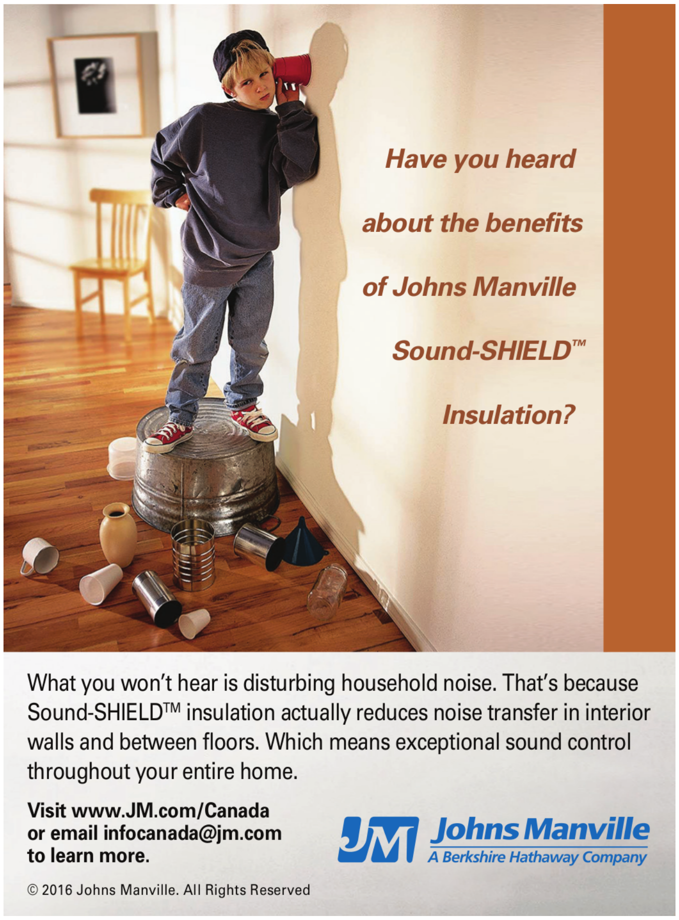

CONCAVE SURFACES AND ACOUSTICS OF PERFORMANCE SPACES
PART II – WAVE ANALYSIS

Ramani Ramakrishnan[*] **and Eva M. Johnston-Iafelice**[†]
Department of Architectural Science, Ryerson University, Toronto, Ontario, Canada

Résumé

La croyance conventionnelle nous amène à penser que le fait d'avoir des surfaces concaves comme enveloppe d’une pièce occupée ne produit pas un son de qualité. L'effet du point focal des surfaces concaves peut provoquer des niveaux de pression acoustique élevés, des colorations et des échos. Cependant, tout au long de l’histoire, de nombreuses pièces avec des grandes surfaces incurvées semblent produire de bonne acoustique. Des recherches récentes ont suggéré de procéder à une analyse des ondes pour établir l'impact des surfaces concaves. Contrairement à la partie I de cette étude, l’évaluation de la distribution des niveaux de pression acoustique dans les pièces à surfaces concaves, a été réalisée en résolvant l’équation des ondes. La raison principale en est que la théorie de rayon image n'est valide qu'à des fréquences supérieures à la fréquence de coupure de Schroeder. La théorie des ondes est utilisé e pour les fréquences inférieures à 100 Hz. La modélisation par éléments finis a été appliquée pour résoudre le problème de la distribution du niveau de pression acoustique dans les pièces présentant des surfaces concaves. Dans cette étude, trois lieux ont été étudiés : la galerie Paul Cocker à l’Université Ryerson à Toronto, l’église Anglicane St. Pauls à Toronto, et le Wigmore Hall à Londres. Les résultats pour trois fréquences de basses (25 Hz, 50 Hz et 100 Hz) ainsi que leur combinaison seront présentés dans cette étude.

Mots clefs: Surfaces concaves; focalization; théorie des ondes; répartition des niveaux de pression sonore; simulation acoustique.

Abstract

Conventional wisdom states that having concave surfaces as the envelope of any occupied space does not produce good sound. The focussing effect of concave surfaces can cause high sound pressure levels, coloration, and echoes. However, throughout history there have been many enclosed rooms with large curved surfaces as envelopes that seem to produce good acoustics. Recent research suggested that wave analysis must be undertaken to establish the impact of concave surfaces. In contrast to Part I of the current investigation, evaluation of the sound pressure level distribution, in rooms with concave surfaces, was performed by solving the governing wave equation. The main reason is that the image-ray theory is valid only at frequencies greater than the Schroeder cut-off frequency. The wave theory is used for frequencies lower than 100 Hz. Finite element modelling was applied to solve for the sound pressure level distribution within rooms with concave surfaces. Three spaces, the Paul Cocker Gallery in Ryerson University, Toronto, St. Pauls Anglican Church in Toronto and Wigmore Hall in London were investigated in this study. The results for three low frequencies (25 Hz, 50 Hz and 100 Hz) as well as their combination will be presented in this paper.

Keywords: Concave surfaces; focussing; wave theory; sound pressure level distribution; acoustic simulation.

1 Introduction

It is a textbook truism that concave surfaces within confined spaces focuses sound whereas convex surfaces diffuse sound. On the other hand, many churches, opera theatres, auditoriums, and concert halls alike were designed with curved features from an architectural perspective. Many of these performance spaces were seen to provide acceptable and satisfactory acoustic character and focusing was found to be not an issue.

The main aspect investigated in the two papers is to find out if curved surfaces in performance spaces generate unsatisfactory acoustic results. In Part I, analysis was conducted applying hybrid image-ray acoustics. In Part II, wave analysis was conducted to evaluate acoustic performances in low frequencies in auditoria with curved envelopes. The results are highlighted below. Full details of the investigations can be gleaned from the research report by Johnston-Iafelice [1].

2 Background

The rationale for the current investigation was detailed in Part I of the two-part papers. The main thrust for the study was the anecdotal observation by O’Keefe during a performance in Runnymede United Church in Toronto. He noted a strong and positive subjective response to a base note of the ‘G String (37 Hz)’ even though he was sitting away from the focal plane. Brief details of O’keefe’s subjective perception were discussed in Part I of the paper. The current investigation was undertaken to answer the

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[*] rramakri@ryerson.ca
[†] johnstoniafeliceeva@gmail.com

truisms accorded to concave surfaces in performance spaces.

3 Case Study Spaces and Wave Analysis

Three spaces were chosen for the investigation. They, as shown in Figures 1, 2, and 3, are: a) Paul Cocker Gallery situated within the Architectural Science Bulding, Ryerson University, Toronto; 2) St. Martin-in-the-Fields Anglican Church, Toronto; and 3) Wigmore Hall in London England.

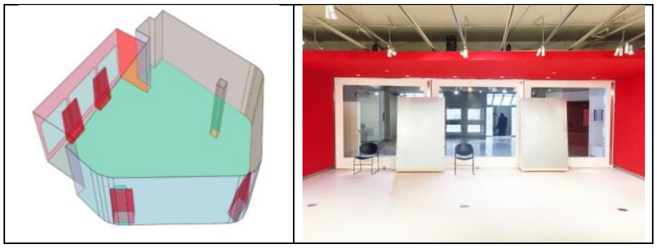


Figure 1: Paul Cocker Gallery, Ryerson University, Toronto.

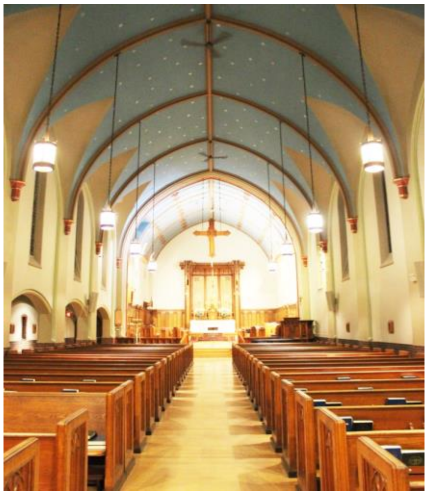


Figure 2: St. Martin in the Fields Anglican Church, Toronto.

Figure 3: Wigmore Hall, Lonmdon, England.

Paul Cocker Gallery was used as a test case to conduct both simulations as well as site measurements. It had no strong curved surfaces. However, three different concave surfaces were created and placed within the gallery to investigate the effects of curved surfaces. On the other hand, Wigmore Hall and the Anglican church had strong concave surfaces as seen in Figures 2 and 3.

The room acoustics software, ODEON, was used in Part I of the two-part papers [2]. Room acoustics software conventionally use a Hybrid-Image-Ray method to evaluate the results in band frequencies up to 8000 Hz. However, the hybrid method loses accuracy in low frequency below a cut-off frequency, called Schroeder frequency, given by Equation 1 below.

$$f_s = 2000\sqrt{\frac{T_{60}}{V}} \qquad (1)$$

Where, V is the volume of the space and T_{60} is the reverberation time. The main thrust of our investigation was the ‘G String’ event observed in Runneymede United Church. Hence, low frequency analysis was undertaken through wave theory where the exact wave equations were solved using a finite element method (FEM). The FEM solutions were evaluated applying a commercially available powerful multi-physics softaware, COMSOL [3]. FEM divides the solution region into a number of elements (i.e., meshing), and solves the governing equation with a pre-set source defined. A simple example of the meshing of Wigmore Hall with a point source within the stage area, below the cupola, is shown in Figure 4 below.

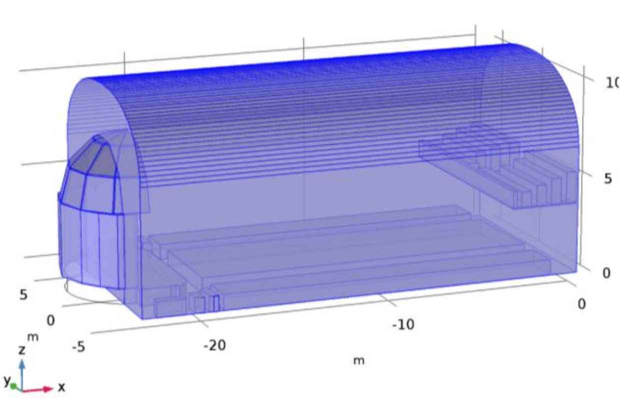


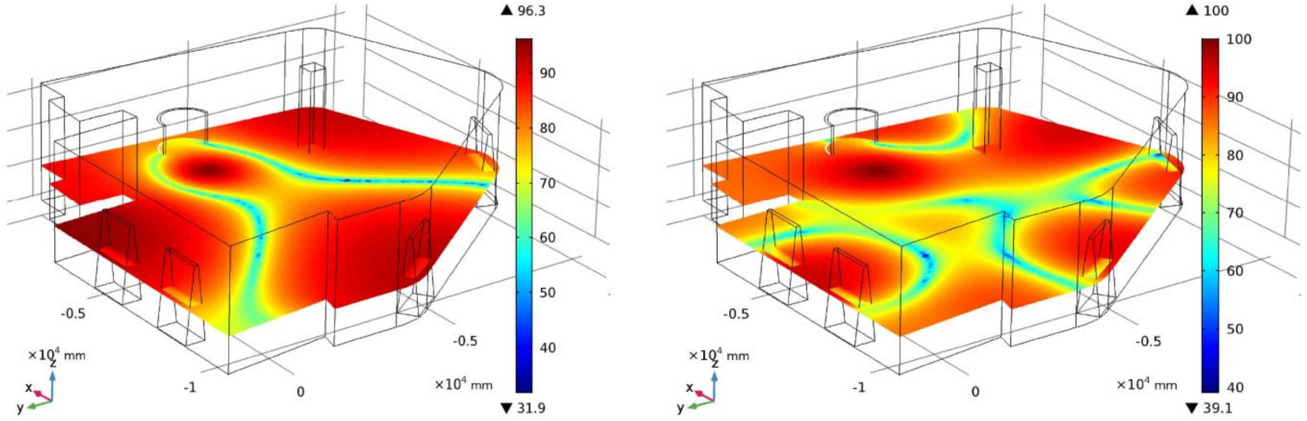
Figure 4: An Example of COMSOL FEM meshing of Wigmore Hall.

4 Results and Discussion

A point source was placed at different locations of the interior space of the three test cases; the Gallery, the Church and Wigmore Hall, and the Sound Pressure Level variation were evaluated along a horizontal plane as well as a vertical plane. The FEM results are highlighted below.

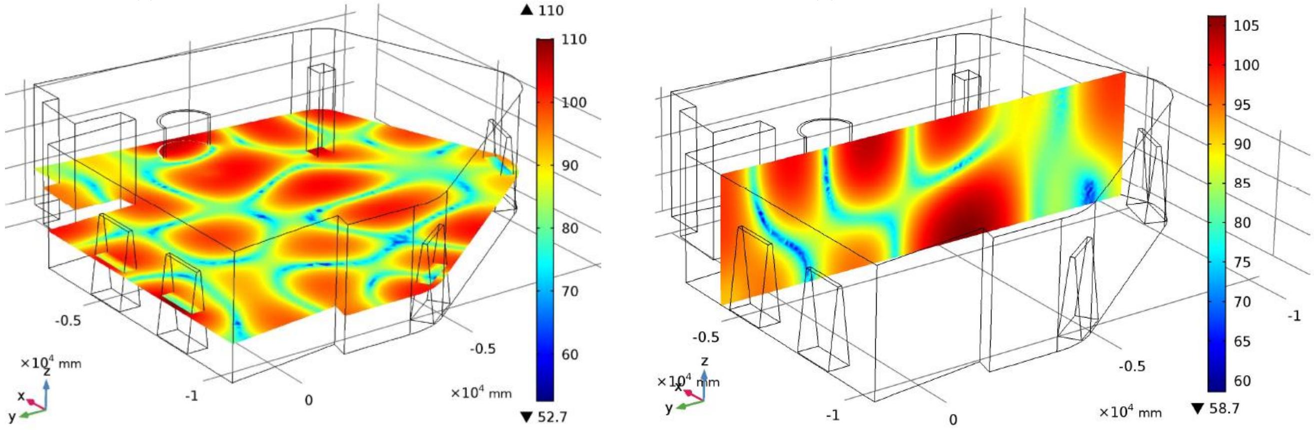
4.1 Paul Cocker Gallery

It must be noted that the Gallery does not contain any interior concave surfaces. Hence, three different curved surfaces were fabricated and placed within the gallery. The results for one of the curved spaces are highlighted in the figures below.



(a) Horizontal Plane at 25 Hz

(b) Horizontal Plane at 50 Hz



(c) Horizontal Plane at 100 Hz

(d) Vertical Plane at 100 Hz

Figure 5: SPL distribution for the Gallery, Source outside the curve.

Results for SPL variation with the source outside the concave surface are shown in Figure 5. The results for 25 Hz, 50 Hz and 100 Hz, along a horizontal plane, are shown in Figures 5a, 5b and 5c respectively. Results for 100 Hz, along a vertical plane, are shown in Figure 5d.

The main observation is that the concave surface did not focus the sound and the SPL variation is mainly controlled by the room modes. Similar results for the point source placed inside the focal plane of the concave surface are shown in Figure 6 below.

Similar observation can be gleaned from Figure 6 that the concave surface has no impact on the SPL variation.

4.2 St. Martin-in-the-Fields Anglican Church

Results for SPL variation with the source near the main altar of the Church is shown in Figure 7. The results for 25 Hz, 50 Hz and 100 Hz, along a horizontal plane, are shown in Figures 7a, 7b and 7c respectively. Results for 100 Hz, along a vertical plane, are shown in Figure 7d.

The main observation is that the concave surface did not focus the sound and the SPL variation is mainly controlled by the room modes

4.3 Wigmore Hall

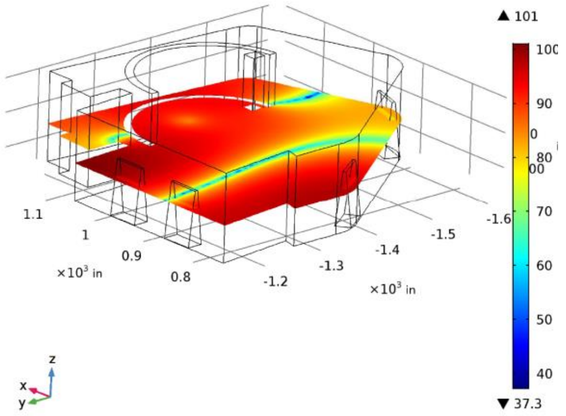
Results for SPL variation with the source on the stage below the cupola are shown in Figure 8. The results for 25 Hz, 50 Hz and 100 Hz, along a horizontal plane, are shown in Figures 8a, 8b and 8c respectively. Results for 100 Hz, along a vertical plane, are shown in Figure 8d.

The main observation is that the concave surface did not focus the sound and the SPL variation is mainly controlled by the room modes. Similar results were observed for both the Gallery and the Church.

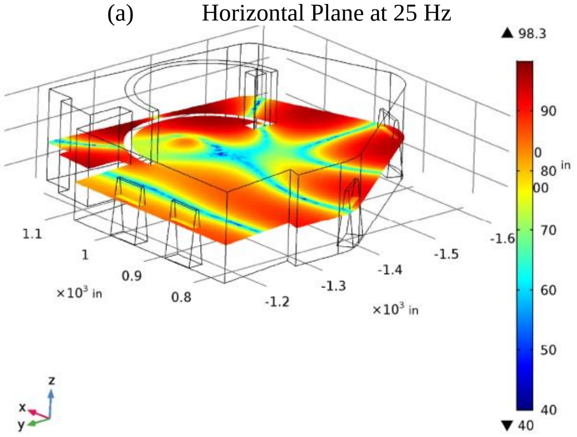
It must be also pointed that the results presented in Figures 5, 6, 7, and 8 were for single frequencies. However, in actual performances, each note is accompanied by its harmonics and sub-harmonics and single tones are never generated. Hence, the actual SPL variation will be a combination of many frequencies, being generated simultaneously.

4.4 Discussions

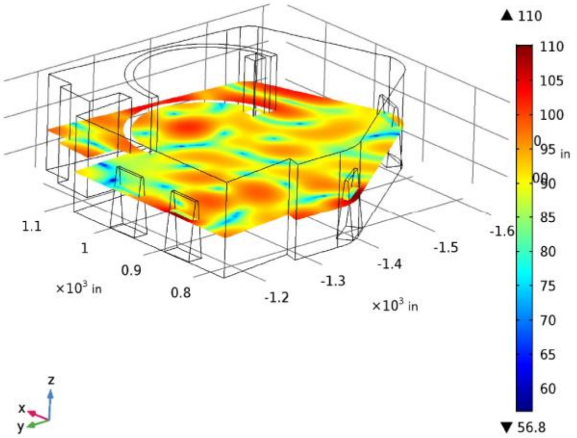
It must be pointed out that the focussing effect of the concave surfaces depend on the size of the surface and the wavelength (λ) of the generated sound as shown by Vercammen [4. 5]. Results for 25 Hz (λ = 13.6 m), 50 Hz (λ = 6.8 m), and 100 Hz (λ = 3.4 m) were presented in this paper. And hence results for the Gallery is truly valid for 100 Hz. The results for Wigmore Hall and the Church are valid for 50 Ha and 100 Hz and on the borderline for 25 Hz. However, the results were presented for all the three frequencies to show the behaviour trend of concave surfaces at low frequencies.



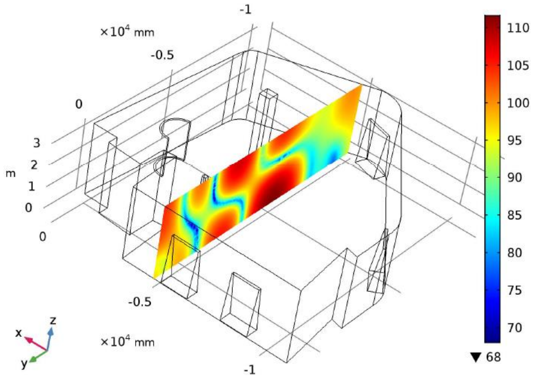
(a) Horizontal Plane at 25 Hz



(b) Horizontal Plane at 50 Hz

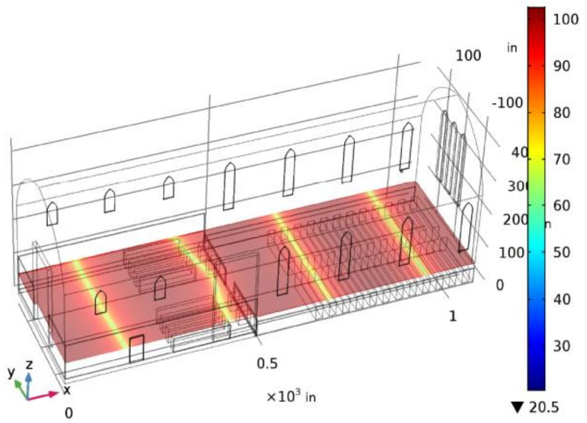


(c) Horizontal Plane at 100 Hz

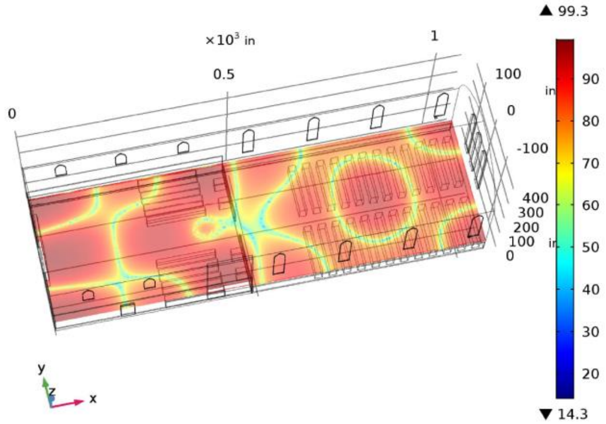


(d) Vertical Plane at 100 Hz

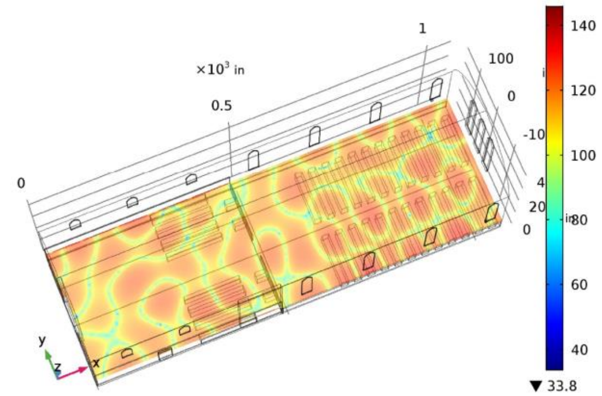
Figure 6: SPL distribution for the Gallery, Source inside the curve.



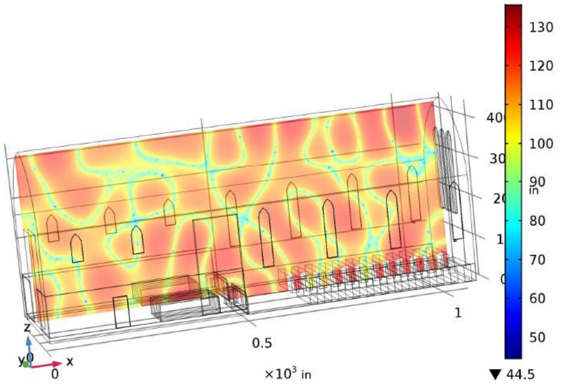
(e) Horizontal Plane at 25 Hz



(f) Horizontal Plane at 50 Hz

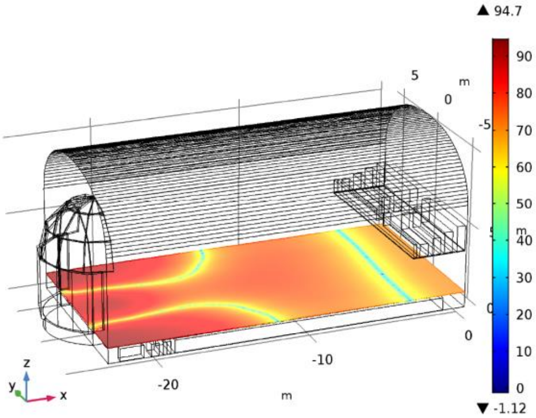


(g) Horizontal Plane at 100 Hz

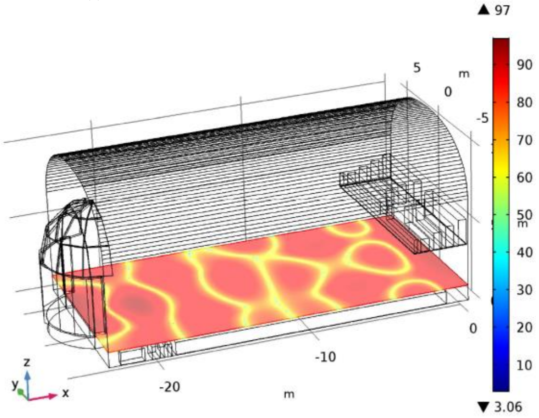


(h) Vertical Plane at 100 Hz

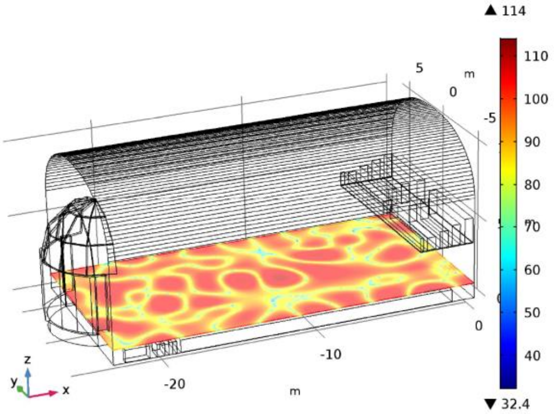
Figure 7: SPL distribution for the Anglican Church.



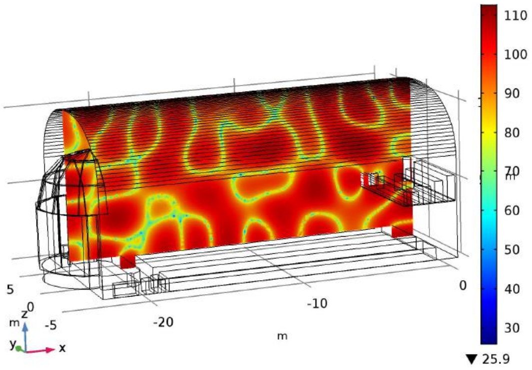
(i) Horizontal Plane at 25 Hz



(j) Horizontal Plane at 50 Hz



(k) Horizontal Plane at 100 Hz



(l) Vertical Plane at 100 Hz

Figure 8: SPL distribution for the Wigmore Hall.

5 Conclusions

Impact of curved spaces was investigated. Part II of the two-part papers applied a wave analysis to evaluate the impact in low-frequencies. The results presented in Section 4 clearly indicated that concave surfaces have no negative impact on SPL distribution throughout the audience space. In addition, SPL at low frequencies is dominated by the room modes.

Acknowledgements

We would like to acknowledge the contribution made by John O'Keefe, a senior acoustic consultant of Toronto as well as his anecdotal details of the event inside Runnymede United Church in Toronto.

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PERFORMANCE AND PREFERENCE OF RESPONSE SCALES FOR SEMANTIC DIFFERENTIALS IN AUDITORY PERCEPTION AMONG UNIVERSITY STUDENTS

Wonyoung Yang* **and Jin Yong Jeon**†
Department of Architectural Engineering, Hanyang University, Seoul, Korea.

For Murray, my dearest mentor

Résumé

On sait que les échelles de réponse sont essentielles à la qualité des réponses. Une échelle numérique unipolaire à 11 points conforme à la norme ISO/TS 15666:2003 a été largement utilisée pour évaluer la perception auditive à l'intérieur et à l'extérieur, ainsi que pour les évaluations de terrain et la recherche psychoacoustique. Toutefois, dans de nombreuses disciplines, une échelle visuelle analogique a été utilisée à des fins académiques plus approfondies. Cette étude vise à comparer la performance et la préférence de deux échelles de réponse, une échelle visuelle analogique bipolaire et une échelle numérique unipolaire, pour les différences sémantiques dans la perception auditive à l'aide d'un dispositif basé sur le Web. Deux échelles de réponse différentes ont été comparées dans cinq stimuli acoustiques (niveau de bruit de fond de 38 dBA, bruits de l'eau et bruit du trafic de 42 et 61 dBA, respectivement) avec deux mesures répétées. Les deux échelles de réponse étaient acceptables pour leur fiabilité et leur sensibilité. Cependant, l'échelle analogique visuelle bipolaire était plus fiable que l'échelle numérique unipolaire à 11 points dans les mesures répétées, et l'échelle numérique unipolaire à 11 points était plus sensible que l'échelle analogique visuelle bipolaire pour distinguer les différences subtiles entre sources sonores. L'échelle analogique visuelle bipolaire était évidemment préférée par les participants. Le choix des adjectifs sémantiques est une condition préalable essentielle pour déterminer les échelles de réponse pour la perception auditive. En résumé, une échelle visuelle analogique unipolaire est proposée pour évaluer la perception auditive à des fins de recherche psychoacoustique chez les jeunes adultes instruits.

Mots clefs : échelles de réponse, échelle unipolaire, échelles bipolaire, échelle visuelle analogique, échelle numérique unipolaire à 11 points, préférence du répondant, intensité, caractère bruyant, agacement

Abstract

It is known that response scales are critical for achieving the quality of the responses. A unipolar 11-point numerical scale in accordance with ISO/TS 15666:2003 has been widely used for assessing auditory perception both indoors and outdoors, as well as for field assessments and psychoacoustic research. However, in many disciplines, a visual analogue scale has been used for more in-depth academic purposes. This study aims to compare the performance and preference of two response scales, a bipolar visual analogue scale, and a unipolar numeric scale, for semantic differentials in auditory perception using a web-based device. Two different response scales were compared in five acoustic stimuli (background noise level of 38 dBA, water sounds and traffic noise of 42 and 61 dBA, respectively) with two repeated measurements. Both response scales were acceptable for their performance of reliability and sensitivity. However, the bipolar visual analogue scale was more reliable than the unipolar 11-point numerical scale in repeated measurements, and the unipolar 11-point numerical scale was more sensitive than the bipolar visual analogue scale in distinguishing subtle differences between sound sources. The bipolar visual analogue scale was obviously preferred by participants. The choice of semantic adjectives is a critical prerequisite for determining response scales for auditory perception. In summary, a unipolar visual analogue scale is proposed for assessing auditory perception for psychoacoustic research purposes for young educated adults.

Keywords: Response scales, unipolar scale, bipolar scale, visual analogue scale, 11-point numerical scale, respondent's preference, loudness, noisiness, annoyance

1 Introduction

The evaluation of the acoustic environment is mainly based on the subjective rating scale responses to questions about acoustic sensation and perception. The quality of the responses depends on the design of the response scales [1]. The 5-point verbal and 11-point numerical scales proposed by ICBEN (International Commission on Biological Effects of Noise) [2] are the two major methods for measuring the response to subjective questions about acoustic sensation and perception.

For better understanding of how humans react to sound, it is necessary to investigate both the negative and positive aspects of sound. The ICBEN recommendation was developed for assessing and comparing environmental noise annoyance, and was later adopted as the international

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* wyang@hanyang.ac.kr
† jyjeon@hanyang.ac.kr

standard ISO/TS 15666:2003 [3]. No positive acoustic aspects were taken into account in the ICBEN methods. About a decade later, the soundscape was defined as an acoustic environment perceived or experienced and/or understood by a person or people, in the context of the first ISO standard, ISO/TS 12913-1:2014 [4]. Situational differences between measuring annoyance and measuring soundscape preference were taken into consideration in the methods. The 5-point verbal response scale was adopted as the international standard ISO/TS 12913-2:2014 [5] for soundscape data collection and reporting.

For more in-depth psychological understanding of human sensation, perception, and recognition of sound as well as speech, a visual analogue scale (VAS) was used in previous psychoacoustic studies [6-16]. VAS may be preferred in research due to better sensitivity [17]. VAS is known for its high sensitivity to discriminate subjective feelings [18]. At first glance, it may seem that VAS may have better precision and be more sensitive to detect changes than numerical scales, simply because of the finer gradations of response levels [19].

Comparisons of the visual analogue scale and the numerical scale have been reported in clinical, market research, and psychology [17, 20-31], and these studies have yielded contradictory findings. The use of VAS on a multipoint scale is beneficial with regard to sensitivity,[17, 21, 24] respondent preference [20], accuracy [32], and response time [30]. On the other hand, a few studies have evidence supporting the use of a multipoint scale over VAS regarding response rates [25, 26], respondent preference [33], and response time [25, 28]. However, many studies reported no significant difference in the use of the scales [22, 23, 25-28, 31, 33].

Munson et al. [11] recommended the use of continuous rating scales in their phonetic research, because visual analogue scales are well correlated with acoustic parameters and can be easily implemented both in field research on phonological acquisition and in the clinic. In audiology, VAS loudness and VAS annoyance are valid and effective measurements for capturing the reductions in the severity of tinnitus in patients with chronic tinnitus [13]. In indoor environmental discipline, although visual analogue scale has been used in several laboratory studies [8-10, 15, 16], to date, no study has compared response scales to verify the quality of subjective responses in psychoacoustic research.

Recently, a few comparative studies between 5-point verbal and 11-point numerical scales reported noise annoyance [34-37]. Brink et al. [34] found that standardized average annoyance scores were slightly higher when using the 11-point numerical scale, whereas the percentage of highly annoyed respondents was higher based on the 5-point verbal scale. The frequency distributions of the two upper categories (very and extremely) of 5-point verbal scale in the highest categories out of 10 of 11-point numerical scale are almost the same. Nguyen et al. [35] expanded the annoyance response study in Japan and Vietnam. In Japanese, it was found that the highest category of 11-point and 5-point scales basically corresponds to the top category of 5-point and 11-point scales, respectively. However, in Vietnamese, the highest category of 5-point and 11-point scales corresponded to the two upper categories of 11-point and 5-point scales, respectively. It was found that logistic regression curves with high annoyance, defined by the three upper categories of the 11-point scale, have a good fit to the quadratic curves with high annoyance, defined by a cutoff point of 28%, as recommended by Miedema and Vos. [38]. However, these curves are separated from logistic regression curves with high annoyance, defined by the two upper categories of the 5-point scale in both countries. Bjerre et al. [36] reported on consistency between the 5-point verbal scale and the 11-point numerical scale in their on-site and laboratory evaluations of the urban soundscape. Tristán-Hernándes et al. [37] found no statistically significant differences between the 5-point and 11-point scales when evaluating noise annoyance inside university facilities.

The purpose of this study was to investigate the performance and preference of two response scales, a bipolar visual analogue scale, and a unipolar numerical scale, for semantic differentials in auditory perception using a web-based device. Specific research interest was the impact of polarity and types of the scale, which were the questionnaire related factors in young adults.

2 Method

2.1 Participants

Overall, 50 university students (23 men and 27 women) participated in a 60-minute session. No hearing impaired participants were examined by the interview. Informed consent was obtained from each of the participants, and they received financial support for their participation. The mean age of participants was 22.5 (S.D. 2.0) years.

2.2 Testing laboratory and experimental conditions

The experiment was conducted in a test laboratory (4.0 m × 5.0 m × 2.4 m), which was built for indoor environmental research. The indoor environment was maintained at the air temperature of 24.5 ºC and humidity of 40%. The ventilation system was in operation during the experiment. The local air velocity was measured to be less than 0.1 m/s. The mean illuminance levels along the desk surface during the experiments were 995.0 lx.

A loudspeaker system (Turbosound Milan M10) was used as a sound source and was located on the rear side to minimize the spatial sensitivity of sound sources. The reverberation time in the testing laboratory was measured as 0.3 s at 500 Hz for octave bands (01 dB dB4). The ambient noise level in the laboratory was 38 dBA (01 dB solo) when the thermal and ventilation systems were operated.

Four different sound sources (water sound and traffic noise of 42 and 61 dBA) were reproduced through the loudspeaker, considering the average measured daytime noise exposure levels [39]. Water sounds, representing a positive sound, were acquired from an open website [40], and traffic noises, representing a negative sound, were recorded in the living room of a residential building. The levels of the sound sources were adjusted using an audio controller. The differences in sound level across the positions of the participants were measured at ± 0.3 dBA. Figure 1 shows the octave band frequency spectra of the sound sources, including ambient noise in the chamber.

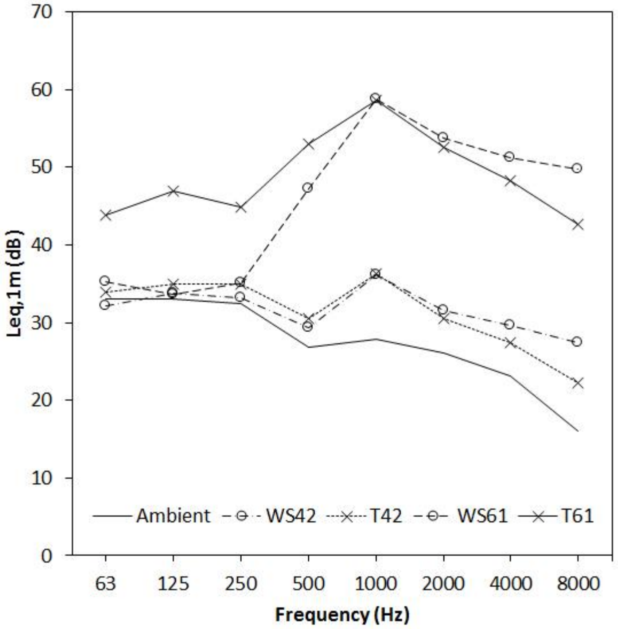

Figure 1: Frequency spectra of sound sources

2.3 Response scales

A web-based tablet interface was used for subjective assessments. Figure 2 shows the two response scales and their tablet interfaces. A unipolar 11-point numerical scale (unipolar11) with endpoint and midpoint labels was adopted based on ISO/TS 15666:2003,[3] which was developed for socio-acoustic noise annoyance surveys. It is assumed that a 0-to-10 scale would be more understandable and manageable than the shorter ones. Most people are familiar with the base-10 numeric systems through currency and other familiar counted materials. Radio buttons were also used to create 11 discrete scales from 0 to 10. Three verbal labels “Not at All,” “Neutral,” and “Extremely” were placed at the top of “0,” “5,” and “10.” The number of questions has doubled on the bipolar scales, because a unipolar scale could only evaluate to a degree of one attribute.

A bipolar visual analogue scale (bipolar VAS) was introduced in the study. The questionnaire content was identical to the unipolar 11-point scale, except for the polarity. VAS consists of a plain, mostly horizontal line with a length of 100 mm and mostly verbal end labels. Respondents give a rating by placing a mark on the line. In this study, a numerical value from -10.0 to 10.0 was assigned to the responses for statistical analysis. A slider was placed at the left end in the default setting as an indicator of the rating mark. However, respondents were required not to drag, but click on the slider to avoid potential technical problems of dragging with their fingers.

The semantic attributes of the questionnaire were four pairs of adjectives: soft versus loud, quiet versus noisy, pleasant versus annoying, and uncomfortable versus comfortable. For a unipolar scale questionnaire, each semantic attribute was listed one by one. For a bipolar scale, soft, quiet, pleasant, and uncomfortable were positioned on the left end, and noisy, loud, annoying and comfortable were positioned on the right end.

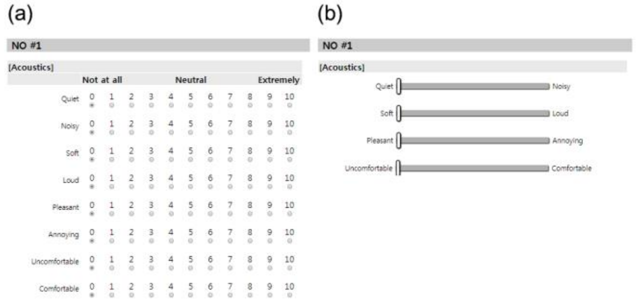

Figure 2: Two types of questionnaire: (a) unipolar 11-point, (b) bipolar VAS

2.4 Experimental design and procedure

A factorial within-subject design with repeated measurements was employed with two independent variables: response scale (unipolar 11 and bipolar VAS) and sound source (ambient, water sound 42 dBA, traffic noise 42 dBA, water sound 61 dBA, and traffic noise 61 dBA).

A maximum of six participants simultaneously assessed the acoustical conditions in a test laboratory. The response data provided by the participants were automatically saved on a server. In each session of 60 min, a 20-min adaptation period was implemented at the beginning of the session for relaxation and environmental adaptation, as shown in Figure 3.

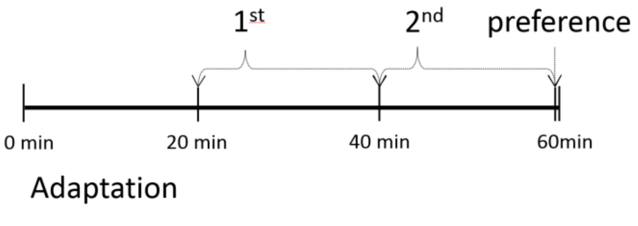

Figure 3: Experimental procedure for each session

Participants were seated during the adaptation period. Each sound stimulus was presented for 50 s, and a response time was provided until all participants in the test group submitted their responses. Ambient sounds for four different response scales were assessed at the beginning and at the end. Four sound sources combined with four response scales were randomly presented in each test session, and their replicas were also presented in random order.

At the end of the session, a paired comparison was conducted to investigate participants' preferences for the scales between the unipolar 11-point scale and the bipolar visual analogue scale.

2.5 Statistics

Statistical analyses were performed using two different approaches: original and normalized data analyses. The original data from respondents were used to analyze the correlation performance for reliability. Fisher's Z transformation was applied to compare the correlation coefficients of repeated measurements on each response scale. The original data were also applied to a factorial analysis of variance (ANOVA) to validate the effects of sound sources on each response scale. ANOVA is a powerful statistical test and it was used in this case, although normality cannot be guaranteed for subjective ratings [41, 42].

A repeated-measurement ANOVA was also used to test the scale factor for two repeated measurements. The original data were converted to unipolar 0.0-to-10.0 scales to perform ANOVA on two response scales with different numerical ranges. If a response value was greater than zero, it was treated as a right-end semantic attribute, and if a response value was less than zero, it was treated as a left-end semantic attribute. Three corrections (Greenhouse-Geisser, Huynh-Feldt, and the lower boundary) for violations of sphericity were used to test the sphericity. The Mauchly sphericity test requires more than three repeated measurements, but only two measurements were performed in this study. An epsilon (ε) value of 1 was found for the three corrections across all subjective attributes, which indicates that the condition of sphericity was exactly met. A Bonferroni post-hoc test was applied.

3 Results

3.1 Original data analysis

Correlations were assessed for a pair of the first and second measurements for each response scale. The bipolar VAS had higher correlation strength than the unipolar 11-point scale using the Fisher's Z transformation ($P < 0.05$) for all subjective attributes in Table 1. In the unipolar 11-point scale, the reliabilities of loudness, noisiness, and annoyance were significantly higher than those for softness, quietness, and pleasantness. Loudness and noisiness showed higher correlation coefficients than any other subjective attributes. In the bipolar VAS, a pair of quietness and noisiness showed the highest reliability, and the pairs of softness/loudness and pleasantness/annoyance followed. The attributes associated with acoustic comfort, both for the unipolar 11-point scale, and for the bipolar VAS, were observed as the least reliable attributes.

The bipolar soft/loud pair correlates better with the unipolar loudness than the unipolar softness. The unipolar noisiness correlates better with the bipolar quiet/noisy pair than with unipolar quietness.

The bipolar acoustic uncomfortable/ comfortable pair also correlates better with unipolar acoustic comfort. The unipolar 11-point scales were, in general, correlated better with the right-end attributes of the bipolar VAS than the left-end attributes of the bipolar VAS. The bipolar quiet/noisy pair was observed as the most reliable measure in repeated measurements, and it showed the best reliability in response scale comparisons.

The bipolar soft/loud pair correlates better with the unipolar loudness than the unipolar softness. The unipolar noisiness correlates better with the bipolar quiet/noisy pair than with unipolar quietness. The bipolar acoustic uncomfortable/ comfortable pair also correlates better with unipolar acoustic comfort. The unipolar 11-point scales were, in general, correlated better with the right-end attributes of the bipolar VAS than the left-end attributes of the bipolar VAS as listed in Table 2. The bipolar quiet/noisy pair was observed as the most reliable measure in repeated measurements, and it showed the best reliability in response scale comparisons.

Table 3 lists the results of the Bonferroni post hoc test for each subjective attribute according to the sound sources. Mean values that do not share the letters in each attribute are significantly different. The unipolar scale could differentiate between quietness, noisiness, pleasantness, annoyance, acoustic discomfort, and acoustic comfort between the water sounds and the traffic noise, even at the same sound levels. However, the bipolar scale cannot differentiate any subjective attributes between water sounds and traffic noise at 42 dBA, except for the pair of acoustic uncomfortable/ comfortable. The unipolar quietness could distinguish between background noise and 42 dBA. The unipolar discomfort and the bipolar discomfort/comfort pair also could differentiate between background noise and 42 dBA sounds.

Table 1: Pearson's correlation coefficients between repeated measures ($P < 0.0005$) and Fisher's Z transformation ($P < 0.05$) results (coefficients that do not share a letter are significantly different, A > B > C > D)

N=250	Pearson's CC (P<.0005)	Fisher's Z transformation (P<.05)
Unipolar 11		
Soft	0.766	D
Loud	0.897	AB
Quiet	0.856	C
Noisy	0.905	AB
Pleasant	0.772	D
Annoying	0.845	C
Uncomfortable	0.735	D
Comfortable	0.715	D
Bipolar VAS		
Soft-Loud	0.875	B
Quiet-Noisy	0.913	A
Pleasant-Annoying	0.871	B
Uncomfortable-Comfortable	0.813	C

Table 2: Pearson's correlation coefficients between the unipolar 11-point scale and the bipolar VAS ($P < 0.0005$) and Fisher's Z transformation ($P < 0.05$) results (coefficients that do not share a letter are significantly different, A > B > C > D)

	Unipolar 11			
Bipolar VAS	Left-end		Right-end	
Soft-Loud	-0.772	C	0.868	B
Quiet-Noisy	-0.870	B	0.905	A
Pleasant-Annoying	-0.767	C	0.791	C
Uncomfortable-Comfortable	-0.702	D	0.756	C

Table 3: Results of Bonferroni pairwise comparisons according to sound sources (Mean values that do not share a letter are significantly different, A > B > C > D. $P < 0.05$)

	BN	W42	T42	W61	T61
Soft	A	A	A	B	B
Loud	B	B	B	A	A
Soft-Loud	C	C	C	**B**	**A**
Quiet	**A**	**B**	B	C	C
Noisy	C	C	C	**B**	**A**
Quiet-Noisy	C	C	C	**B**	**A**
Pleasant	A	**A**	**B**	C	D
Annoying	C	C	C	**B**	**A**
Pleasant-Annoying	C	C	C	**B**	**A**
Uncomfortable	C	C	C	**B**	**A**
Comfortable	**D**	**C**	**B**	AB	A
Uncomfortable-Comfortable	**D**	**C**	**B**	AB	A

3.2 Normalized data analysis

The original data of the bipolar VAS from -10.0 to 10.0 were normalized to unipolar 0.0-to-10.0 scales to perform ANOVA with repeated measurements on the two response scales with different numerical ranges.

Table 4 lists the significance levels and size of the effect of the repeated-measurement ANOVA results for normalized subjective responses. The effects of repetition were found only in acoustic discomfort. The effects of the response scales were found in softness, loudness, noisiness, pleasantness, annoyance, and acoustic comfort. The right-end attributes, loudness, noisiness, annoyance, and acoustic comfort showed higher values with the unipolar 11-point numerical scale than with the bipolar VAS. Softness and pleasantness among the left-end attributes had higher values with the bipolar VAS than with the unipolar 11-point scale. No effects of the response scales were found in quietness and acoustic discomfort. The effects of sound sources were found in all subjective attributes, as expected. The positive attributes, namely, quietness, pleasantness, and acoustic comfort can distinguish differences between background noise, water sounds of 42 dBA and traffic noise of 42 dBA. However, these positive attributes can not differentiate between the sounds of 61 dBA water sound and traffic noise. On the other hand, the negative attributes, namely, loudness, noisiness, annoyance, and acoustic discomfort can distinguish between the sounds of a 61 dBA water and traffic noise, but can not distinguish sounds of lower levels. Figure 4 shows normalized mean values with two different response scales according to sound sources.

3.3 Preference results

The 86% of participants voted for the bipolar VAS as shown in Figure 5. Only two options of choice were provided to participants. Non-response did not occur in this question.

Table 4: Results of significance level ($P < 0.05$) and effect size (η^2) of repeated-measurement ANOVA using normalized data (D: discomfort, C: comfort) uncomfortable

		Softness		Loudness		Quietness		Noisiness		Pleasant-ness		Annoyance		Discomfort		Comfort	
Within subjects																	
Repeat	P													0.027			
	η^2													0.015			
R1	Mean													4.454	A		
R2	Mean													3.894	B		
Between subjects																	
Scale	P	<.0005		<.0005				<.0005		0.008		0.010				0.004	
	η^2	0.029		0.071				0.129		.0270		0.036				0.030	
Unipolar 11	Mean	4.392	B	4.022	A	4.712	A	4.066	A	4.126	B	3.694	A	3.932	A	4.978	A
Bipolar VAS	Mean	5.339	A	3.133	B	4.551	A	2.811	B	4.726	A	2.786	B	3.370	A	4.156	B
Sound	P	<.0005		<.0005		<.0005		<.0005		<.0005		<.0005		<.0005		<.0005	
	η^2	0.117		.0.349		0.443		0.223		0.130		0.307		0.218		0.188	
BN	Mean	6.865	A	0.841	C	7.671	A	0.813	C	6.470	A	1.087	C	1.826	C	6.802	A
W42	Mean	6.620	A	1.301	C	6.749	B	1.370	C	6.053	A	1.398	C	1.901	C	6.271	A
T42	Mean	6.255	A	1.434	C	6.528	B	1.462	C	5.182	B	1.790	C	2.276	C	5.403	B
W61	Mean	2.675	B	6.848	B	1.445	C	6.176	B	2.693	C	5.304	B	5.316	B	2.619	C
T61	Mean	1.913	B	7.465	A	0.763	C	7.373	A	1.731	C	6.622	A	6.684	A	1.739	C

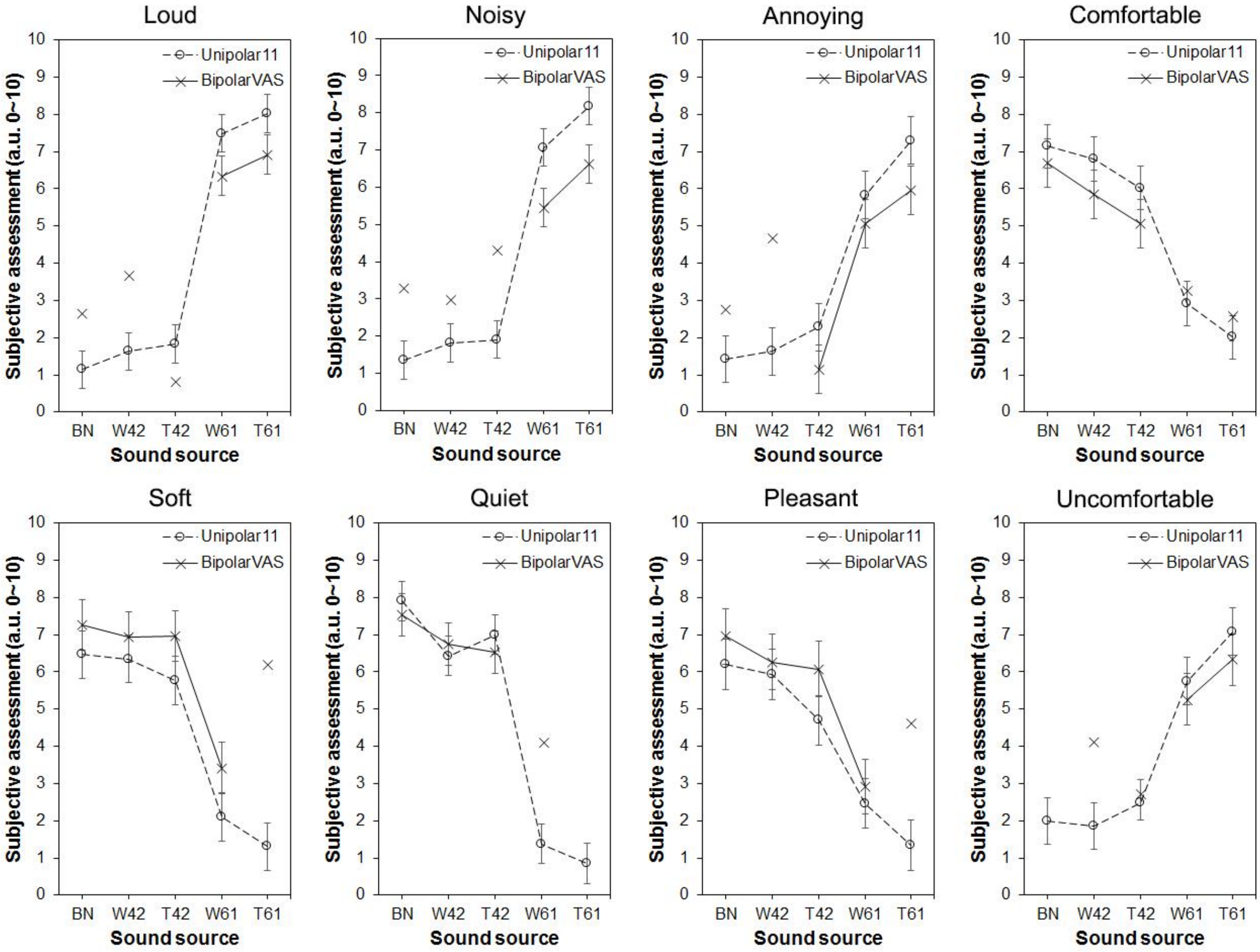

Figure 4: Normalized mean subjective judgment with a significant difference on the response scale (black: bipolar VAS, red: bipolar 7, blue: unipolar 11, purple: combined

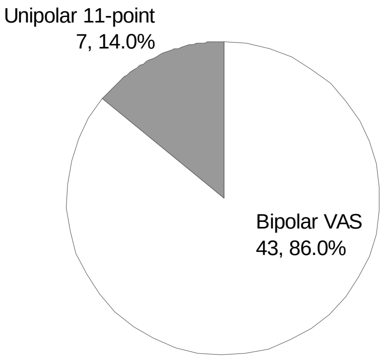

Figure 5: Paired comparison test results between a bipolar VAS and a unipolar 11-point scale

4 Discussion

4.1 Numeric scale vs. visual analogue scale

Reliability over repeated measurements of the two response scales was acceptable [43]; however, it was higher with the bipolar VAS than with the unipolar 11-point scale within each pair of subjective attributes. This is consistent with Rausch and Zehetleitner [28], although they could not have statistical significance in terms of reliability in comparison between the VAS and the 4-point scale as measures of a conscious experience of motion. However, Lewis and Erdinç [31] reported that the reliability of 7- and 11-point Likert-type scales and the VAS had no obvious advantage over each other in the context of user experience research. Clear evidence regarding the highest reliability has not yet been found.

4.2 Unipolar vs. bipolar

The scale sensitivity, the degree of differentiation by sounds, was higher with the unipolar 11-point scale than with the bipolar VAS. The bipolar VAS had two adjectives on each side of the scale. As listed in Table 2, the correlation coefficients between the unipolar 11-point scale and the bipolar VAS were higher than 0.7 on all subjective attributes, which meant a strong correlation [43]. However, the bipolar VAS of a pair of subjective attributes was highly correlated and yielded a similar precision in discriminating sound sources with the unipolar 11-point scale of the right-end attributes, rather than the left-end ones with statistical significance (Table 3). This means that the left-end subjective attributes of the bipolar VAS cannot be assessed as reliably as the right-end subjective attributes. The polarity of the response scale affected the sensitivity of subjective attributes. However, it is not clear whether the position of the right-end is simply preferable to the left-end, or the subjective attributes of loudness, noisiness, annoyance, and acoustic comfort are more impressive than the softness, quietness, pleasantness, and acoustic discomfort for the participants.

The impact of scale polarity on data quality has not yet been clearly investigated. Alwin [44] reported that unipolar scales are somewhat more reliable than bipolar scales.

However, in this study, the polarity of the scale was related to sensitivity, not reliability.

4.3 Participants preferences

The bipolar visual analogue scale was preferable to the unipolar 11-point scale among young adults in this study. User preferences on rating scales were studied mainly in medicine or psychology. The effects of socio-economic educational factors were significant on the user preferences of response scales according to studies in medicine [27]. It has been observed that VAS is not a priority of preferences for response scales in pain scale studies [27, 45, 46]. In psychology, Preston and Colman [47] reported respondents' preference on the response scales for 149 undergraduate students. For young adults, scales with 6, 7, and 10 response categories were the most preferable for ease of use, but the 101-point scale was the most favorable rating for adequate expression of feelings.

User preference may be a factor in choosing a rating scale, given the positive association between user performance and their subjectively expressed preferences [48].Understanding the socio-economic and educational status of respondents would be the basis for considering user preferences for response scales.

4.4 Semantic adjective attributes

The differences between the background noise, the water sound of 42 dBA, and the traffic noise of 42 dBA could be distinguished by quietness, pleasantness, and acoustic comfort, which are all positive attributes, except for softness. The differences between the water sound and traffic noise of 61 dBA showed up in all the negative attributes, without exception. The bipolar VAS could not differentiate the left-end adjectives. Furthermore, there were no adjective attributes in the unipolar 11-point scale that could distinguish all five different sound sources. Choosing the right semantic attributes is a prerequisite for defining response scales. Participants tended to focus on semantics. The response of the participants was not so sensitive to the response to sounds belonging to the semantic category, if the sounds that they heard were not in the semantic category. For example, as soon as the sounds were not heard loudly subjectively, their subtle differences of sounds were not evaluated in loudness assessment, and vice versa. Therefore, in the case of a broad range of sound levels to be assessed, semantic attributes should be chosen more carefully based on the purpose of the study.

Research information on semantic differentials in auditory perception is still scarce. More research is needed in this area.

4.5 Limitations

First, the test configurations were combined with numerical versus analogue and unipolar versus bipolar to reduce the number of comparisons. If a two-by-two matrix (2 response types x 2 polarities) was used for comparisons, more direct results could be obtained. Secondly, the test participants were limited to young, educated participants. However, the non-randomized sample was justified by the purpose of the study. Thirdly, the preference question was a simple paired comparison, therefore it was impossible to analyze the cause and the effect on the participant preference on the response scales.

5 Conclusion

The bipolar visual analogue scale and the unipolar 11-point numerical scale were compared to assess their performance and the preference of auditory perception among university students. Both response scales were acceptable for their reliability and sensitivity. However, the bipolar visual analogue scale was more reliable than the unipolar 11-point numerical scale in repeated measurements, and the unipolar 11-point numerical scale was more sensitive than the bipolar visual analogue scale to distinguish subtle differences between sound sources. Participants obviously preferred the bipolar visual analogue scale. The choice of semantic adjectives is a critical prerequisite for determining response scales for auditory perception. In summary, a unipolar visual analogue scale is proposed for assessing auditory perception for psychoacoustic research purposes for young educated adults.

Acknowledgments

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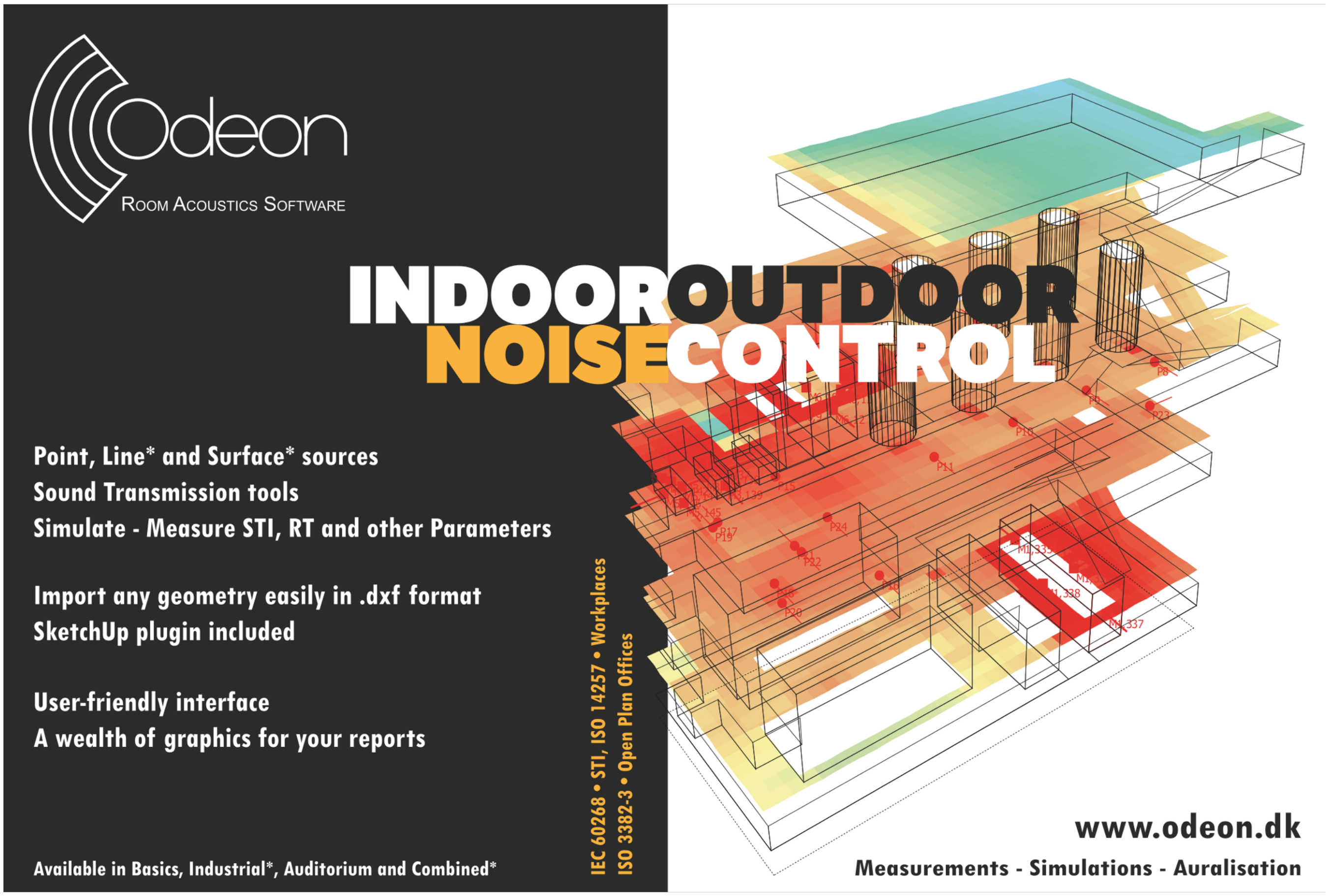

LEARNING AND INTERACTING IN NOISY CLASSROOMS: TEACHER PERCEPTIONS OF THE CHALLENGES FOR STUDENTS WHO ARE HARD OF HEARING

Janet R. Jamieson[*1], Brenda T. Poon[†1], and Anat Zaidman-Zait[‡2]
[1]University of British Columbia, Vancouver British Columbia, Canada.
[2]Tel Aviv University, Tel Aviv, Israel

Résumé

Le but de cette étude exploratoire était d'étudier l'impact du bruit de fond sur les expériences scolaires quotidiennes des enfants sourds et malentendants (SM) à l'école primaire. Les observations effectuées dans 11 salles de classe du primaire dans une ville de l'Ouest canadienne ont permis de constater que les élèves et les enseignants participaient à quatre types d'activités en classe (travail de siège individuel, enseignement direct par l'enseignant, activités en petits groupes et transition). Les activités non structurées, les vastes salles de classe et les niveaux élevés de bruit de fond ont constitué le défi le plus difficile pour les étudiants SM en termes d'apprentissage et d'interactions sociales. Seize enseignants en classe et spécialistes ont été interrogés pour connaître leur perception de l'expérience de leurs 11 étudiants SM, qui apprenaient et interagissaient dans des salles de classe bruyantes. Toutes les entrevues ont été analysées selon une approche d'analyse de contenu. Les enseignants ont estimé que les bruits de fond avaient eu de graves effets négatifs sur les élèves, tant sur le plan scolaire que social. Les implications pour la théorie, la pratique et la politique sont discutées.

Mots clefs: sourd, malentendant, acoustique des salles de classe, bruit de fond

Abstract

The purpose of this exploratory study was to investigate the impact of background noise on the daily school experiences of deaf and hard-of-hearing (DHH) children in elementary school. Through observations in 11 elementary classrooms in a western Canadian city, students and teachers were found to participate in four types of classroom activities (seatwork, direct teacher instruction, small group activities, and transitions). Unstructured activities, large classroom space, and high levels of background noise caused the most challenge for DHH students in terms of learning and peer interactions. Sixteen classroom and specialist teachers of the DHH were interviewed to learn their perceptions of their 11 DHH students' experience learning and interacting in noisy classrooms, and all interviews were analyzed through a content analysis approach. The teachers perceived that the students experienced serious negative impacts from background noise both academically and socially. Implications for theory, practice, and policy are discussed.

Keywords: deaf, hard of hearing, classroom acoustics, background noise

1 Introduction

For children to succeed in academic settings, the ability to hear the teacher and each other is critical. However, it has long been noted that poor classroom acoustics can impede learning because of high levels of background noise, which negatively impact children's ability to listen and concentrate, and subsequently their academic performance. For example, chronic exposure to background noise in their classrooms reduced the academic attainment of a group of 7- to 11-year-old children in the U.K., across the subject areas of reading, mathematics, and science [1]. Similar findings have been reported in secondary schools, where interfering background noise had a detrimental effect on the performance of 11- to 15-year-old students in reading, numeracy, and memory tasks [2]. Thus, poor classroom acoustics have been shown to have a negative impact on academic performance across grade levels, subject areas, and cognitive skills.

An especially important finding concerns children at the elementary school-age level with additional learning needs, whose academic performance has been shown to be more severely affected by background noise than that of their typically developing peers [3]. More specifically, a growing body of research over the past two decades has investigated and confirmed the negative impact of poor classroom acoustics on children with hearing loss [4-6]. The focus of these studies has been primarily on speech perception in noisy classroom conditions; this is particularly salient because language access may be challenging for students with hearing loss even in optimal listening conditions.

Overall, the focus on the impact of poor classroom acoustics on the academic attainment of children with hearing loss is timely and relevant because of the current widespread educational placement of most deaf and hard-of-hearing (DHH) children into inclusive (i.e., general education) classrooms alongside their hearing peers, where

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[*] janet.jamieson@ubc.ca
[†] brenda.poon@ubc.ca
[‡] anatzaidman@tauex.tau.ac.il

spoken language is the primary mode of communication [7, 8]. Given the absence of legislation concerning standards for acoustics in Canadian classrooms, it seems reasonable to assume that most children with hearing loss are receiving their education in noisy classroom settings. Classroom activities undoubtedly contribute to high levels of background noise. Contemporary approaches to teaching and learning in elementary school settings (i.e., kindergarten-Grade 12) emphasize increasing student engagement through such approaches as the flexible use of learning spaces and collaborative learning experiences, as is evident in British Columbia's new curriculum [9], for example. These approaches suggest a range of types of classroom activities, including group work and peer communication, that are associated with elevated levels of background noise.

For DHH students who spend the entire school day in inclusive classrooms, it is important to understand the impact of noisy classrooms on not only their academic performance but also their social interaction with peers – that is, on the *entirety* of their daily school experience. This is particularly critical in the case of the youngest learners, who may not yet be aware of and/or have the skills to articulate the impact of challenging listening conditions on learning and socializing.

The purpose of this exploratory study was to investigate the experience of learning and interacting in noisy classrooms for DHH children in elementary school. The Canadian province of British Columbia (B.C.) was judged to be an apposite location to undertake this research, as the majority of students with hearing loss in B.C. are placed in inclusive educational settings, and there is no government policy for classroom acoustic standards. The students are supported not only by their classroom teachers but also by itinerant teachers of the DHH, who provide regular (usually weekly) specialized one-to-one support to the students and their classroom teachers. Because some of the children involved in the study were as young as kindergarten age (i.e., 5 years old), their classroom and specialist teachers served as knowledgeable informants.

This study was guided by the following overall research question: According to teacher perceptions, what is the impact of noisy classrooms on the learning and social interactions of DHH students in inclusive classroom settings?

a) What are the types of classroom activities in which the students engage, and what are the acoustic demands of these activities?
b) How does background noise impact the students' learning experience? What are the challenges they experience?
c) How does background noise impact students' social interactions? What are the challenges students experience?

2 Method

2.1 Participants

Students

Eleven hard-of-hearing children, all students in a suburban school district in B.C., were nominated for inclusion in the study by the three district itinerant teachers of the DHH. All students met the following criteria: they attended elementary school (i.e., between kindergarten and Grade 7); had permanent moderate to severe bilateral hearing loss; had no additional special needs; used spoken English to communicate at school; and had full-time educational placement in their respective classrooms. All students wore hearing aids and all classrooms were equipped with sound field systems, which the classroom teachers were expected to use but some of which were used only intermittently or inconsistently, according to the itinerant teachers of the DHH. Three students were in kindergarten-Grade 2, four were in Grades 3-4, and four were in Grades 5-7. Five of the children were boys and six were girls.

Teachers

The teacher participants were 11 classroom teachers, representing one teacher for each of the 11 students; two Special Education Assistants (SEAs), who provided additional educational support for the entire class in two of the classrooms); and the three district itinerant teachers of the DHH. (Each student received specialized support from one of the three itinerant teachers.)

2.2 Procedure and analysis

Observations of types of classroom activities

The first two authors, both with experience in education and the education of students with hearing loss, developed a list of types of academic classrooms activities, based on teacher education literature and their own classroom observations. They discussed and revised the list until it exhaustively accounted for all academic activities observed in a pilot observation in an elementary school classroom in B.C. The final list resulted in four general categories: direct teacher instruction (directed either individually to the hard-of-hearing student or to the whole class); individual seat work (in which students completed work individually at their desks); small group work (in which students worked together in groups of two or more); and transitions (in which students were directed to and moved on to another activity). These were used to track academic activities in the 11 classrooms.

During the observations, a researcher seated unobtrusively at the back of the class tracked the time of the start of each of the four classroom activities. An activity was assumed to continue until the onset of another one. Two researchers completed the activity tracking. To ensure inter-observer reliability, both researchers independently coded the first classroom observation. An 80% inter-observer agreement was obtained, and the disagreements were resolved through discussion. The observers then conducted the remaining observations individually.

Teachers' interviews on the experience of learning and interacting with peers and teachers in noisy classrooms

All teachers participated in individual semi-structured interviews conducted by a graduate research assistant, who had experience as both a general education teacher and a teacher of the DHH. The focus of all interviews was the teachers' perceptions of their DHH students' learning and social interaction experiences in their classrooms. Among the questions posed was one concerning the professional's opinion of any difficulties students experienced in the classroom. The teachers all provided expanded information on this topic throughout the rest of their respective interviews.

All interviews were transcribed. The first author then extracted all comments pertaining in any way to acoustic/listening conditions or activities in which the DHH students experienced difficulty. The first author and a second graduate research assistant, both with experience in general education and the education of students with hearing loss, individually read and re-read the extracted comments. A content analysis approach [10] was used to provide a rich description of the data set of teachers' comments within each activity category. The two coders jointly coded all comments for codes, themes, and sub-themes.

3 Results

3.1 How does background noise impact the students' learning experience?

The types of academic activities in which the students engaged across the 11 classrooms, and the proportion of time spent in each activity type, are shown in Table 1.

We identified four main themes concerning the impact of background noise on the DHH students' learning experiences, namely: the most challenging academic activity types; DHH students' emotional responses to missing information; DHH students' strategies when missing information; and teachers' strategies for supporting their DHH students when they miss information.

Theme 1: The most challenging academic activity types

All teachers listed two specific activity types as the most challenging for their students with hearing loss. The first was accessing teacher instructions, which tended to occur during direct teacher instruction and transitions from one activity to another. Although collectively direct teacher instruction and transitions occurred only 27.7% of the time, it was during these times that instructions about the next activity were provided. When students with hearing loss missed those directives, they were often lost in subsequent seatwork. As one teacher remarked: *I think it takes her a little bit longer to catch onto things because she maybe doesn't hear what I say to her or she misses things because of the background noise.* (Teacher M1)

The second activity type that all teachers mentioned as problematic for their DHH students was group work, such as small group work in the younger grades and group discussions in the upper grades. One teacher stated: *Group instructions/discussions when there is peripheral noise are difficult for him and he doesn't get much in those situations.* (Teacher CH1)

In addition, several teachers cited the difficulty their hard-of-hearing students encountered in participating in any type of activity, whether structured or unstructured, in large spaces, where acoustics were especially challenging. This included, but was not limited to, large classrooms, gymnasiums, and music rooms, all of which were characterized by high levels of reverberation, as well as the school playground. This was echoed in the following two teacher statements: *In an unstructured situation, it falls apart very rapidly and she sort of misses what's going on. Gym has been a challenge for her, the acoustics in the room, following what's going on.* (Teacher CC1-HRT)

He's really affected by background noise. In unstructured situations, it's hard for him, the reverberation around him confuses him. (Teacher DL2-HRT)

Theme 2: DHH students' emotional responses to missing information

Many teachers described three types of strong emotional responses from their DHH students when they missed information or instructions or were unable to follow group discussions: frustration, anger, and/or disruptive behavior; confusion; and/or apparent self-consciousness about peer reactions and resistance to request or accept support.

Table 1: Activity types by overall time across classrooms (in %)

Activity type	% time	Activity characteristics
Seatwork	48.5	Students work individually at their desks; highly structured activity; quiet discussion with neighbouring peers or teacher; moderate levels of background noise
Small group work	23.8	Simultaneous activity/discussion in many small groups throughout the classroom; much less structured activity than seatwork; high levels of background noise
Direct teacher instruction	19.6	Teacher is the only speaker; topic is well defined and the activity is highly structured; moderate levels of background noise from the classroom (e.g., HVAC) and student "shuffling" in seats
Transition	8.1	Teacher may be speaking, students moving to new activity and possibly chatting with each other; unstructured interval; high levels of background noise

In the words of one teacher: *Put him in a gym, a music class, he is off the wall. He can't figure out what's going on, he's trying to visualize it, his voice gets louder and louder, his behaviour gets worse, and he's often told to sit out, to sit down, to calm down.* (Teacher P1-HRT)

Theme 3: DHH students' strategies when missing information

When DHH students missed information or instructions in the classroom, they reverted to following what their peers were doing and/or "social bluffing" (i.e., pretending to have understood missed instructions or conversation). As one teacher said: *She's afraid to make herself look different, she doesn't want to appear that she's misheard. So she'd rather go and fake it, than she would do something about it and reveal herself.* (Teacher DL1-HRT)

It is noteworthy that none of the teachers mentioned the strategy of a student request for assistance. It seems that students' coping strategies were determined in large part by their emotional responses and their determination to hide the negative impact that high levels of background noise had on them, but not on their typically hearing peers. Not requesting assistance, it appeared, was part of a student strategy to hide the difficulty.

Theme 4: Teachers' strategies for supporting their DHH students when they missed information

Many teachers described their own instructional strategies when they were aware that their DHH students had missed instructions or important information. These strategies included a one-on-one check with the student for comprehension, repeating instructions for the student, or breaking instructions into chunks. *There are many times where, if there's instruction happening or there's just a discussion going on, she will only get part of it and a lot of it is…having to have things broken down into smaller chunks in order for her to understand or to needing that extra repetition.* (Teacher CC1-HRT)

Paradoxically, although from the teacher's perspective these strategies were designed to provide additional, needed support, from the student's viewpoint they may have conflicted with students' desire to hide their difficulty.

It is also worth noting that some teachers described how students' hearing aids might have actually contributed to their DHH students' communication difficulties. For example: *It's hard for them [DHH students] to stay focused because they pick up all the background noise from their hearing aids and so they're distracted very easily.* (Teacher DL4)

In fact, none of the teachers mentioned any benefits of hearing aids or classroom sound field systems.

3.2 How does background noise impact peer interaction and socialization?

Three main themes were uncovered pertaining to the impact of background noise on DHH students' interaction and socialization with peers, namely: the most challenging social activities; DHH students' emotional responses to social challenges; and DHH students' strategies when confronted with social difficulties with peers.

Theme 1: The most challenging social activities

The activities that the teachers reported as most challenging socially to their DHH students were any interactions that occurred in unstructured locations, such as on the playground (recess), at lunch, or in side social conversations during class. The students with hearing loss tended to miss auditory-based social cues that were available to their typically hearing peers. As one teacher described: *He misses a lot of social cues, he does not hear parts of conversation, unless he's looking directly at them and so he misses a lot of stuff.* (Teacher P1)

Theme 2: DHH students' emotional responses to social challenges

Many teachers described two types of emotional responses from their students when they missed social cues or information because of background noise. The first was being self-conscious around peers sometimes to the point of distress. One teacher described this: *If she's misheard instructions or misheard her peers on the playground, it became a major deal for her and she becomes very emotional and in the earlier years she would actually break down and cry to the point that she had to be removed from the classroom in order to recover and it would take her sometimes an hour to recover. So it has affected her behaviour, she doesn't act out, she doesn't instigate anything, but it's more how she internalizes what's going on….* (Teacher DL1-HRT)

The second was reacting toward peers in frustration or anger, as described by one teacher:
Well, definitely in small groups when you're playing games and things, she gets frustrated because they'll say she didn't follow the rules or didn't do this or that and she won't quite understand what she's done wrong. (Teacher DL4)

Theme 3: DHH students' strategies when confronted with social difficulties with peers

Just as their teachers described that their DHH students preferred to bluff in the classroom rather than admit to not having heard instructions, they also reported that their students preferred bluffing in social interactions. *With the other kids, socially, he'll tend to compensate; he'll follow along, copy what the others are doing, pretend he knows what people said.* (Teacher CH1-SEA)

The teachers also noted that students with hearing loss tended to withdraw socially or wait for social invitations rather initiate interactions, as described here: *She was very hesitant to even get talking to the other kids in the class…and I noticed at the beginning of the year, she'd go outside and she'd stand and she'd wait for someone to approach her [at recess].* (Teacher M1)

4 Discussion

The first research question concerned the types of classroom activities in which DHH students participate alongside their typically hearing peers, and the acoustic demands of these activities. Four broad activities accounted exhaustively for the classroom time: seatwork, small group work, direct teacher instructions, and transitions. A prerequisite to student success, or at least on-task performance, in individual seatwork was hearing the teacher's instructions, which tended to be delivered during direct teacher instruction or class transitions from one activity to another. According to the teachers' perceptions, even during direct teacher instruction, when the teacher was usually the only person speaking, background noise from the typical "shuffling" of other students, internal noises such as the heating and ventilation system, and external noises from the hallway or outside often interfered with the DHH students' hearing and/or understanding the instructions. DHH students also experienced difficulties understanding instructions delivered during transitions, which were both unstructured and usually contextualized in high levels of background noise from student movement and occasional side conversations. Small group work, which accounted collectively for 23.8% of classroom activities and was characterized by high levels of background noise, posed a particular concern. All teachers reported that DHH students experienced considerable difficulties in following or contributing to discussions in these situations. This is a serious, ongoing issue for students with hearing loss, as contemporary approaches to teaching and learning involve an emphasis on peer/collaborative learning in small group activities [e.g., 9].

Overall, then, DHH students spent almost three-quarters of their time in classroom activities in which background noise jeopardized their successful performance or participation through inconsistent access to the teachers' instructions and/or student discussions. This was true for both structured (e.g., seatwork) and less structured (e.g., small group work) activities, although unstructured activities with high levels of background noise (e.g., small group work) were the most problematic.

The second and third research questions concerned the challenges background noise imposed on DHH students' learning experiences and social interactions, respectively. According to their teachers, DHH students paid a high price for not understanding teachers or peers in background noise. Whether communication breakdowns occurred academic activities or social interactions, DHH students tended to react with frustration, which often led to anger, when unable to follow instructions or conversations. This is consistent with students' predominant reaction was social bluffing, in which they pretended to understand, and then copying their peers' actions, as a way to "hide" their difficulty following the conversation. This parallels the findings of Israelite, Ower, and Goldstein [11], who found that secondary students with hearing loss preferred to conceal their hearing loss from their hearing peers, at least initially. It is not surprising that many teachers reported that their DHH students displayed the extremes of either disruptive or withdrawal behavior when communication was not easily accessible to them. The latter reaction is consistent with Wauters and Knoors [12], who found that children with hearing loss who were in inclusive educational settings scored higher than their hearing peers on socially withdrawn behaviour.

The teachers perceived that these reactions were at least partially due to or complicated by the communication barriers of background noise, which were most apparent in large spaces and unstructured activities. Taken together, the overall findings of the study emphasize that the negative impacts of moderate to high levels of background noise permeate the both academic and social experiences of DHH children's daily lives at school.

The findings are consistent with previous calls for the urgent application of acoustic standards in public schools, such as the ANSI Standard S12.60 for Classroom Acoustics [13] as has been advocated by more than 20 national and provincial organizations in Canada representing children with hearing and/or language exceptionalities [14]. Given that classrooms typically contain 20-30 students and that contemporary teaching-learning approaches involve student engagement through interaction, classrooms do – and should – have at least moderate levels of background noise. However, when background noise becomes an accessibility barrier for any group of students – in this case, students with hearing loss – it is incumbent upon governments to ensure that publicly funded education spaces support the learning of all students.

The findings also underscore the important role that classroom teachers play in supporting their students with hearing loss. The teachers described several strategies to ensure these students' comprehension during class activities, including consistent use of classroom sound field systems, frequent checks for comprehension (a strategy described by several teachers), and classroom management strategies to provide a balance between structured and unstructured activities.

There were several limitations of this research, including the small number of student and teacher participants and the fact that the study was conducted in only one geographic location. At the same time, it should be emphasized that the teachers were highly knowledgeable informants about their DHH students' daily lives at school. Furthermore, several checks increased trustworthiness and credibility, including development of exhaustive classroom activity categories, audio recorded interviews, and joint coding of the interviews.

The findings underscore of the importance of future research on the social and academic impact of background noise on the daily lives of DHH children at school. The findings also raise several questions, most notably: What is the impact of background noise on the academic and social experiences of DHH students in classrooms designed with evidence-based acoustic standards? Is the impact different than in a non-acoustically treated classroom? Future research on this topic would be strengthened by broadening the participant base in terms of numbers of students and teachers, as well as including a broad range of geographic locations.

5 Conclusion

This study broke new ground by exploring both academic and social impacts of background noise on this vulnerable group of children, and by involving teacher informants, who were very knowledgeable about both the classroom setting and their DHH students. The overall findings of the study underscore the negative pervasive effect of moderate and high levels of background noise on the DHH students' daily experiences in school, at the elementary school level. Negative impacts were most strongly perceived in large spaces, unstructured activities, and in conditions of high levels of background noise. Difficulty in understanding teacher instructions; participating in noisy group activities; and joining in easily accessible, reciprocal conversations with peers were among the most serious challenges to DHH students' academic and social experiences. Students responded to communication barriers from background noise with frustration, anger, and often with social withdrawal. All of these reactions resulted in negative impacts on their academic performance and social interactions with peers. The findings emphasize the pressing need for acoustic standards in elementary school classrooms.

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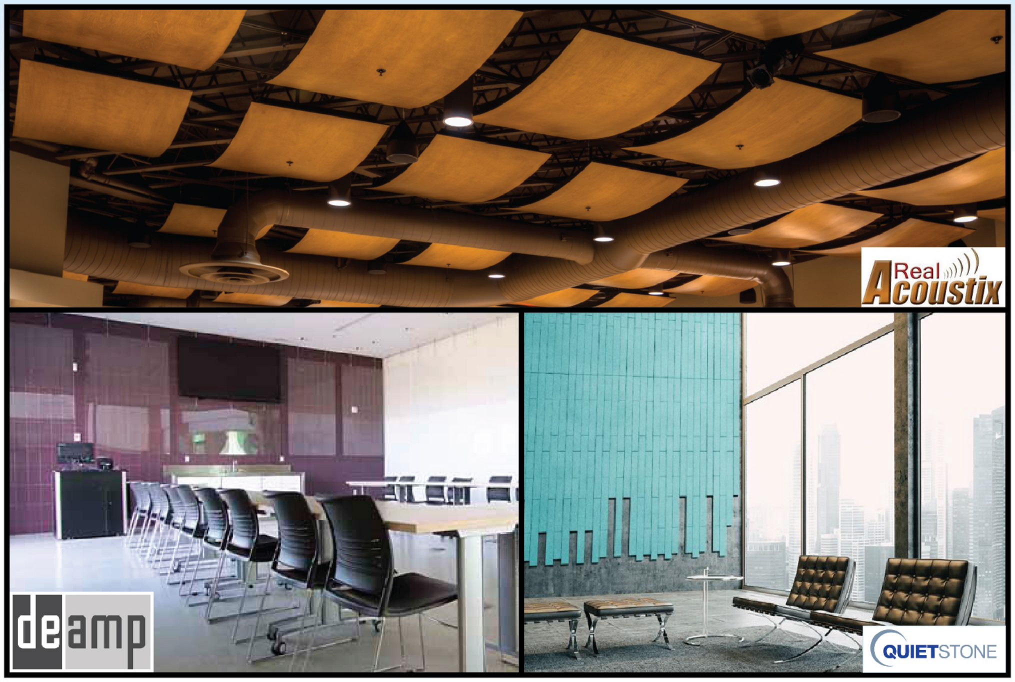
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SPEECH-IN-NOISE RESEARCH: FROM CIVILIAN TO MILITARY OPERATIONAL ENVIRONMENTS

Ann Nakashima
Defence Research and Development Canada, Toronto Research Centre, Toronto, Ontario, Canada

Résumé

L'importance de l'intelligibilité de la parole dans les environnements d'apprentissage et de travail est soulignée par l'abondance de recherches effectuées sur l'acoustique des salles et sur la communication auditive. En plus des facteurs environnementaux tels que le bruit de fond et la réverbération, il est également nécessaire de prendre en considération les facteurs individuels, tels que la perte d'audition, le port d'appareils auditifs et de dispositifs de protection de l'ouïe, ou encore les compétences linguistiques. Les études antérieures dans ces domaines ont fourni une base de connaissance pour l'étude de la communication dans les environnements complexes très bruyants. Pour les membres de Forces armées canadiennes, les hauts niveaux de bruit dans les aéronefs, les véhicules blindés et les navires militaires exigent l'utilisation de protecteurs auditifs et de systèmes de communication. Dans cet article, nous examinons certains des défis associés à la communication dans les environnements opérationnels et comment les tests de parole dans le bruit sont adaptés au contexte militaire. Les similitudes et les différences entre la recherche portant sur la communication auditive dans les salles de classes, les environnements civils et militaires sont également abordés.

Mots clefs : bruit militaire, communication auditive

Abstract

The importance of speech intelligibility in learning and occupational environments is evidenced by the abundance of research in room acoustics and auditory communication. In addition to environmental factors such as background noise and reverberation, individual factors including the presence of hearing loss, wearing of hearing aids and hearing protection devices (HPDs) and language proficiency must be considered. Previous work in these areas has provided a foundation for the study of communication in complex, high noise environments. For Canadian Armed Forces (CAF) members, the high noise levels inside aircraft, armoured vehicles and sea vessels demand the use of HPDs and integrated radio communication systems. In this paper, we review some of the challenges associated with speech communication in military operational environments and how speech-in-noise testing is adapted for military relevance. Similarities and differences amongst auditory communication research in classrooms, occupational and military environments will be discussed.

Keywords: military noise, auditory communication

1 Introduction

Noisy environments are inherently difficult for speech communication. In searching the literature for strategies to deal with speech communication in noise, there is a large body of research on speech in classrooms. Noise levels and their impact on students and teachers have been studied in a full range of educational levels from pre-school to university [1-3]. In addition to causing communication problems, noise adversely affects the recall of text and word comprehension [4], which has a negative impact on learning. Classroom noise also has adverse health effects on teachers relating to hearing loss and mental health [2] and voice problems [5]. Typical solutions that are recommended for classrooms are to decrease the room volume and/or add sound-absorptive materials, which have the effect of reducing the reverberation time and the speech-to-noise ratio (SNR) in the room [6]. Since the proximity of students (listeners) relative to the noise sources is also relevant, listeners and workstations should be moved away from noise sources such as heating, ventilation and air conditioning (HVAC) outlets.

In many occupational settings, it is not possible to change the environment or move away from noise sources, yet speech communication is critical to job function. In a comprehensive summary of hearing-critical tasks and noise environments of law enforcement and public safety workers, it was concluded that the primary functional hearing ability was speech communication, while the primary interfering factor was noise [7]. It was found that in most of the environments, the likelihood of effective speech communication was less than 0.5 for normal voice levels, and communication at distances greater than 5m was unlikely [7]. In high-noise environments, effective communication can only be achieved through the use of communication headsets.

Even in environments that are acoustically well-designed for speech, or when communication headsets are

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[*] ann.nakashima@drdc-rddc.gc.ca

used, individual factors play a significant role in effective communication. Listeners with hearing impairment (HI) have more difficulty with speech understanding in low SNR and higher reverberation conditions than those with normal hearing [8]. Industrial workers with hearing loss worry about safety and job performance, including the ability to communicate [9]. Non-native (L2) listeners are also at a disadvantage compared to native (L1) listeners for speech understanding in unfavourable acoustical conditions, which is possibly exacerbated by increased cognitive effort [10]. Recent work has shown encouraging progress in predicting the likelihood of effective speech communication for normal hearing and HI individuals [11], but to the author's knowledge, there is no analogous metric for non-native speakers.

Can the results of previous work on speech communication in classroom and occupational environments be applied in the study of military operational environments? In terms of the noise environment, there is little room to improve the acoustic conditions in military vehicles. In the tight confines of an aircraft cockpit, armoured vehicle or frigate control room, there is no space to move operators away from HVAC outlets and other noise sources. Hard, reflective surfaces and walls inside vehicles further elevate the noise levels. The issue of HI-speech understanding is critical since noise-induced hearing loss is common in military operators (MOs) [12]. Foreign accent and L2 listeners can adversely affect communication effectiveness, particularly in multi-national operations. This is a topic of a current North Atlantic Treaty Organization (NATO) Human Factors and Medicine working group (HFM-285). Although MOs anecdotally report fatigue from noise exposure, other operational stressors such as vibration are often present. These confounding factors make it difficult to attribute non-auditory performance decrements to noise exposure alone. Therefore, the acute and long-term cognitive and mental health effects of military noise exposure are not well-understood.

This paper discusses 1) the challenges for speech communication in military environments, 2) how speech-in noise testing is adapted for relevance to military settings, and 3) the common elements of speech communication in educational, occupational and military environments and future work.

2 Speech in military noise environments

2.1 Military noise levels

Sample noise levels that have been measured in Canadian Armed Forces (CAF) operational environments are shown in Table 1. At the lower end of the scale, frigate control rooms can be about 60 dBA during quiet watch, but can rise above 70 dBA during periods of high activity due to more occupants and more talking (louder voices) in the room [13]. Armoured vehicle noise levels range from 70 dBA while idling to as high as 115 dBA when moving at highway speeds with the hatches down [14]. Reported cockpit noise levels in military aircraft range from 95 to 105 dB [15], while one study of an RCAF Chinook helicopter reported cabin noise levels as high as 113 dBA with the door open [16]. Finally, MOs are exposed to high levels of impulse noise from weapons. Small arms fire has been measured at around 150 to 170 dB peak at shooting ranges [17] while artillery noise can exceed 180 dB peak [18]. Given these ambient noise levels, unaided speech communication would only be possible in frigate control rooms. Communication headsets are required in most military operational environments.

Table 1: Sample noise levels in CAF environments.

Environment	Average or range of noise levels
[13]Frigate (bridge)	62 – 70 dBA
[13]Frigate (operations room)	65 – 75 dBA
[14]Armoured vehicles	70 – 115 dBA
[15,16]Aircraft	95 – 113 dBA
[17]Rifle shooting range	150 – 170 dB peak

2.2 Auditory workload

MOs often experience high auditory workload, owing to high ambient noise, face-to-face conversations and traffic from multiple radio networks. A recent communication study on a Canadian Patrol Frigate identified 25 different shipboard voice networks, with the operators concurrently monitoring 2.5 networks on average, in addition to face-to-face interactions with their collaborators. Of the factors that negatively influenced communication effectiveness, noise was most frequently reported, followed by the need to talk to multiple people or monitor multiple networks concurrently. Level-dependent earplugs were suggested for MOs who communicate face-to-face in moderate levels of noise, in order to facilitate communication while reducing noise annoyance [19]. Adding a visual element to an auditory message, e.g., text on the screen, can be helpful in improving the accuracy of coding messages correctly [20, 21]. Unfortunately, these strategies can be difficult to implement in command posts where the MOs are already monitoring multiple screens.

2.3 Hearing thresholds

The CAF Medical Standards document categorizes hearing ability of MOs from H1 (best) to H4 (worst) based on pure-tone audiometric thresholds as shown in Table 2 [22]. All Military Occupational Structure Identifications (MOSIDs) require hearing H3 or better, with some requiring H2 [22]. Importantly, the requirements for H2 and H3 are outside of the limits for normal hearing [23], and it is recognized that CAF members in these hearing categories typically have significant high-frequency hearing loss. Such hearing impairment could be a substantial barrier to speech communication in operations. A previous focus group study found that MOs would rely on younger members, presumably with better hearing, for confirmation of commands [24]. Although MOs believed that the use of hearing protection devices (HPDs) could reduce hearing loss, their use was inconsistent in practice [24]. The hearing ability of MOs and use of HPDs must be considered when designing studies of speech understanding in noise.

Table 2: CAF hearing categories [22].

Category	Required Hearing Level
H1	≤ 30 dB HL from 500 to 8000 Hz, both ears
H2	≤ 30 dB HL from 500 to 3000 Hz, both ears
H3	≤ 50 dB from 500 to 3000 Hz, either ear
H4	> 50 dB from 500 to 3000 Hz, either ear

3 Speech-in-noise tests for military

3.1 Choosing a test

One reason for using speech-in-noise tests is to assess an individual's functional hearing for their job, which has also been called auditory fitness for duty (AFFD). Assessment of speech understanding in noise is particularly important if a hearing loss is indicated on the audiogram. In the United States, Army members with H3 hearing are tested using the speech recognition in noise test (SPRINT) [25]. It is noted that H3 for the US Army is described as "speech reception threshold in best ear not greater than 30 dB HL, measured with or without hearing aid [26]," which is different from the CAF definition shown in Table 2. The SPRINT uses pre-recorded monosyllabic words in multi-talker speech babble, and has recently been implemented in a shortened form to improve efficiency for clinical use [25]. However, its use in future functional hearing assessment is unlikely due to its open set response (verbal response that is marked subjectively), which cannot be automated [25]. A possible alternative is the matrix test, which uses sentences comprised from a closed set of words from fixed categories. It is an automated test that has been implemented in many different languages, making it accessible for international use [27].

For the CAF, it is critically important to have equivalent tests in English and French. The hearing in noise test (HINT) has been adapted for Canadian Francophone populations, and it has been used successfully for personnel in police, coast guard and other public safety services [28]. Possible drawbacks for widespread use of the HINT across the CAF are the required clinical setup and administration time. The Canadian Digits Triplet Test (CDTT) is potentially very useful because it is bilingual, can be administered quickly, and does not require an audiometric booth [29]. Previous research has shown that the Digit Triplet Test in other languages is sensitive to high-frequency hearing loss [30], which could be useful as an early indicator of hearing loss.

The coordinate response measure (CRM) is a speech corpus of phrases consisting of a call sign, colour and number (e.g, "Ready baron, go to blue five now") [31]. The CRM has been implemented for research in multi-talker environments. This is useful for studying speech understanding in noise with multi-channel communication headsets, which is discussed in the next section.

3.2 Speech understanding with hearing protection and communication headsets

Aside from evaluating the unaided, unoccluded functional hearing of an MO, another question is whether or not an acceptable level of performance can be achieved when using a particular HPD or communication headset. While people tend to raise their voices in noise (Lombard effect), perception of own voice is different when wearing a HPD; the occlusion effect causes differences in speech level production and fundamental vocal frequency [32]. Therefore, the speech-to-noise ratio (SNR) that is required at the listener's ear might be different when wearing an HPD or headset compared to unoccluded. When using communication headsets, users are able to adjust the volume to their preferred level. In environments with lower background noise, such as frigate control rooms (see Table 1), it is possible and necessary to have face-to-face communication within the room. However, when the MOs are not co-located or the background noise levels are too high, noise-reducing communication headsets must be worn. While communication headsets facilitate speech understanding by feeding the radio channel directly to the ear, the additional contribution from the radio must be considered for consideration of noise exposure. A previous study of communication headset use in occupational settings found that users adjusted the radio volume at an average effective SNR of 13.7 dB, after accounting for the attenuation of the headset [33].

When considering speech understanding with communication headsets, it is reasonable to look to a standard for guidance. The American National Standards Institute/Acoustical Society of America (ANSI/ASA) S3.2, Method for Measuring the Intelligibility of Speech over Communication Systems allows for three sets of test material: phonetically balanced word lists, the modified rhyme test, the diagnostic rhyme test. It states that test participants must be audiometrically normal, with required hearing levels of ≤ 20 dB HL from 125 to 8000 Hz. As discussed in Section 2.3, many CAF members would not meet this hearing requirement. In addition, for complex listening environments, such as monitoring multiple radio networks in a command post, simple word recognition might not be a good indicator of ability. The CRM has been implemented in diotic and dichotic listening conditions where the participant was required to respond by pressing the correct key sequence (e.g., blue, five) rather than repeat what was heard [20, 21]. Distractor tasks and audio-visual presentation of the command were also used. It was found that visual cues help [20] and there was a slight advantage for messages presented to the right ear [21].

While the CRM studies mentioned above looked at performance as the percentage of correct responses, performance is also measured by determining the SNR at which 50% of the words are correctly identified; this is called the speech-reception threshold (SRT). Since performance on speech-in-noise tests depends highly on the choice of speech material and type of noise, it is useful to compare the relative SRT of HI, L2 listeners to normal-hearing, L1 listeners for a given test. A previous study found that listeners with varying levels of HI required SRTs of 4 to 10 dB higher than normal-hearing listeners across different speech-in-noise tests [35]. It has also been reported that non-native speakers, even if fluently bilingual, require higher SRTs than native speakers [36], and obtain lower scores on fixed SNR tests [37]. HI and L2 listeners have greater difficulty with speech understanding while wearing HPDs than normal-hearing listeners and L1 listeners [38-40].

3.3 Interference caused by personal protective equipment

Since environmental hazards for military personnel are not limited to noise, HPDs are often worn in combination with other types of personal protective equipment (PPE). Flight helmets are typically designed for HPDs because of the integrated communication requirement. For other types of helmets, HPDs are designed to be mounted on them. Such integrated PPE combinations are easily tested. However, other types of PPE might not be designed for optimal hearing protection and communication. Balaclavas that would be worn in cold environments have been shown to reduce the attenuation of an earmuff worn in combination. Although consonant perception in quiet was not affected by the balaclava, speech-in-noise and sentences were not tested [41]. Reduced speech understanding has been shown for respirators and safety glasses that are worn in toxic environments [42].

3.4 Beyond speech-in-noise tests

There are other aspects of situational awareness aside from speech communication that are critical to the effectiveness and survival of MOs. Detection, recognition and localization of sounds, especially warning sounds, are important aspects of functional hearing [43]. While outside the scope of this paper, recent work on AFFD is well described elsewhere [7, 11, 44].

4 From civilian to military operational settings

On the surface, there appear to be few similarities for speech communication in classrooms, civilian occupational and military environments. Although the environments, noise levels and auditory tasks are different, the common element is the human. Whether conducting research for face-to-face or radio headset communication, the human factors that have been considered across these environments include:

- HI talkers and listeners;
- L2 talkers and listeners;
- Noise interference (background noise, competing talkers);
- Cognitive effort.

Research on HI-participants in classrooms includes hearing aid and cochlear implant users, which is different from military populations with noise-induced hearing loss (NIHL). Similarly, AFFD with hearing aids for civilian occupations [45] is not relevant to MOs who work in noisy environments, where the use of hearing aids is contraindicated due to interference with HPDs. However, the non-native communication literature is much larger for classroom and civilian settings than for military environments. Previous work suggests that cognitive load could be especially high for L2 speakers who learned after early childhood [46], which is likely more typical for MOs. Training and other methods to improve L2 speech understanding in noise should be investigated further.

To the author's knowledge, listening effort and the associated cognitive load have not been thoroughly investigated in military operational settings. Effortful listening is described as "the deliberate allocations of mental resources to overcome obstacles in goal pursuit when carrying out a (listening) task" [47]. A recent paper has provided a framework for understanding effortful listening (FUEL), which could be useful in designing studies for complex environments [47]. Listening effort has been previously measured through dual-task paradigms [48] and more recently through pupillometry [49].

5 Conclusion

The typical solutions for improving speech understanding in noise cannot all be transferred from civilian to military settings. In particular, it is not feasible to fix the acoustical environment or gain distance from noise sources in order to improve communication effectiveness. However, the use of modern communication headsets and adaptation of speech-in-noise tests have enabled progress in the military context. To better understand the individual factors that affect communication, further research on HI and L2 speech understanding, and their relationship with cognitive effort, will benefit workers in all environments.

Acknowledgments

This paper was written as a special tribute in memory of Professor Murray Hodgson, his work, and the work he inspired. The author wishes to express her heartfelt appreciation for Professor Hodgson's mentorship and friendship.

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RESEARCH TRAJECTORIES IN CLASSROOM ACOUSTICS: INVESTIGATING CHILDREN PERCEPTION BEYOND TASK PERFORMANCE

Nicola Prodi[*] **and Chiara Visentin**[†]
Dipartimento di Ingegneria, Università di Ferrara, Ferrara, Italy

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Résumé

L'acoustique des salles de classe a été un sujet de recherche pendant des décennies et suscite toujours l’intérêt des scientifiques en raison des multiples aspects impliqués, allant des problématiques autour de l’auditeur, comme les compétences cognitives, à la conception acoustique de la pièce ou l’influence du bruit ambiant sur l’orateur. Le professeur Murray Hodgson a été une personne clé dans ce domaine, et ses recherches ont été une source d’inspiration pour la communauté scientifique, et en particulier pour les auteurs de ce papier. Dans cette étude, il est d’abord discuté que les indicateurs acoustiques objectifs permettant d’obtenir une intelligibilité de la parole adéquate dans une salle de classe ne permettent pas de discriminer des conditions d’écoute perçues différemment par les sujets. Pour cette raison, une évaluation supplémentaire a été développée, basée le concept d’«effort d’écoute» issu de l’audiologie. La méthode est implémentée par une des mesures indirectes de l’effort d’écoute, qui est le temps de réponse au stimulus auditif. Le présent travail est un état de l’art des principaux résultats obtenus quand l’approche a été appliquée à plusieurs problèmes en lien avec l’acoustique des salles de classe.

Mots clefs : acoustique des salles de classe, bruit, intelligibilité de la parole, temps de réponse

Abstract

Classroom acoustics has been a topic of research for decades and still attracts the interest of scientists because of the many aspects that are involved, which range from listener-centered issues such as cognitive proficiency to the acoustical design of the room and also to the speaker’s voice alterations in noisy conditions. Prof. Murray Hodgson has been a key person in the field and his findings have inspired many others that followed, including the present authors. In this work it is firstly discussed that the objective acoustical indicators whose provision warrants suitable speech intelligibility in the classroom are not able to disentangle listening conditions which are perceived and rated differently by the listeners. For this reason an additional assessment has been developed based on the audiologically–oriented concept of “listening effort”. The method is implemented by means of one of the proxy measures of listening effort that is the response time to the auditory stimulus. The present work reviews the main results obtained when the approach was applied to several problems related to classroom acoustics.

Keywords: classroom acoustics, noise, speech intelligibility, response time

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Foreword

During the year 2003 a short course on classroom acoustics was held at the University of Ferrara, Italy, where prof. Murray Hodgson was invited to present his findings. It was a special occasion to discuss open problems and share views with him. He was a leading expert in the field and the topic was having a revival in Italy. In fact many complaints had been raised on the inadequacy of the acoustical environment inside classrooms. In addition measurement campaigns had already confirmed the prevalence of poor acoustics in the large majority of the school buildings. In the discussion it was a shared view that research should have guided a process of improvement of classroom acoustics and it should have provided insight into the many aspects that make up the impact of acoustics on the learning process.

These were the first moves of a research trajectory that was clarified in the years to follow and that is still under development. The present work is primarily an account of the work done so far by means of a review of the main published works. Although the work does not add new results to the already disseminated literature, it is primarily intended as a resume of the path whose start dates back to the meeting with Prof. Murray Hodgson.

1 Introduction

The literature on the topic of classroom acoustics in the mid years 2000 was already rich and comprised several types of studies covering a large set of chronic and acute problems that can be roughly listed as:

A) Epidemiological studies on the effects of noise emitted by transport infrastructures on the academic achievements of the exposed students, with few longitudinal assessments;
B) Studies that investigated the link between internal classroom acoustics and verbal communication;

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[*] nicola.prodi@unife.it
[†] chiara.visentin@unife.it

C) Studies on specific issues (data collection, simulation and assessment, interventions and acoustical treatments);
D) Studies on cognitive mechanisms, hearing impairment and various types of interactions.

In addition, also very accurate reviews were available that resumed the state-of-the-art knowledge [1, 2] (later on the more cognitive-oriented review of Klatte et al. [3] came up). Moreover at that time in North-America the interest in the topic was high and for instance the Acoustical Society of America (ASA) had revised its guidelines [4]. As a backing to these activities several studies investigated the limits of objective indicators in order to achieve optimal conditions (such as [5] and later [6]).

Assessing the acoustical conditions in the real classrooms of primary schools by measures with the latest technical means was deemed a good starting point also in the local Italian studies [7], together with the attempt to set acoustics in the context of the overall comfort in schools [8]. A first outcome was apparent: several noises could provide the same intelligibility experimentally, but they were perceived differently. Thus they had a peculiar impact of the communication process, and hence probably on learning. More generally, already in the literature [9] it was found that the same intelligibility could give raise to a broad subjective evaluation of listening difficulty. Objective qualification was not able to describe these facts even with speech indicators such as the Speech Transmission Index (STI) [10].

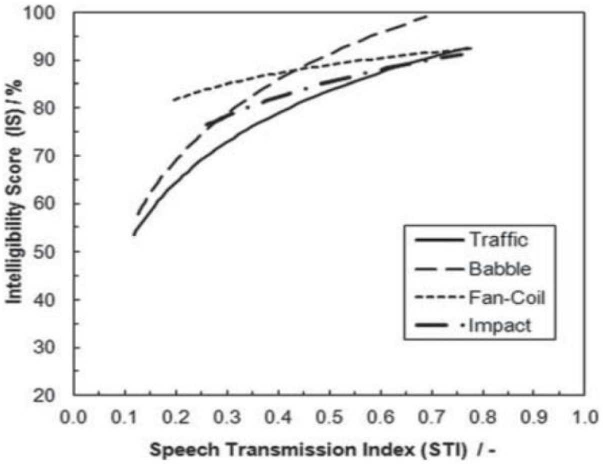

Figure 1 (from [7])**:** Measured speech intelligibility scores of pupils under several types of background noise tracked by the STI. A range of ambiguity starts from STI=0.5 on.

At that point the examination of the literature told that the limits of the acoustical qualification of classrooms were still serious. First, based only on the current acoustical indicators, the design of classrooms was not sufficiently refined to warrant at once high performance and comfortable listening conditions for pupils. In fact their intelligibility depended on the type of noise and, moreover, the threshold values defined for the acoustical parameters were fit for adults but not necessarily for children. Second, beside speech recognition also listening comprehension should be addressed in classrooms; however, this aspect was not under control of the conventional metrics. Third, other tasks besides linguistic ones may be impaired by the presence of adverse acoustic conditions, for instance the tasks related to reasoning and mathematics. No indication was available to control for that.

Despite several other unclear aspects had been raised in the literature, in this context the most urgent issue to address was deemed the first listed above. This involved improving the means of qualification and design of classrooms by going beyond the speech reception performance.

2 Speech reception beyond task performance: which direction?

Given the limits of the current objective indicators enforced in the standards it appeared that some important mechanisms underpinning speech reception could not be captured properly causing an unpredictable outcome, especially for students at disadvantage. Several studies [11, 12] replaced speech intelligibility with accuracy in task-specific tests and the effects on attainments were confirmed [13], but the methods were not easily adaptable to be used in the design and evaluation of remedies. So, an alternative solution should be searched for.

Cognitive psychologists discussed that listening «easily» at school is an essential pre-requisite to learning [14]. This happens because only when listening is not a difficult task there are cognitive resources available for further processing of the input information; those steps of learning requiring more cognitive load are thus facilitated. So, the problem could be theoretically turned back into a listening-related one, with a focus on the “ease” of listening and not just on the task performance. To develop this idea a basic approach could be borrowed from the field of audiology. In fact in that area the conditions of effortful listening were an increasingly urgent topic of research. A consensus definition of “listening effort (LE)” was outlined only much later [15] by resorting to psychophysics theoretical models of capacity and attention. LE depends on input demands, capacity and on their interplay, and it is influenced by unconscious and intentional attention. Moreover, LE is a complex and multi-faceted construct which is not possible to uniquely quantify with a single measure.

Several methods to grasp aspects of LE were already available. They could be divided into three broad typologies: subjective (e.g., self-ratings of effort), physiological (e.g., pupillometry, skin conductance, saliva cortisol etc...), behavioral (e.g., dual-tasks) methods [16, 17]. In particular one of the oldest behavioral quantities proposed in the literature is the response time (RT) [18]. This measure can be implemented in dual-task or in single task experimental paradigms. In the latter case, the RT to the auditory stimulus is used: it is defined as the time elapsed from the end of the presentation of the stimulus to the response given by subject, either verbally or manually. RT is not an estimate of LE, but it is a measure of speed of processing. By construction, it is assumed that an increase of RT is associated to an increase of LE. A fairly large number of studies used it with profit in auditory experiments since it is relatively easy to collect, but data need careful handling to deal with inter and intra-subject variabilities.

In the above process of development the first step was thus to implement a mixed measurement process where the task was one (speech reception) and the measures retrieved were two, performance and response time.

3 First application in a virtualized classroom

Binaural impulse response measurements were taken inside two identical classrooms ($V=250m^3$) which were close one another. One of them was treated with sound absorbing ceiling tiles while the other was not [19]. The rooms had both 24 desks with chairs for pupils and a bigger desk with chair for the teacher. They had a large window on one lateral wall. Their furniture consisted in two closets and few posters. Background noise was also sampled during the acoustical measurements and consisted in activity noise from occupants and babble noise from the adjacent corridor. Various combinations of reverberated target signal and noise were rendered under controlled conditions (unoccupied untreated, A; occupied untreated, B; occupied treated, C). The rendered sound fields had signal-to-noise ratios equal to 0, 6 and 12 dB. Diagnostic Rhyme Tests were proposed to 80 normal hearing pupils from III, IV e V grades (8-10 years) and to 42 normal hearing adults.

Analysis of variance (ANOVA) was used for the statistical analysis; the *p* value at the level of 0.05 was the statistical tool to test the significance of the effects. When ANOVA was applied to the speech intelligibility scores (IS) there was a non-significant difference between the grades ($p>0.05$) and a slight significant difference ($p=0.046$) between all pupils and adults. Moreover only condition C was disentangled statistically, but IS could not differentiate the other comparisons. When RT was analyzed two facts become evident: the indicator was very correlated with IS but it was able to resolve some of the previous limits. In fact at equal IS there were significant differences between grades III and V ($p<0.001$), III and IV ($p=0.02$), IV and V ($p=0.034$) and between all pupils and adults ($p=0.039$) (Fig. 2).

Therefore, it was decided to combine the two metrics into a single indicator being their ratio. This responded to two instances: first, making the method of assessment more compact and second, framing the method into the psychophysics concept of cost. In fact, in the area of psychophysics it is not unusual to define the ratio of a performance measure to the time needed to achieve it as the "cost" or "efficiency" of the related process [20]. By using this analogy the ratio of IS versus RT, termed "listening efficiency (DE)", was by definition the number of items correctly recognized per second (units [s^{-1}]).

The quantity was employed to analyze the same data set and provided further insight into the bias of performance between pupils and adults. In particular it was found that the room-acoustical criteria developed for adults may cause a severe underperformance of pupils, which could be quantified as equal to nearly 0.1 STI units, or 0.2 s^{-1} in listening efficiency terms. Said it more practically, in the above experiment the gap would be equivalent to a loss of an additional entire item (a disyllabic word in this case) every five seconds employed in the speech recognition process.

4 Studies in real classrooms

Later on studies considered real classrooms. A first study had the twofold aim of ranking harmful noises in the classroom and of better detailing the performance with age. The work involved as much as 741 pupils distributed over 47 classes at six primary schools. A test bench was developed so that an entire class could be tested at once inside their classroom. The target signal and the noises were played back through separate loudspeakers. Three types of noises were included, that is "babble and activity" – A, "tapping" – Tp and "traffic" – Tr. As in the previous studies a speech recognition test was used. The signal-to-noise ratios were fixed at 0, 6 and 12 dB and, depending on the noise type, the level of the target signal was set at 60, 66 or 72 dBA at 1 m in front of the loudspeaker. Each pupil was equipped with a touchscreen smartphone to collect responses. The test lasted approximately 45 min. A dedicated statistical procedure was set up to compare the noises. It was based on the aggregation of the data into separate strata corresponding to the rating intervals of the STI.

While taken separately, both IS and RT could not achieve a fully unambiguous ranking of the noises. On the contrary, when using DE the full ordering of the noises was statistically significant. The result was driven by the better listening conditions; it was found that the A noise was the less efficient, followed by Tp and Tr in succession (Fig. 3 and Tab. 1).

Within the same study, it became evident a developmental effect on RT, since older pupils were always faster to respond than the youngest pupils, even in quiet conditions.

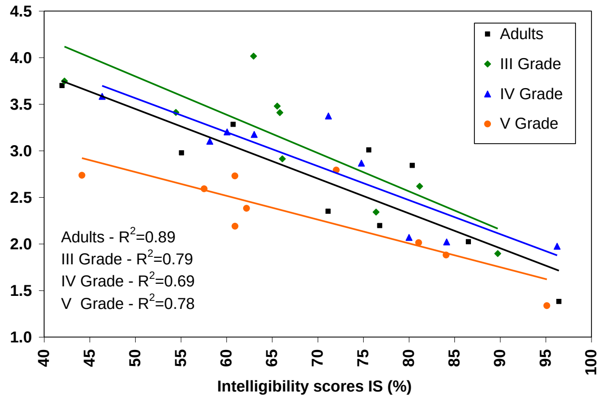

Figure 2 (from [19]): Plot of response times values mapped to intelligibility scores for different grades and adults. The correlations are statistically significant. The previous results outlined that RT could add useful information beyond IS results.

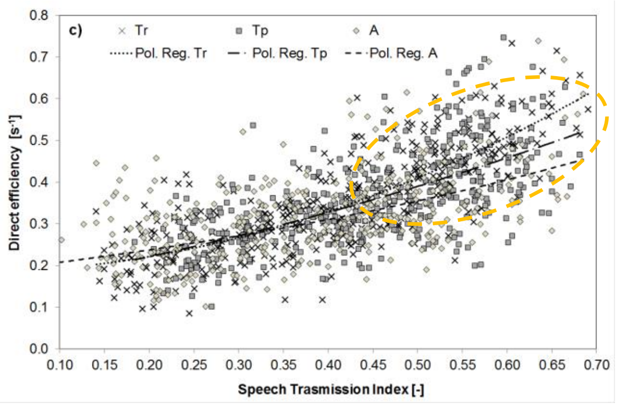

Figure 3 (from [21])**:** Plot of the listening efficiency DE values from a large field experiment. Tr : traffic noise ; Tp : tapping noise ; A : activity noise. The polynomial regression curves for the three noises are included.

Table 1: Using DE in the ranking of noises inside real classrooms. Output of the statistically verified inequalities between the different noises in the case of the Diagnostic Rhyme Test for the three grades III, IV and V. The "Fair" and "Good" rating intervals mostly contribute to the assessment.

Test	Grade	Strata				All	Fair & Good
		Bad	Poor	Fair	Good		
DRT	III	A=Tp=Tr	A=Tp=Tr	**A<Tp=Tr**	**A=Tp<Tr**	**A<Tp<Tr**	**A<Tp<Tr**
	IV	A=Tp=Tr	A=Tp=Tr	**A<Tp**	**A=Tp<Tr**	**A<Tp<Tr**	**A<Tp<Tr**
	V	**Tr<Tp=A**	A=Tp=Tr	**A=Tp<Tr**	A=Tp=Tr	**A<Tp=Tr**	**A<Tp<Tr**

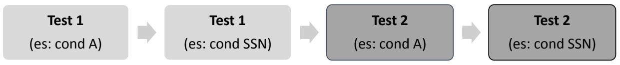

Figure 4 (from [25])**:** Outline of the succession of the tests between the first and the second part of the experiment. The experiment lasted 15 to 30 mins.

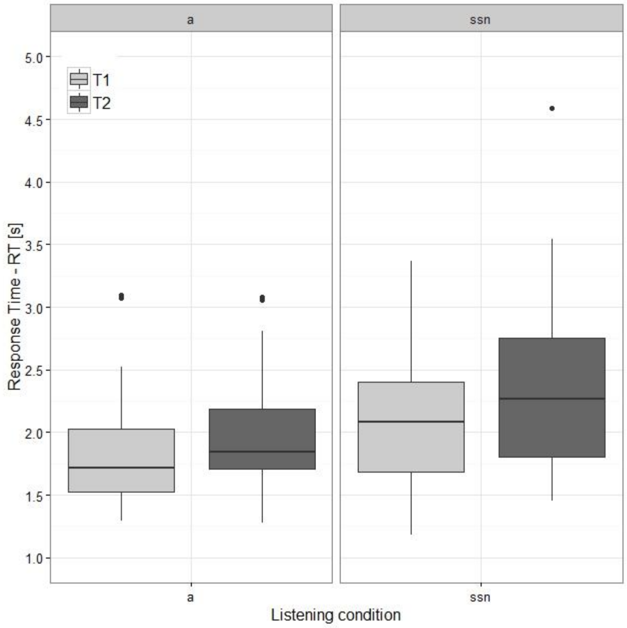

Figure 5 (from [25]): Values of RT obtained for the 7 years old pupils. Conditions are quiet (a) and speech spectrum noise (ssn). RT is significantly higher in the repetition only in the presence of noise.

Such age proficiency was controlled for and finally it could entirely account statistically for the age effect found in the tests.

Data so far always considered the mean values of the quantities over a set of trials that span along the test duration. Such analysis could not depict the eventual changes of performance during a real lesson of approximately 45 minutes. On the other hand, hints were given that performance could have not been stable during the lesson. In fact, during private communications, often teachers outlined a loss of performance during lessons due to a continuous noise.

The subset of data for 8-10 years old pupils was used in [22] to address this issue. It was found that during a lesson period only older pupils' performance changed. In particular, when the acoustical conditions were more favorable, they suffered a decrement of performance.

This loss occurring in more favorable acoustics could not be firmly ascribed to eventual "fatigue" occurring to children during the lesson. In fact the construct of "fatigue", which differs from LE, needs dedicated evaluation methods as pointed out in specific studies [23, 24], and RT measures alone are not entirely appropriate for the scope.

Anyhow, the changes of performance during a lesson period highlighted by the study told that LE could be modulated by noise and age and thus needed confirmation with a dedicated data set, and for younger pupils too.

For this reason later on a specific investigation [25] addressed the impact of noise over the lesson period by splitting it into two equal parts and by running the same tests twice (Fig. 4). A quiet condition and one with a speech shaped stationary noise were used. Pupils aged 5 to 7 years took part in the experiments which consisted in With Picture Identification Tests (5 years) and Diagnostic Rhyme Tests (6 and 7 years). The tests were conducted inside their classrooms with the same apparatus as in prior studies.

Although the results for the 5 years old pupils were mixed, those for the 6 and 7 years old were clear and consistent between the two groups.

The IS showed a main effect of noise (p<0.001) but nothing more. On the contrary, RT showed a significant effect of noise (p<0.001), an effect of test repetition (p<0.001) and an interaction of the two (p =0.002). In Fig. 5 the results for the 7 years old pupils are shown. The meaning is that the effect of noise is relevant in the repetition only, and that it happens while the IS are still unaffected.

5 Using response time in the acoustical design

The studies so far proved that RT is sensitive to several relevant issues of speech perception in rooms for younger pupils. Then one of the original questions could be raised: is it possible to employ the concepts above during acoustical design? Said it differently, is such indicator also sensitive to changes of the room acoustics, such as shape and properties of materials? Should this be the case, RT would have potentials in directing the acoustical design towards less effortful listening and hence to a more learning-oriented one. This was the main question of a successive study [26] that employed a mix of field and auralized experiments. In this case university students of Italian and German mother tongue were recruited.

They performed tests first in a real classroom which was a box-shaped room with a volume of 197 m^3. It had flat surfaces apart the lateral partition with the adjacent corridor which was acoustically treated with a sound absorbing paneling. The classroom was furnished with wooden desks and chairs and hosted a maximum of 25 students. Then an auralized version of the same space was developed where either the sound treatment was removed or the volume was doubled. As always done in similar experimental designs, in order to minimize learning effects and to familiarize the participants with the test procedure a set of trials was proposed before the test in the real classroom took place.

RT was capable of detecting the changes, while IS were largely unsuccessful (Fig. 6). Moreover, RT proved more reliable than a subjective assessment, mainly because the anchors that the two groups employed were likely to differ in a relevant manner.

In the same study the metric RT was validated between field and auralized tests. This step allowed taking RT in the virtual field as an indicator of effort during listening in the corresponding real space.

6 Addressing second language learners

A successive investigation [27] was accomplished at UBC Vancouver with the direct participation of Prof. Hodgson. The study regarded the so-called English second language students (L2) that is those who went to Canada from non-English speaking Countries. In particular impulse responses in a real classroom were used to create reverberated conditions and recorded noises were added at various signal-to-noise ratios. The tests took place in an anechoic chamber and the panel included both mother tongue L1 (13) and L2 (24) listeners. Given the L2 disadvantage already reported in the literature for worse acoustical conditions, the sound fields were set to provide near ceiling IS (i.e. close to 100%).

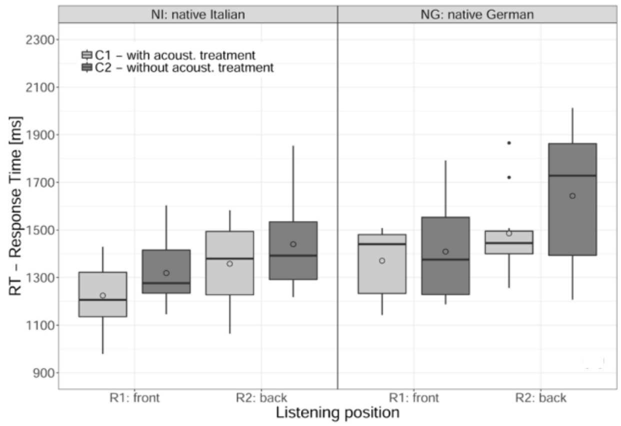

Figure 6 (from [26])**:** Values of RT obtained for native Italian and native German students. Front and back positions in a virtual classroom with and without sound absorbing treatment.

The first condition was anechoic; the other two shared the same value of STI=0.57 but the former had reverberation only, while the latter had some added noise.

The results of IS confirmed no significant effect neither of condition nor of groups and no interaction between the two variables. On the other hand, when RT was analyzed (Fig. 7) there were two main effects of listeners' group (p=0.02) and listening condition (p<0.001) but there was no interaction between the two variables.

The data showed that L2 were always at a disadvantage compared to their L1 peers. The absence of interactions witnessed that such gap between the groups did not depend on room acoustics but on more fundamental internal processing.

7 Concluding remarks and future directions

The research trajectory that was exposed in this work took its first moves in the early years 2000 and thanks to the suggestions and discussions that on many occasions the authors had with Prof. Hodgson.

The data accumulated so far in diverse scenarios and with different panels of users do confirm that RT is a sensitive quantity that can output information not accessible with accuracy measures. In particular environmental variables such as the type of noise and room acoustics have been reflected in the results. Several additional variables can be included for instance by altering the characteristics of the speaker, those of the listener and finally the transmission path between the two. It is believed that the method could display a benefit when applied to numerous practical applications encompassing both the perception of speech in room acoustics and the audiological fields where it was firstly introduced. In agreement with the initial intentions, one of the most relevant fields of application is the design of rooms for speech in order to provide conditions where listeners can be highly efficient in the listening task.

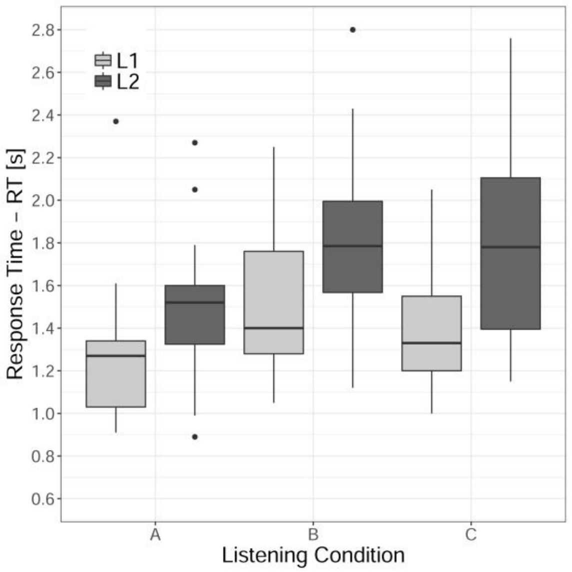

Figure 7 (from [27])**:** Values of RT obtained for L1 and L2 across the three acoustical conditions. A: anechoic; B: reverberated only; C: reverberated with noise.

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SoundAdvisor Model NMS044

ACOUSTIC TREATMENTS AIMING TO ACHIEVE THE ITALIAN MINIMUM ENVIRONMENTAL CRITERIA (CAM) STANDARDS IN LARGE REVERBERANT CLASSROOMS

Umberto Berardi *1, **Gino Iannace** †2 **and Amelia Trematerra** ‡2
[1] Department of Architectural Science, Ryerson University, Toronto, Ontario, Canada.
[2] Università degli Studi della Campania « Luigi Vanvitelli », Borgo San Lorenzo Aversa (Ce), Italy

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Résumé

Une législation italienne récente a établi les critères environnementaux minimaux (CAM) pour tout environnement de travail. En ce qui concerne les écoles, des objectifs de confort acoustique adéquat sont requis en termes de contrôle du bruit et de qualité acoustique. Les écoles doivent se conformer à la norme UNI 11532 pour la durée de réverbération (T), la clarté (C50) et l'intelligibilité de la parole (STI). Dans les salles de classe, les valeurs suivantes sont requises : T <0,7 s, C50> 0 dB et STI> 0,6. Dans les installations sportives telles que les gymnases ou les piscines, les exigences CAM sont T <1,5 s, C50> -2 dB et STI> 0,5. Pour atteindre ces objectifs, l'insertion de traitements acoustiques est souvent inévitable. Les acousticiens utilisent couramment la théorie du champ parfaitement diffus pour calculer la quantité de matériau absorbant nécessaire pour se conformer à la législation en vigueur. Le but de ce travail est d'évaluer l'emplacement optimal d'une quantité minimum de traitement absorbant permettant d'atteindre les CAM dans certaines classes de l'université. Ces salles de classe ont un sol en marbre et des murs en plâtre et, à 1,0 kHz, ont des valeurs T comprises entre 2,5 s et 4,5 s, C50 entre 3 dB et -0,5 dB et ST entre 0,34 et 0,47. À l'aide d'un logiciel acoustique, il a été possible d'estimer la quantité minimale et de placer de manière optimale les panneaux absorbants afin d'atteindre les CAM des salles de classe sélectionnées.

Mots clefs : salles de classe, clarté, temps de réverbération, intelligibilité de la parole, critères environnementaux minimaux italiens.

Abstract

A recent Italian legislation has established the Minimum Environmental Criteria (CAM) for any working environment. In regards to schools, adequate acoustic comfort targets are required in terms of noise control and acoustic quality. Schools must comply with the Italian technical standard UNI 11532 for their reverberation time (T), clarity (C50) and speech intelligibility (STI). In classrooms, the following values are required: T<0.7s, C50>0dB, and STI>0.6. In sports facilities such as gyms, the CAM requirements are T<1.5 s, C50> -2 dB, and STI> 0.5. To achieve these objectives, the insertion of acoustic treatments is often unavoidable. The new requests for classrooms are leading acousticians to propose sound correcting interventions in many educational buildings. Acousticians typically use the perfectly diffused theory to calculate the minimum amount of needed sound-absorbing material to comply with current legislation. The purpose of this work is to evaluate the optimal position in which to place the minimum amount of sound-absorbing treatments to reach the CAM in some university classrooms. These classrooms have a marble floor and plastered walls and, at 1.0 kHz, have T values between 2.5 s and 4.5 s, C50 between 3 dB and -0.5 dB, and STI between 0.34 and 0.47. Using an acoustic software, it was possible to estimate the minimum quantity and the optimal placement of the sound-absorbing panels to insert in each classroom to reach the CAM.

Keywords: classrooms, clarity, reverberation time, speech intelligibility, Italian Minimum Environmental Criteria.

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1 Introduction

In classrooms, non-optimal acoustic conditions negatively influence speech understanding and students' performance. Students who sit in the front rows, close to the teacher, better understand listen to the class than those students who are sitting in far back rows. It is common that in the back rows of large classrooms, the teacher's voice gets weaker and the excessive reverberation makes hard to listen clearly to it. The reverberation of a classroom has a negative effect on speech understanding, and this effect increases as the distance between source and receiver increases.

Many studies on excess reverberation in classrooms have been reported [1-6]. Some authors in Brazil have verified the acoustic quality of new schools by measuring different acoustic parameters. The effects of the distribution of spaces on acoustic comfort were also analyzed [1].

Other authors have studied the acoustics of the classrooms through the use of software, and have proved that the sound field in classrooms can be far from being perfectly diffused. Therefore, the Sabine diffused field

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[*] uberardi@ryerson.ca
[†] gino.iannace@unicampania.it
[‡] amelia.trematerra@unicampania.it

theory should not be applied in classrooms without critical analysis of the specific conditions [2].

Analyzing audio recordings acquired in some classrooms, both occupied and empty, it has been shown that the reverberation time is not the only acoustic parameter that influences the acoustic comfort of classrooms, but clarity, speech transmission index and ambient noise due to the simultaneous presence of other students in adjacent classrooms should be analyzed too [3].

In another study, the acoustic parameters calculated within high school classrooms in northern Italy were compared both with software and with the classical formulas of the perfectly diffused field in order to obtain an accurate prediction of reverberation time [4]. In this case, the absence of a diffused field has been indicated as an important element for a detailed design. Other authors report the acoustic measurements performed inside classrooms after the renovation, and evaluated the effectiveness of the intervention [5, 6].

In architectural acoustics, small deficiencies, such as insufficient reverberation, can be tolerated, but other deficiencies like a barely perceptible echo, often result highly annoying and disturbing perceptions

The echo is a sensation in which the listener distinctly perceives a replica of the direct sound. In large classrooms the presence of large parallel reflecting walls generates a reflected sound that if the direct time and the delay of the reflected sound is less than 50 ms, improves the understanding of the speech. However, when the distance between the parallel flat walls is larger than 10 meters, undesirable flutter echo phenomena may occur due to the interference between the direct and the reflected sound from the walls. This common condition in many classrooms significantly degrades the speech understanding. Furthermore, the presence of large vaulted ceilings produces acoustic focusing effects by concentrating sound energy at defined points, and contributes to a non-uniform distribution of the sound [7-10].

A recent Italian legislation has established the Minimum Environmental Criteria (CAM) for working environments. With regard to schools, acoustic comfort targets are required in terms of noise control and acoustic quality. Schools must comply with the UNI 11532 [11] for their reverberation (T), clarity (C50) and speech intelligibility (STI). In classrooms, the following CAM values are required: T<0.7 s, C50>0 dB, and STI>0.6. Moreover, in educational sports facilities such as gyms, the requirements are T<1.5 s, C50>-2 dB, and STI>0.5. To achieve these objectives, the insertion of acoustic treatments is often unavoidable.

Acousticians commonly use the perfectly diffused theory to calculate the amount of needed sound-absorbing material to comply with current legislation. However, to prove the efficacy of sound absorbing treatments, the perfectly diffused theory cannot always be assumed. The purpose of this work is to evaluate the optimal position in which to place the minimum amount of sound-absorbing treatments to reach the CAM in some university classrooms.

2 Case study

Using an acoustic software, it was possible to estimate the minimum quantity and the optimal placement of the sound-absorbing panels to reach the CAM of five classrooms located in the Department of Architecture and Industrial Design of the Università degli Studi della Campania [12]. The classrooms are located in an ancient building in Aversa near the city of Caserta. The building, called “San Lorenzo ad Septimum”, was built in the X century as Benedictine monastery. In the XV century the building was expanded. Then, in 1807, the monastery was closed and a school for young boys was set up. Since 1990 the Department of Architecture and Industrial Design is located in this historical building, with 13 classrooms and administrative offices.

Figure 1 shows the Department of Architecture and Industrial Design aerial view, while Fig. 2 shows the cloister on two levels with arches and columns.

The building is located in a suburban area of the city, away from traffic lines. In addition, the classrooms are located at the rear of the building in relation to the access road and therefore the ambient noise is very low and is such that it does not affect the acoustic comfort. During the acoustic measurements, the background noise expressed as equivalent sound level (LeqA) was always below 40 dBA.

Figure 1: Department of Architecture and Industrial Design aerial view.

Figure 2: Department of Architecture and Industrial Design showing the cloister on two levels with arches and columns, behind which there are classrooms.

The classrooms located in this historic building, have irregular shapes, a marble floor, vaulted ceilings, and plastered smooth walls.

Five university classrooms were analysed; the dimensions are reported in Table 1. Figure 3 shows some of the classrooms investigated in the present study.

Figure 3: Photos of the classrooms: P3 (top), S2(center), T5 (bottom left), and T4 (bottom right).

Table 1: Average dimensions of the five selected classrooms.

classroom	Volume, m^3	Average height, m	Base area, m^2
P3	416	5.4	77
S3	1,850	7.2	257
T5	2,517	12.1	208
S2	626	4.6	136
T4	275	5.5	50

3 Acoustic measurements

For each classroom, acoustic measurements were carried out using an omnidirectional sound source. Following this, the impulse responses were recorded, and the acoustic parameters were analyzed. The sound source was placed in each classroom at the height 1.6 m, and the measurements were done in different points in the classrooms at typical ear height of 1.2 m, to obtain an average value of the acoustic parameters for speech understanding.

The acoustic parameters were measured according to the ISO 3382 [13], with a microphone GRAS 40 AR endowed with the preamplifier 01 dB PRE 12 H through the interface 01 dB Symphonie. The omnidirectional sound source was fed by a MLS signals [14]. The acoustic parameters measured were the reverberation time (T), the Clarity (C50), and the Speech Transmission Index (STI) [15, 16]. The acoustic measurements were carried out without students, in empty condition. These classrooms at 1.0 kHz, have T30 values between 2.5s and 4.5s, C50 between 3 dB and -0.5 dB, and STI between 0.34 and 0.47, values far from those reported in the new Italian regulations about the CAM. The need for acoustic interventions was hence evident.

4 Simulations

To evaluate a possible solution to reduce the reverberation time and allow the achievement of an adequate acoustic comfort, the architectural acoustics software "Odeon" was used [17, 18]. The software was used because the perfectly diffuse field model was not applicable in the investigated rooms [19-23].

Odeon adopts a hybrid method using the ray tracing and image source methods for the acoustic simulations. The reverberation time was chosen as a reference parameter for the calibration, which was done by tuning the absorbent coefficient values of the walls so that the reverberation time measured coincided with the predicted one. The calibration was stopped when the difference between the time measured and the time calculated is inferior to 5% of all the octave bands calculated between 125 and 4000 Hz. Regarding the scattering coefficient, the desks and chairs were simulated as flat planes, with a scattering coefficient of 0.5 for the unoccupied condition [24, 25].

The best location to install the sound-absorbing panels to reduce the reverberation time and improve the acoustics characteristic, preserving aesthetics and following historic preservation instructions were searched. The results of the acoustic measurements for each classroom and the relative acoustic correction among several positions of the sound-absorbing panels are reported in Section 6.

5 Absorbent panel for the acoustic correction

To obtain the vales of the sound absorption coefficients used for the computer simulation of the acoustic correction, an impedance tube was used according to ISO 10534-2 [26]. In this way, it is possible to obtain the absorbent coefficient measurements at normal incidence using samples of diameter 10 cm. This geometry corresponds to an upper frequency limit measurement of 2000 Hz. Polyester absorbent panels, with thickness of 4 cm were chosen. Table 2 reports the octave band values of sound absorption coefficient measured for the selected material samples. The average value of the absorbent coefficient was obtained from measurements with four different specimens. The value at the frequency band of 4000 Hz was assumed equal to the value at 2000 Hz, as porous materials typically have growing absorption at higher frequency and the recorded value at 2000 Hz was 0.9.

6 Results

This study aimed to know the effects of the insertion of absorbent materials in the classrooms on speech understanding. According to the UNI 11532, the acoustic parameters T, C50, and STI were analysed.

For each classroom, different surface areas of absorbent material that correspond to the walls behind the teacher's position were considered. For each classroom the measured values of T30, C50, and STI are shown and then the same parameters calculated by Odeon software after the acoustic correction are discussed. The sound-absorbing material are inserted in the virtual model of classroom on the vertical wall behind the teacher's position or on the ceiling. The equivalent area of sound-absorbing material changes for each classroom because the vertical wall is different for each classroom. Table 3 shows the STI values in numerical range from bad to excellent that were considered in order to assess the different scenarios.

6.1 Classroom P3 - hypothesis of correction

The classroom P3 has a volume of 416 m^3, an average height of 5.4 m and a base area of 77 m^2. The walls are plastered, the floor is marble, the ceiling is vaulted, with double glazed side windows, wooden benches and chairs.

Figure 4 shows the acoustic correcting panels simulated under ceiling or on the wall behind the teacher's desk. Tables 4 to 6 report the STI, T30, and C50 values respectively, for the following scenarios: A) empty room; B) 89 sqm located in front of the teacher in the lateral ceiling area, C) 89 sqm behind teacher in the lateral ceiling area; D) 89 sqm behind teacher in the central ceiling area.

6.2 Classroom S3 - hypothesis of correction

The classroom S3 has a volume of 1,850 m^3, an average height of 7.2 m and a base area of 257 m^2. The walls are plastered, the floor is marble, the ceiling is double-pitched wood, and there are wooden desks and chairs. Figure 4 shows the acoustic correcting panels simulated under ceiling or on the vertical wall behind teacher. Tables 7 to 9 report the STI, T30, and C50 values respectively, for the following scenarios: A) empty room; B) 364 sqm on the wall behind teacher; C) 422 sqm ceiling on the wall behind teacher; D) 412 sqm side walls; E) 437 sqm ceiling on the entrance wall.

6.3 Room T5 - hypothesis of correction

The classroom T5 has a volume of 2,517 m^3, an average height of 12.1 m and a base area of 208 m^2. The walls are plastered, the floor is in marble, the vaulted plaster ceiling, there are side windows with double glazing, there are wooden benches and chairs.

Figure 6 shows the acoustic correcting panels simulated under ceiling or on the vertical wall behind teacher. Tables 10 to 12 report the STI, T30, and C50 values respectively, for the following scenarios: A) empty room; B) 240 sqm on ceiling panels; C) 320 sqm on ceiling and entrance wall; D) 420 sqm on ceiling and on the walls at the entrance and behind the teacher; E) 440 sqm only on side walls, F) 550 sqm on the ceiling and the side walls.

Table 2: Sound absorption coefficients measured according to ISO 10534-2

	Frequency, Hz					
	125	250	500	1 k	2 k	4 k
Abs coefficient	0.2	0.4	0.6	0.8	0.9	0.9

Table 3: Judgment for different STI Value.

bad	Poor	fair	good	excellent
0 - 0.3	0.3 - 0.45	0.45 - 0.6	0.6 - 0.75	0.75 - 1

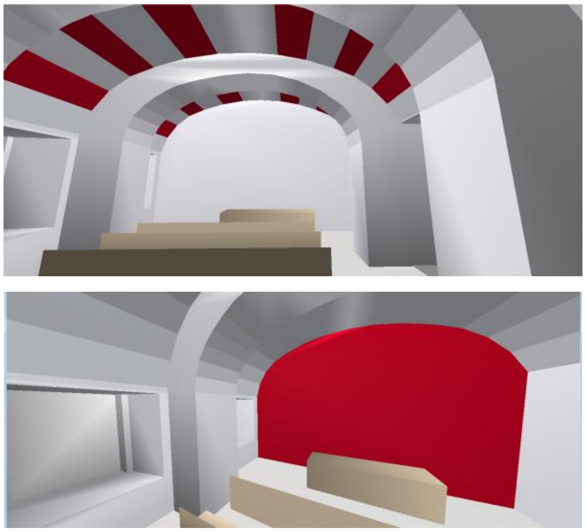

Figure 4: Panels under ceiling or on the wall behind teacher in the room P3

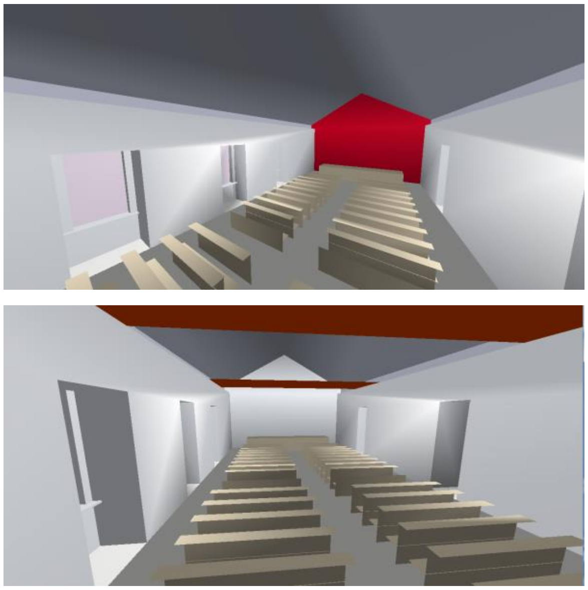

Figure 5: Panels on the wall behind teacher or under the ceiling in the room S3.

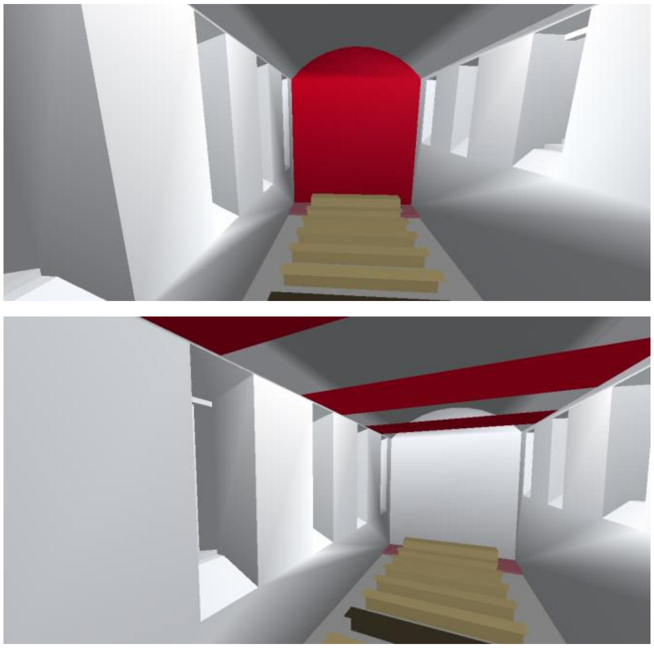

Figure 6: Panels on the wall behind teacher and under ceiling in the room T5.

Table 4: STI values assumed in room P3 for different scenarios.

	Scenarios	STI
A	empty room measured	0.43
B	89 sqm– lateral ceiling area	0.63
C	89 sqm behind teacher – lateral ceiling area	0.65
D	89 sqm behind teacher – central ceiling area	0.67

Table 5: T30 values assumed in room P3 for different scenarios

Scenario (as for table 4)	Frequency, Hz					
	125	250	500	1 k	2 k	4 k
A	2.8	2.7	2.2	2.2	1.8	1.6
B	2.1	1.0	0.8	0.7	0.7	0.6
C	2.1	1.0	0.8	0.7	0.7	0.6
D	2.0	0.9	0.7	0.6	0.6	0.6

Table 6: C50 values assumed in room P3 for different scenarios

Scenario (as for table 4)	Frequency, Hz					
	125	250	500	1 k	2 k	4 k
A	-6.0	-5.5	-4.8	-4.5	-3.3	-2.7
B	-4.8	-0.3	0.7	1.9	2.7	3.1
C	-4.5	0.3	1.6	3.1	3.9	4.1
D	-4.3	0.5	1.9	3.5	4.3	4.5

Table 7: STI values assumed in room S3 for different scenarios

	Scenarios	STI
A	empty room	0.43
B	364 sqm - wall behind teacher	0.63
C	422 sqm ceiling - wall behind teacher	0.65
D	412 sqm side walls	0.67
E	437 sqm ceiling - entrance wall	0.68

Table 8: T30 values assumed in room S3 for different scenarios

Scenario (as for table 7)	Frequency, Hz					
	125	250	500	1 k	2 k	4 k
A	3.1	2.8	2.8	2.7	2.3	2.0
B	2.9	1.2	0.9	0.7	0.5	0.4
C	2.8	1.1	0.9	0.6	0.4	0.4
D	2.8	1.1	0.9	0.6	0.4	0.4
E	2.8	1.2	1.0	0.9	1.0	0.9

Table 9: C50 values assumed in room S3 for different scenarios

Scenario (as for table 7)	Frequency, Hz					
	125	250	500	1 k	2 k	4 k
A	-5.8	-5.2	-5.2	-4.8	-4.1	-3.1
B	-5.8	-1.0	0.5	2.5	5.2	6.0
C	-5.5	-0.3	1.9	3.9	4.5	5.0
D	-5.8	-0.5	1.2	3.7	7.5	8.3
E	-5.5	0.0	2.7	5.5	6.6	6.9

Table 10: STI values assumed in room T5 for different scenarios

	Panels distribution	STI
A	empty room	0.36
B	240 sqm ceiling panels	0.53
C	320 sqm ceiling and entrance wall	0.59
D	440 sqm only side walls	0.59
E	420 sqm ceiling and wall entrance and teacher	0.60
F	550 sqm ceiling and side walls	0.70

Table 11: T30 values assumed in room T5 for different scenarios

Scenario (as for table 10)	Frequency, Hz					
	125	250	500	1 k	2 k	4 k
A	4.8	5.6	4.2	4.0	3.1	2.2
B	3.0	2.4	1.7	1.4	1.2	1.0
C	2.7	2.0	1.4	1.1	1.0	0.8
D	2.4	1.7	1.2	0.9	0.8	0.7
E	2.3	1.6	1.1	0.9	0.8	0.7
F	2.1	1.4	0.9	0.7	0.6	0.6

Table 12: C50 values assumed in room T5 for different scenarios

Scenario (as for table 10)	Frequency, Hz					
	125	250	500	1 k	2 k	4 k
A	-8.3	-8.7	-6.9	-6.6	-5.5	-3.7
B	-7.0	-2.9	-1.2	0.3	0.7	1.7
C	-6.7	-1.9	0.3	2.3	2.7	3.6
D	-6.3	-1.1	1.0	3.2	3.6	4.4
E	-6.3	-2.0	0.0	1.8	2.7	3.5
F	-5.8	0.3	2.5	4.8	5.5	6.3

6.4 Classroom S2 - hypothesis of correction

The classroom S2 has a volume of 626 m^3, an average height of 4.6 m and a base area of 136 m^2. The walls are plastered, the floor is marble, the ceiling is plaster floor, there are side windows with double glazing. There are wooden benches and chairs.

Figure 7 shows the acoustic correcting panels simulated on the vertical wall behind teacher or under ceiling. Tables 13 to 15 report the STI, T30, and C50 values respectively, for the following scenarios: A) empty room; B) 150 sqm side - front of the teacher; C) 150 sqm lateral - behind the teacher; D) 150 sqm ceiling - behind teacher.

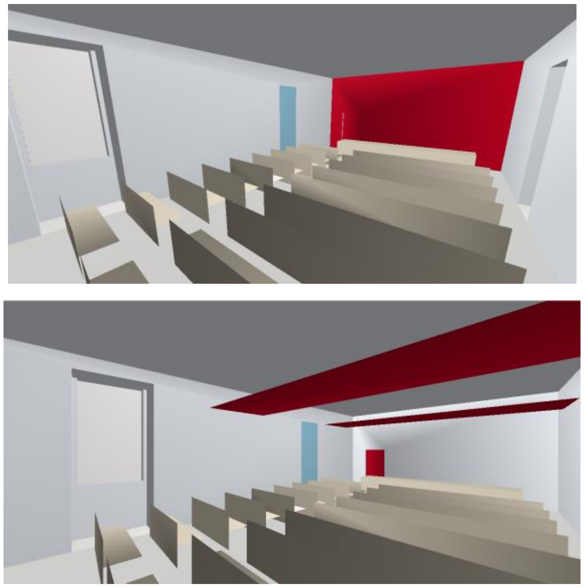

Figure 7: Panels on wall behind teacher and under the ceiling in the room S2.

Table 13: STI values assumed in room S2 for different scenarios

	Scenarios	STI
A	empty room	0.44
B	150 sqm lateral - front of the teacher	0.65
C	150 sqm lateral - behind the teacher	0.66
D	150 sqm ceiling - behind teacher	0.66

Table 14: T30 values assumed in room S2 for different scenarios

Scenario (as for table 13)	Frequency, Hz					
	125	250	500	1 k	2 k	4 k
A	2.8	2.8	2.7	2.6	2.3	1.7
B	2.0	1.1	1.0	0.9	0.9	0.8
C	2.1	1.0	0.9	0.8	0.7	0.7
D	2.0	1.0	0.9	0.7	0.7	0.7

Table 15: C50 values assumed in room S2 for different scenarios

Scenario (as for table 13)	Frequency, Hz					
	125	250	500	1 k	2 k	4 k
A	-5.0	-5.0	-4.8	-4.5	-3.7	-2.3
B	-3.3	0.9	2.1	3.5	3.9	4.8
C	-3.3	0.7	2.1	3.5	4.3	5.0
D	-3.1	1.0	2.5	3.9	4.1	4.8

6.5 Classroom T4 - hypothesis of correction

The classroom T4 has a volume of 275 m^3, an average height of 5.5 m and a base area of 50 m^2. The walls are plastered, the floor is in marble, the vaulted plaster ceiling, there are side windows with double glazing, there are wooden benches and chairs. Figure 8 shows the acoustic correcting panels simulated under ceiling or on the vertical wall behind teacher. Tables 16 to 18 report the STI, T30, and C50 values respectively, for the following scenarios: A) empty room; B) 50 sqm panels on the wall opposite to the teacher's wall; C) 50 sqm panels on the wall at the side of the teacher's desk; D) 50 sqm panels under the vault.

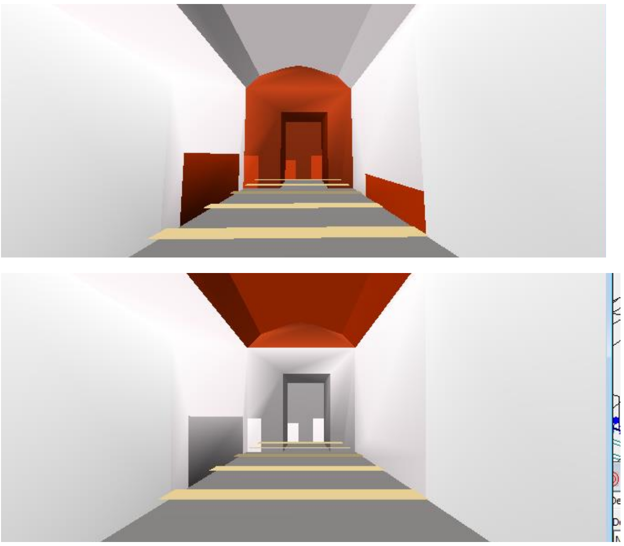

Figure 8: Panels on wall behind teacher and under the ceiling in the room T4.

Table 16: STI values assumed in room T4 for different scenarios

	Scenarios	STI
A	empty room	0.45
B	50 sqm panels opposite teacher's wall	0.63
C	50 sqm panels wall teacher side	0.67
D	50 sqm panels under the vault	0.70

Table 17: T30 values assumed in room T4 for different scenarios

Scenario (as for table 16)	Frequency, Hz					
	125	250	500	1 k	2 k	4 k
A	3.5	2.5	2.1	1.8	1.8	1.5
B	2.5	1.2	1.0	0.8	0.8	0.7
C	2.4	1.0	0.9	0.7	0.7	0.6
D	2.4	0.9	0.7	0.6	0.5	0.5

Table 18: C50 values assumed in room T4 for different scenarios

Scenario (as for table 16)	Frequency, Hz					
	125	250	500	1 k	2 k	4 k
A	-5.1	-3.4	-2.6	-1.8	-1.7	-0.6
B	-3.5	0.8	1.7	2.8	3.2	3.8
C	-3.3	1.5	2.7	4.2	4.7	5.3
D	-3.2	2.7	4.0	5.9	6.3	6.8

7 Discussion

The recent Italian regulations regarding the Minimum Environmental Criteria pay attention to the acoustic comfort inside the classrooms and refer to the UNI 11532 standard conditions. In this standard, appropriate values of the acoustic parameters T, STI and C50 are provided. During the design phase these parameters can be estimated with the use of software for architectural acoustics. In the specific case, a software based on the tracing of the sound beams was used. In fact, for the appropriate estimation of the acoustic parameters the classical formulas of the diffused sound field cannot be used, as this condition does not occur.

The diffuse field model occurs when the distribution of the sound pressure level is uniform and the reverberation time is invariant, a condition that in the classrooms under examination given their geometry does not occur. Because the classrooms have different dimensions and do not have the same geometry, acoustic measurements and an evaluation of the parameters have been performed for each of them. In rooms with a vaulted ceiling there are sound focusing conditions in the central part of the room, these effects are eliminated by covering partially the ceiling with sound-absorbing material. Moreover, given the large dimensions and parallel flat walls, extensive surfaces of sound-absorbing material are needed on the walls to reduce the detrimental flutter-echo effects.

With the help of the Odeon software, it is possible to estimate the minimum amount of sound-absorbing material to be inserted in order to obtain the objectives required by the CAM. The software based on the tracing of the sound beams allows the estimation of the parameters T, C50, and STI as the arrangement of the sound absorbing panels varies. For the five classrooms considered the provision that allows the achievement of the objectives of the CAM with the minimum amount of sound-absorbing material. Place of the panels on the ceiling and the arrangement that allows the CAM to be respected with the minimum amount of sound-absorbing material were obtained.

The most important acoustic aspect in the classrooms is the verbal communication. Therefore, the analysis focused on the acoustic parameters that influence speech intelligibility. During the measurements, the noise of the operation of the air conditioning systems was considered. The operation of the air treatment systems, involves an increase in the level of the background noise, an effect that is manifested above all in reverberant environments, and consequently creates a reduction in speech intelligibility.

Being a historical building there is not a centralized air treatment system, but the heating or cooling is done with single units. The values of the equivalent sound emission levels of these systems, when they are in operation, are lower than 30 dBA and therefore they are such as not to interfere with normal activities.

The amount of surface of sound-absorbing material to be inserted in environments for acoustic correction may change depending on the chosen material. In this case, a 4 cm thick polyester panel was considered.

The choice of a more performing sound-absorbing material involves a reduction of useful surface to be coated. In addition, acoustic measurements were performed in empty classrooms, in the absence of students; therefore, it has not been possible to investigate the contributions of people on the acoustic characteristics of the classrooms.

In classrooms the comprehension of speech could be improved by changing the arrangement of the desks with respect to the listener's position, with a provision that brings students closer to the teacher or the type of furniture could be changed, for example by replacing the wooden chairs with padded chairs that contribute to the reduction of excessive reverberation [27, 28].

The CAMs provide only the values of the acoustic parameters to be respected, but they do not give useful information about the achievement of these objectives. The CAMs provide indications on how to improve the understanding of the speech indicating solutions to increase the sound level of the components of the early reflections that reinforce the sound direct, in fact, as the level of direct sound increases, the intelligibility of speech improves [29]. In addition, the CAM do not say anything about the presence of the students. The acoustic conditions can change with the presence of students [30]. The presence of the students results in a reduction in reverberation time due to the sound absorption of people, but on the other hand, there would be a reduction in the sound level and the increase in background noise, due to the natural activities of the students. To improve the acoustic characteristics of the classrooms analyzed, since the historical and monumental building, invasive criteria for good acoustic design could not be considered [31].

8 Conclusions

The classrooms in the case study historical building, and in the majority of the historical buildings, do not have good acoustics. T measured values at 1 kHz well over 0.7 s, and so classrooms needed significant acoustic corrections. In fact, in the considered case study, as in many similar conditions, the actual coustic conditions are far from the Italian "Minimum Environmental Criteria" (CAM).

Through software simulations, this study has obtained useful information for each classroom geometry, and about the position where to install the absorbent material to have the best acoustic performance and respect aesthetic and historical criteria.

Future developments of the work will be directed towards the optimization of the considered acoustic parameters, so that with optimization techniques, the arrangement of sound-absorbing materials that allows the best acoustic comfort can be chosen in an appropriate manner. In addition, sound-absorbing materials could be used that are acoustically more performing so as to reduce the area to be covered. To improve the comprehension of the voice, it is necessary to proceed to an accurate design of the electroacoustic systems that take into account the dimensions and the geometries of the environments.

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A SURVEY OF THE UNOCCUPIED ACOUSTIC CONDITIONS OF ACTIVE LEARNING CLASSROOMS IN MONTREAL

Shiva Hadavi [*1] **and Joonhee Lee** [†1]
[1]Concordia University, Montréal, Québec, Canada

Résumé

Les éducateurs ont mis au point des stratégies d'enseignement novatrices afin de maximiser les résultats d'apprentissage en classe. Les classes d'apprentissage actif constituent de nouveaux espaces pédagogiques qui facilitent ces stratégies grâce à un engagement accru des étudiants et à des discussions collaboratives. Les exigences acoustiques de ces classes n'ont toutefois pas encore été étudiées. Le présent article aborde par conséquent les conditions acoustiques des classes d'apprentissage actif situées à Montréal. Les paramètres acoustiques comme le bruit de fond, le temps de réverbération et l'indice de transmission de la parole dans des conditions de non-occupation sont examinés. Les résultats montrent que même si les classes sont nouvellement rénovées et conçues pour l'apprentissage actif, la majorité d'entre elles ne répondent pas aux exigences acoustiques standards pour ce qui est du temps de réverbération et du bruit de fond. Des études approfondies sur les conditions d'occupation des classes d'apprentissage actif pourront fournir une meilleure compréhension des exigences de conception acoustique de ces espaces.

Mots clefs : acoustique des salles de classe, intelligibilité de la parole, classe d'apprentissage actif

Abstract

Educators have developed innovative teaching strategies in order to maximize learning outcomes in classrooms. Active learning classrooms are new learning spaces that facilitate teaching strategies with enhanced students' engagement and collaborative discussions. However, the acoustic requirements of the active learning classrooms have not been investigated yet. This paper presents, thus, the acoustic conditions of the active learning classrooms located in Montreal. The acoustical parameters such as background noise, reverberation time and speech transmission index in unoccupied conditions are examined. The results show that although all the classrooms are newly renovated and equipped to be used as active learning classrooms, the majority of them do not meet the standard acoustic requirements of the reverberation time and background noise level. Further studies on occupied conditions of active learning classrooms can provide a better understanding of the acoustical design requirements for these spaces.

Keywords: classroom acoustics, speech intelligibility, active learning classroom

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1 Introduction

Students spend a considerable amount of time in classrooms where they acquire knowledge and skills to be integrated into society. Several factors contribute to learning efficiency and productivity. Environmental comfort analysis, therefore, is a multidisciplinary subject, which requires careful investigations by assorted research fields such as engineering, psychology, statistics, medicine, and educational science. A combination of measurements and questionnaires can provide a more comprehensive overview of environmental quality and occupants' well-being [1-3].

According to Astolfi and Pellerey [4], acoustical and visual qualities were perceived as the most important environmental factors influencing students' academic performance. Inappropriate acoustic characteristics of classrooms such as high background noise levels, long reverberation times and low signal-to-noise ratios (SNR) can affect stress, concentration, and academic performance of students in all different age groups [5]. These adverse effects are more detrimental for students with hearing impairment and second language learners [6-8].

Poor acoustic conditions do not only affect students. Teachers in noisy and reverberant classrooms also have to constantly raise their voices in order to communicate with the students. Exposure to these conditions over time leads to vocal fatigue, voice problems, increased level of stress and cognitive fatigue [9-11].

Active learning classroom

Active learning approaches are based on students' engagement in the learning process. These methods lay more emphasis on developing students' skills rather than transmitting information through direct lectures. Chickering and Gamson [12] suggest that students not only need to listen but also write, read, discuss and participate in solving problems for better performance. The active learning is defined as "instructional activities involving students in doing things and thinking about what they are doing [13]".

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[*] shiva.hadavi1988@gmail.com
[†] joonhee.lee@concordia.ca

This new way of pedagogy leads to a new design of classrooms. Unlike traditional learning spaces for the lecture style, active learning classrooms need to provide space for more student-student interaction [14]. Figure 1 illustrates these active learning classrooms. The active learning inevitably generates noise by small group talks, movements, and electronics in use. The noisy classroom environment can become overwhelming to some students and can easily lead to distractions and off-task behaviours [15].

Figure 1: A typical active learning classroom at Dawson College in Montréal with flexible learning configuration

However, no specific acoustic guideline has been set to meet the special needs of such spaces up to this date. Therefore, this study focuses on the objective evaluation of the acoustic characteristics in the active learning classrooms.

2 Method

The acoustic characteristics of ten active learning classrooms in Montréal are investigated in this study. The classrooms are located in downtown Montreal at Concordia University and Dawson College. The brief descriptions of the ten classrooms are presented in Table 1.

Room impulses response was measured to calculate acoustical parameters such as reverberation time (T) and speech transmission index (STI) in these spaces with three different measurement configurations. The measurement configurations are determined by observing typical locations of students and teachers. The measurement system consists of a B&K omni-directional speaker and a class 1 sound level meter (Type 2250). The heights of the speaker and the receiver are 1.65 m and 1.1 m above the floor respectively.

All the classrooms are rectangular-shaped except the DW-3F38. The schematic plans of the measurement configurations are presented in Figure 2. The six measurement combinations for the three scenarios are investigated. For the first scenario, the speaker is located near the teacher's desk in the front of the classroom. In the second scenario, the speaker is located at the probable teacher's standing position in the middle of the classrooms. The last scenario is for between students' communication. The speaker is located at one of the students' desks in the middle of the classroom. For each scenario, the sound level meter is located at two different receiver positions where are the closest and farthest students' desk from the speaker. Background noise levels were measured for all the classrooms according to ANSI/ASA S16.60-2010/Part1 [16].

Table 1: Descriptions of the ten investigated active learning classrooms

Name	Location	Volume (m^3)	Surface material
CO-CC10	Concordia	249	ACT, cloth curtains, drywall
CO-FB11	Concordia	333	ACT, carpets, drywall
DW-3F3	Dawson	208	ACT, drywall, white boards
DW-3F5	Dawson	206	ACT, drywall, white boards
DW-3F37	Dawson	212	ACT, drywall, smart boards
DW-3F38	Dawson	222	ACT, drywall, smart boards
DW-3F45	Dawson	182	ACT, drywall, white boards
DW-3H10	Dawson	222	ACT, drywall, smart boards
DW-7A2	Dawson	216	ACT, drywall
DW-7A6	Dawson	237	ACT, drywall

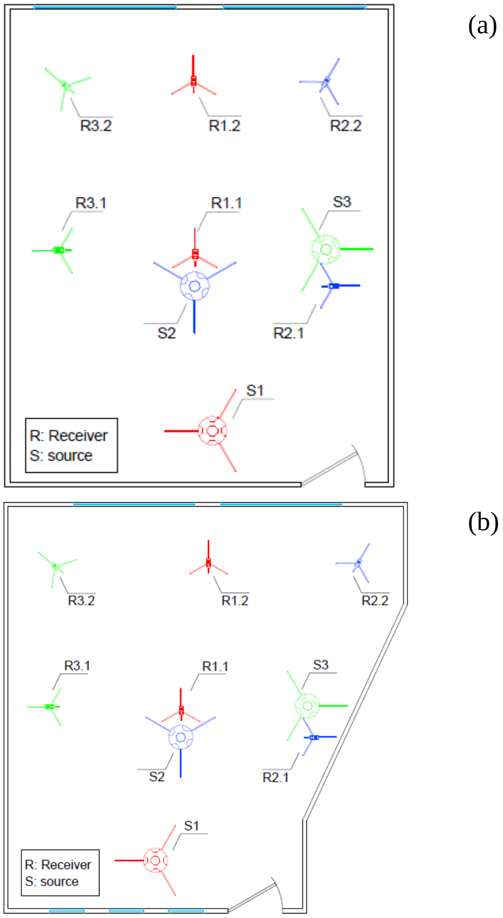

Figure 2: The schematic plan of measurement scenarios for (a) the nine measured classrooms except DW-3F38 and (b) DW-3F38

The measurements were taken while building mechanical system was running in the classrooms. Five consecutive 60-second measurements at the six locations in the classrooms were recorded and the A-weighted equivalent noise level (L_{Aeq}) is obtained by averaging the measured sound levels.

Room impulse responses were measured with a linear-sweep signal to calculate reverberation times and speech transmission index (STI) in the classrooms. The STI is calculated using the indirect method by deriving modulation transfer functions (MTF) from the impulse response [17]. The MDF depends on a signal-to-noise ratio (SNR) and room properties (e.g. reverberation time). The STI and reverberation time are obtained by averaging the results of the six measurement scenarios for each classroom.

3 Results & discussions

3.1 Room acoustics parameters

The measured acoustic parameters (T30, L_{Aeq} and STI) of the classrooms are presented in Table 2.

The results of the middle frequency averaged reverberation times and their corresponding standard deviations are shown in Figure 3. According to ANSI/ASA S16.60-2010/Part1, the maximum reverberation time in the octave band frequencies of 500, 1000, and 2000 Hz should not exceed 0.5 seconds for space less than 283 m^3 and 0.6 seconds for space greater than 283 m^3. For the measured classrooms, the volume of all the rooms is less than 283 m^3 except for the CO-FB11. The low reverberation time in CO-FB11 is due to the acoustic treatment on the ceiling and floor with acoustic ceiling tiles and carpets. Figure 4 illustrates the spatial variations of the reverberation times in 6 different receiver locations. The results do not show any particular trend across different receiver locations for the reverberation time.

The results of the averaged A-weighted background noise levels for all the classrooms and their standard deviation are shown in Figure 5.

Table 2: The measured acoustic parameters of the active learning classrooms

Classrooms	T30 [s]	L_{Aeq} [dBA]	STI
CO-FB11	0.47 (±0.01)	41 (±0.5)	0.78
CO-CC10	0.74 (±0.04)	35 (±1.3)	0.66
Dw-3F3	0.67 (±0.07)	53 (±6.2)	0.7
Dw-3F5	0.64 (±0.05)	35 (±0.6)	0.71
DW-3F37	0.64 (±0.07)	49 (±3.4)	0.69
DW-3F38	0.62(±0.07)	54 (±6.2)	0.68
DW-3F45	0.57 (±0.06)	54 (±7.0)	0.74
DW-3H10	0.57 (±0.08)	56 (±5.0)	0.73
DW-7A2	0.55 (±0.02)	43(±3.9)	0.74
DW-7A6	0.61 (±0.05)	53 (±6.9)	0.72

According to the ANSI/ASA S16.60-2010/Part1, the background noise level should not exceed 35 dBA for core learning spaces. The results show that only CO-CC10 and DW-3F5 meet the criteria for the background noise level. It is expected that all the classrooms have higher background noise levels during regular school time.

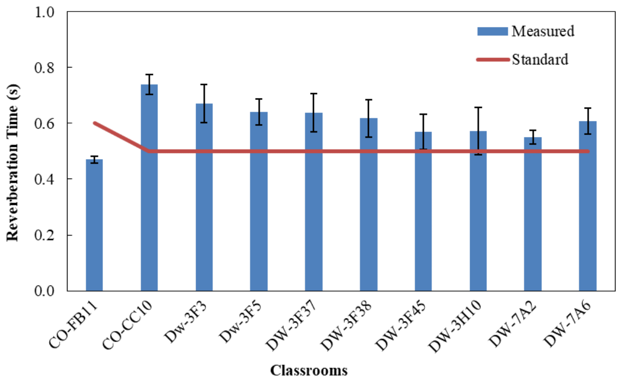

Figure 3: The middle-frequency averaged reverberation times (T30) in the active learning classrooms

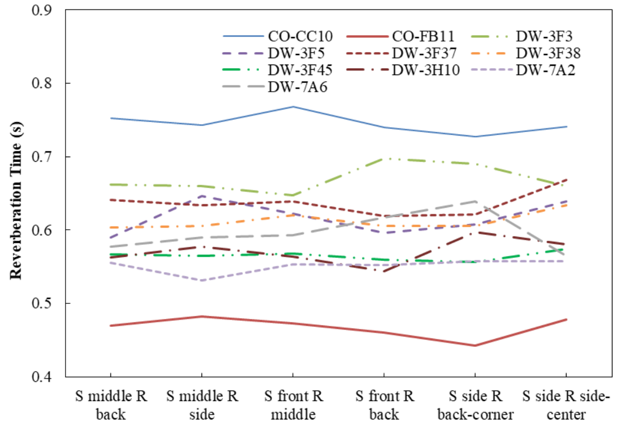

Figure 4: The middle-frequency averaged reverberation times (T30) in the classroom for the six measurement locations

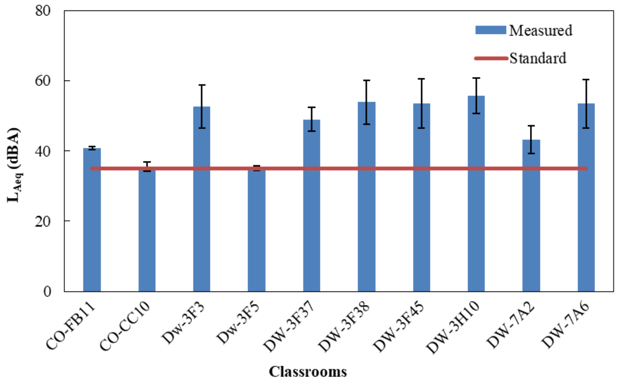

Figure 5: The averaged A-weighted background noise levels for the classrooms and the corresponding standard deviations

3.2 Speech intelligibility in the classrooms

The Speech Transmission Index (STI) for each space was calculated with the measured impulse responses. According to the STI qualification ratings from ISO 9921 [18], four speech transmission index values of 0.2, 0.4, 0.6 and 0.8 correspond respectively to ‘‘Bad”, “Poor”, ‘‘Good” and ‘‘Excellent” speech intelligibility conditions. The STI is also calculated through the fast estimation method proposed by Nowoświat and Olechowska [19]. They introduced a function for fast estimation of STI with a reverberation time value only. The fast estimation equation for STI is expressed as:

$$STI = A \ln T + B, \qquad (1)$$

Where A = -0.2078, B = 0.6488 and T = the averaged reverberation time of mid-frequency octave bands of 500, 1000 and 2000 Hz. The results of the measured STI and calculated STI together with their corresponding speech intelligibility ratings are represented in Table 3.

The calculated STIs based on equation (1) show good agreement with the measured values. CO-CC10 has the lowest STI value among all the classrooms mainly due to its high reverberation time and CO-FB11 has the highest STI with the shortest reverberation time, which confirm the adverse effect of reverberation times on speech intelligibility.

It is noteworthy that the STI ratings show “good” and “excellent” condition for speech intelligibility of the classrooms although only one of the classrooms met the suggested criteria for reverberation time and background noise level.

The proximity of the measured and estimated STI values suggests that the measured STI follows a linear relation with reverberation time values. Correlation between measured STI and measured T30 and L_{Aeq} values are illustrated in Figure 6. The coefficient of correlation (R^2) between T30 and STI is equal to 0.87 and statistically significant. The coefficient of correlation (R^2) between measured STI and L_{Aeq} is 0.0032, which confirms the negligible effect of the background noise level in calculating STI in this study. The results are aligned with the Nowoświat and Olechowska’s findings [19] based on the measured and estimated STIs.

To investigate the correlation between STI values and combined metrics of the A-weighted background sound pressure level (SPL) and reverberation time, the best fitted-surface for the measured STI with SPL and T30 values is illustrated in Figure 7. The best STI rating can be obtained when the reverberation time has the minimum acceptable values and the results show the importance of low reverberation time to maintain the speech intelligibility in classrooms in a desirable range. By increasing background noise level with a constant reverberation time, no specific change in STI values is observed, which is aligned with the previously mentioned assumption about the negligible effect of the background noise level in calculating STI values.

Table 3: The measured STI, estimated STI and their corresponding speech intelligibility ratings of the active learning classrooms

	Measured	Estimated	Rating
CO-FB11	0.78	0.81	Excellent
CO-CC10	0.66	0.71	Good
DW-3F3	0.70	0.73	Good
DW-3F5	0.71	0.74	Good
DW-3F37	0.69	0.74	Good
DW-3F38	0.68	0.75	Good
DW-3F45	0.74	0.77	Good
DW-3H10	0.73	0.77	Good
DW-7A2	0.74	0.77	Good
DW-7A6	0.72	0.75	Good

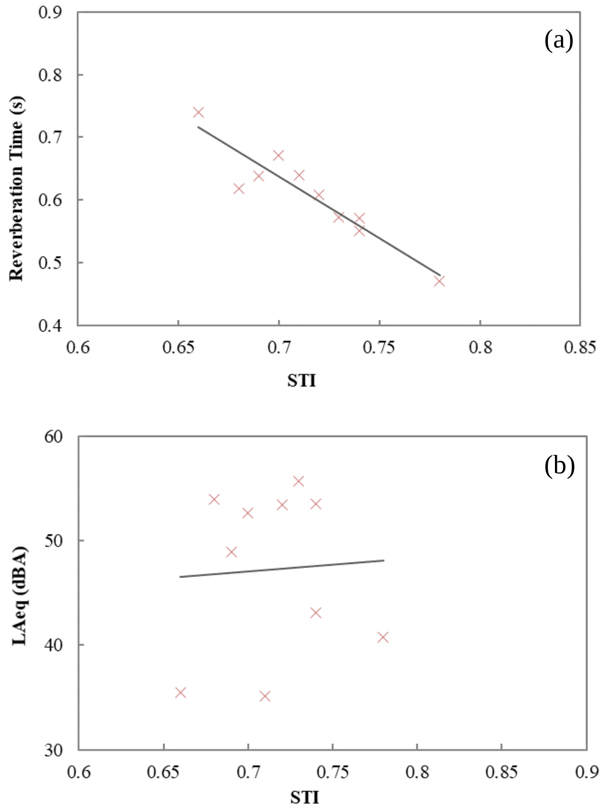

Figure 6: Relationship between STI and (a) the averaged reverberation time (T30) of 500, 1k and 2k Hz octave bands and (b) the background noise level.

4 Conclusion

A survey on the acoustic condition of 10 active learning classrooms has been carried out. All the classrooms are recently renovated and equipped to be used as active learning environments. All of them are finished with acoustic ceiling tiles while COFB-11 is also treated with carpets to increase the acoustic absorption.

The measurements were done in unoccupied conditions during summer time while HVAC was running. The background noise level is obtained by averaging the five 60 seconds measured A-weighted sound levels in the six key locations for each classroom.

It is observed that only two classrooms meet the standard requirements of 35 dBA for averaged A-weighted background noise level. Since all these measurements took place after official schools' hours, it is also expected that the occupied background noise level is higher for the classrooms. Among all the measured classrooms, only CO-FB11, which is treated with both ACTs and carpet, meets the standard requirement for the reverberation time of 0.5 s. Speech intelligibility is also evaluated for the classrooms using measured STI by means of the impulse response method. The STI was also calculated using a fast method proposed by Nowoświat and Olechowska [19]. The correlation between STI and combined metrics of SPL and RT follows the expected trend as indicated in previous studies.

Further research needs to be done in order to evaluate the acoustic conditions of occupied classrooms and investigate the correlation between unoccupied and occupied acoustic parameters in these spaces. The result of objective acoustic surveys of occupied and unoccupied conditions of active learning classrooms, combined with subjective studies on students and teachers' perception of acoustic comfort in such spaces can lead to the better understanding of specific design requirements of these new learning spaces.

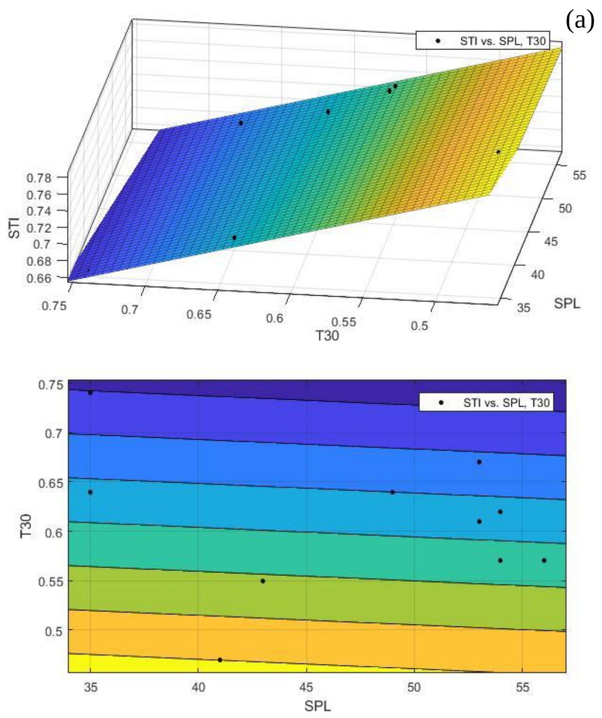

Figure 7: (a) 3D plot and (b) contour plot to illustrate the correlation between STI and combined metrics of SPL and reverberation time.

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TRAJECTORIES IN CLASSROOM ACOUSTICS: VOCAL BEHAVIOR OF TEACHERS

Arianna Astolfi[*]
Politecnico di Torino, Department of Energy, Turin, Italy.

Résumé

L’acoustique des salles de classe a été l’un des principaux thèmes de recherche de Murray Hodgson, que j’ai eu l’occasion de connaître à Rome, lors de la conférence de l’ICA en 2001, alors que j’étais au début de mon parcours, et dans plusieurs autres occasions. À Ferrara, en 2003, il a conclu son exposé sur un cours d’acoustique en classe en insinuant que les problèmes de voix des enseignants auraient dû faire l’objet d’études futures. Je travaille sur cette question depuis sept ans et ce travail résume les résultats et les perspectives relatives à l’évaluation du comportement vocal des enseignants. En particulier, la surveillance de la voix des enseignants au cours de leurs activités quotidiennes repose récemment sur des analyseurs vocaux portables équipés de capteurs de contact qui permettent de mesurer des paramètres liés à l'effort vocal, à la charge vocale, à l'intonation vocale et à la santé vocale. Les résultats obtenus lors des campagnes expérimentales menées au cours des dernières années dans des écoles de niveaux différents sont présentés dans cet ouvrage. Les relations avec l'acoustique des salles de classe, à la fois en termes de bruit et en termes de réverbération trop basse ou excessive, et les résultats subjectifs des enseignants sont également discutées.

Mots clefs: acoustique des salles de classe, contrôle de la voix, effort vocal, charge vocale

Abstract

Classroom acoustics was one of the main research themes of Murray Hodgson, which I had the chance to know in Rome, at the ICA Conference in 2001, when I was at the beginning of my working path, and to further have as scientific converser in many other occasions. In Ferrara, in 2003, he concluded his presentation of a course on classroom acoustics with the hint that the teachers’ voice problems should have been object of future studies. I have been working on this matter for seven years and this work summarizes the results and the perspectives related to the assessment of teachers’ vocal behavior. In particular, teachers' voice monitoring during daily working activities has been recently based on wearable vocal analyzers equipped with contact sensors, which allow for measuring parameters related to vocal effort, vocal load, vocal intonation and health. Results obtained during experimental campaigns that took place in the last years in schools of different grade are presented in this work. The relationships with classroom acoustics, both in terms of noise and too low or excessive reverberation, and the subjective outcomes of the teachers, are also discussed.

Keywords: classroom acoustics, voice monitoring, vocal effort, vocal load

1 Introduction

The research by Murray Hodgson in the field of classroom acoustics is worldwide recognized, as proved by 7 main articles and overall 25 contributions on this subject authored by him in the Journal of Acoustic Society of America.

The effect of classroom acoustics has consequences on learning of students, mostly at the lower grades of education, for which it is mandatory to guarantee speech comprehension in classrooms, and on teachers and teaching, for which it is mandatory to reduce teachers’ vocal effort and load.

According to M. Hodgson *et al.* [1] “Voice problems among teachers represent a rising cause of teacher absenteeism, use of sick benefits, and stress among teachers and students. In British Columbia, the BC Teachers Federation and Workers Compensation Board has received increasing numbers of claims from teachers experiencing occupational voice problems and the percentage of teachers in the clinic population is rising.”

He contributed to this subject by determining the typical long-term speech levels during lectures in classrooms at the University of BC, as well as the speech-signal to background-noise ratio, with the aim to elucidate the characteristics of classroom acoustics relevant to optimal design [2, 3].

Three billion people are the working population in the world and teachers are the 2% (Europe: 2.1%; USA: 2%), i.e. 60M.

Teachers of different types and levels, including teachers of physical education and music, are some of the most affected professional figures. In the world, 6M of teachers suffer of vocal pathologies and 1M only in Europe. Teachers vibrate their vocal folds 25% of the time that they teach [4], as opposed to 12% of time that they do not teach [5] and suffer from voice disorders twice as much as other professional groups. Teachers with documented voice disorders are up to 33% [6] and those with perceived ones are up to 50% [7]. Voice disorders are not still recognized as

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[*] arianna.astolfi@polito.it

occupational disease. They are caused by incorrect use of voice or poor acoustics in the environment where the voice is used.

A long-term voice monitoring is needed in order to prevent damages to the vocal apparatus that are related to vocal effort and load. Particularly, voice monitoring is aimed to warn the talker against at-risk situations, to highlight existing or incoming problems to the vocal apparatus, and to select suitable spaces for the vocal activity. Voice monitoring should be done without the influence of background noise and for this reason contact microphones which estimates vocal parameters from the skin vibration at the speaker's neck are recommended [8].

Vocal analyzers based on contact microphones should be qualified in terms of uncertainty of the measured quantities, particularly for the most important ones such as the mean voice sound pressure level and the mean fundamental frequency [8-10].

2 Voice monitoring of teachers

In order to perform teachers' voice monitoring during teaching time, our research team at the Politecnico di Torino, in collaboration with S.C. ENT 2 U. of the University of Turin and PR.O.VOICE Ltd, start-up incubated in I3P of the Politecnico di Torino, designed two wearable devices based on the former Voice Care™ technology [11, 12]. The light version, named "Vocal Holter App", can be installed on a common smartphone, and the pro version, "Vocal Holter Med™", made up of a dedicated device which performs more extensive and personalized analysis useful to physicians and speech pathologists.

The devices estimate vocal behavior in terms of vocal effort, vocal load, vocal intonation and health. Sound Pressure Level (SPL), phonation time percentage (D_t), Fundamental frequency (F_0) and Cepstral Peak Prominence Smoothed (CPPS), are the main parameters related to the four previous categories. Measurements of these and other parameters are performed at a logging interval of 46 ms. The former Voice Care device was instead set to a logging interval of 30 ms, which allowed to detect the inter-syllabic pause [11].

In a comparison with other three commercial dosimeters the Voice Care device resulted one of the most accurate in the determination of the mean voice sound pressure level and of the mean fundamental frequency [9].

CPPS is a novel parameter considered one of the most promising predictors of dysphonia and its severity [13]. Vocal parameters are provided in the form of statistical metrics derived from the distributions of occurrences. Comparison among results can be made as the measures are also characterized in terms of uncertainty.

Some measurement campaigns have been carried out in-field along the last seven years, with teachers of different grades who taught in schools with different acoustics [4, 14-15]. Results are presented on vocal effort and load and on the effect of classroom acoustics (noise and reverberation) on vocal behavior of teachers. Subjective outcomes have been also gathered and commented.

3 Results

3.1 Vocal effort and load

A vocal effort of 71 dB, SPL_{eq} @1m from the teacher's mouth, has been found on average for both primary and secondary school teachers [14, 15], i.e. between "Raised" and "Loud" [16]. During plenary lessons, primary and secondary school teachers were characterized by a phonation time percentage from 26% to 29% and of about 40%, respectively [14, 15].

A significant difference was found between the morning and the afternoon teaching periods, concerning mean voice sound pressure level, which on average increased during the afternoon by about 5 dB [14].

Moreover, as a result of a longitudinal study in secondary schools, teachers who worked in bad classroom acoustics showed a 2 dB increase in the vocal effort and a 10% decrease in the voicing time percentage at the end of the school year compared to the beginning [15].

3.2 Vocal fatigue

Vocal fatigue is here considered as a negative vocal adaptation that occurs as a consequence of prolonged voice use in critical conditions [17]. In this context, a tendency to increase the voicing periods as the reverberation time increases was on average observed for university professors and school teachers, and more generally for speakers who are highly motivated to make themselves understood in a perturbed speaking situation [18]. Particularly, reverberation time higher than 0.9 s in classrooms implicated higher accumulations of voicing periods for teachers, thus suggesting that vocal fatigue is highly related to classroom reverberation time [19].

3.3 Noise and Lombard effect

The involuntary tendency of speakers to increase their voice level as the noise level increases, in order to improve intelligibility of the speech signal is called Lombard effect.

Lombard effect with slopes between 0.4 and 0.7 dB/dB was found on average during plenary lessons in primary and secondary schools [4, 14-15]. A longitudinal study carried out in secondary school classrooms showed as this effect was not maintained at the end of the school year [15]. In both the school typologies, it was found an increase in the mean fundamental frequency with the increase in background noise at a rate of 1-3 Hz/dB.

3.4 Effect of reverberation

The reverberation time that should be set in primary and secondary school classrooms in order to minimizes the voice level should be in the range between 0.7 and 0.8 s, at mean frequencies [4, 14-15]. Teachers raise their voice at both lower and higher reverberation time. In the case of lower reverberation time teachers rise their voice due to the lack of voice support from the room [20], while in the case of higher reverberation time it is supposed that they rise their voice due to the amplified background noise. A tendency of background noise level to increase with increasing reverberation time was in fact observed at a rate of 13 dB/s [14].

The minimum speech level that was measured on average in the case of optimal reverberation time was approximately 65 dB SPL_{mean} at one meter from the teacher's mouth, which corresponds to a "normal" vocal effort [16].

Another research revealed that under simulated acoustic environments talkers adjusted their vocal effort linearly with the Voice Support, which represents the degree of amplification offered by the room to the voice of a speaker, at his own ears. The slope of this relationship, called the room effect, of -0.24 dB/dB, was significant only in the case of noise levels of approximately 60 dB [21]. This could be seen as an opposite result compared to the previous finding obtained in-field, but it should be noted that in laboratory a speech shaped noise has been used for the experiments, which is a stationary noise sequence whose spectrum follows the long term average speech spectrum, and not a real talking noise that can be find in real classrooms. Further investigations on this aspect should be done in the future.

3.5 Subjective outcomes

On average, the vocal comfort for speakers was found to be more closely related to noise annoyance than to room reverberance [21].

In the case of absence of noise, Decay Time at the ears is an acoustical parameter strongly related to the perceived sensation of vocal comfort, which is defined as the average of the subjective impression related to several aspects of voice use in different acoustic environments [20]. Decay Time at the ears is a decay time derived from an impulse response measured from the mouth to the ears of a talker. Particularly, a recommended Decay Time at the ears of 0.49 s and a range between 0.29 and 0.53 s were found to minimize vocal effort and maximize the vocal comfort of primary school teachers [14]. This result is in agreement with a study conducted with speakers in laboratory [20].

4 Conclusion

The work by M. Hodgson in the ambit of teachers' voice was mainly focused to find algorithms for the estimation of the speech sound pressure level in classrooms and to its propagation in different room acoustic conditions. According to his plans dated 2003, teachers' voice problems should have been object of future studies.

Thanks to his suggestion, progresses have been made so far on the topics of vocal effort and vocal load, vocal fatigue and health, influence of noise and reverberation on vocal output and vocal comfort, for teachers of different grades of education. All this thanks to voice monitoring.

Future research is needed to investigate relationships between voice emission and perception in realistic complex and challenging auditory scenes.

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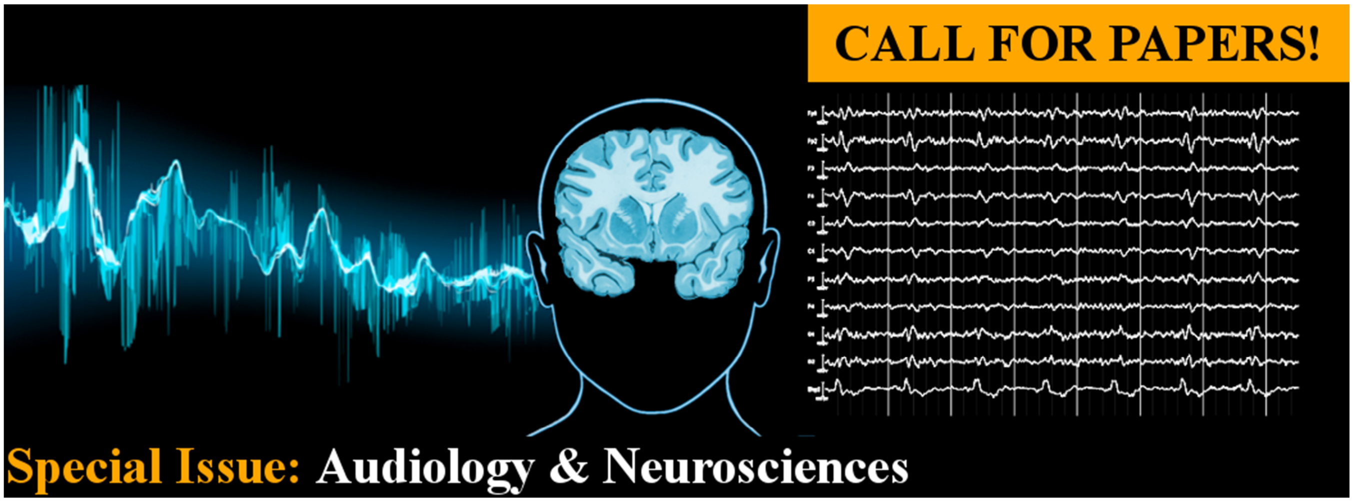

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Numéro Spécial: Audiologie & Neurosciences

L'acoustique est un vaste domaine qui offre des centaines d'emplois à travers le Canada, et ce, dans différents secteurs tels que l'éducation, la recherche, la consultation professionnelle, etc... Afin de bien refléter cette diversité, l'Acoustique Canadienne a publié régulièrement au cours des 40 dernières années une série de numéros spéciaux pour souligner les divers champs d'applications de l'acoustique

L'Acoustique Canadienne fait donc un appel à soumettre une série d'articles pour le prochain numéro spécial planifié pour juin 2019. **Ce numéro spécial inclura principalement (mais ne se limitera pas à) des contributions dont le sujet est en lien avec l'audiologie et les neurosciences, tel que :**

- Applications de l'acoustique en électrophysiologie (EEG, EOG, ECOG, etc…)
- Évaluation de l'audition et de la surdité (audiométrie, DPOAE, etc…)
- Tout autre sujet en audiologie/neurosciences en lien avec l'acoustique et/ou la musique.

COMMENT EN FAIRE PARTIE?

Pour contribuer à ce numéro spécial « audiologie et neurosciences », les auteurs sont invités à soumettre un article, sous la rubrique « Numéro spécial » dans notre système en ligne au http://jcaa.caa-aca.ca **avant le 2 avril 2019**. Il est possible de soumettre un même article dans les deux langues officielles.

Chaque article sera révisé par le comité éditorial de l'Acoustique canadienne qui veillera à ce que les politiques de publications de la revue soient respectées (contenu original, contenu non commercial, etc. – voir les politiques de la revue pour de plus amples détails).

UN NUMÉRO UNIQUE DANS LEQUEL VOUS VOULEZ PARAÎTRE!

Ce numéro spécial « audiologie et neurosciences » peut être considéré comme un véritable répertoire à propos de l'audiologie et des neurosciences au Canada. Ils sont publiés en format papier et envoyés à tous les membres nationaux et internationaux de l'ACA. Une version électronique est aussi disponible en ligne sur le site internet de la revue. Le contenu de ces numéros est indexé, donc facilement trouvable au moyen de moteurs de recherche classiques, tels que Google, Bing, etc… Les auteurs sont invités à bien choisir les mots clefs pour maximiser la visibilité de leur article.

Pour toutes questions, vous pouvez communiquer avec Mr. Olivier Valentin (olivier.valentin@etsmtl.ca). Pour réserver un espace de publicité dans un de ces numéros spéciaux, veuillez communiquer avec Bernard Feder (advertisement@caa-aca.ca).

UNE TELLE OPPORTUNITÉ NE SE REPRODUIRA PAS AVANT 7 OU 9 ANS,
ASSUREZ-VOUS D'EN PROFITER MAINTENANT!

CANADIAN ACOUSTICAL ASSOCIATION
ASSOCIATION CANADIENNE D'ACOUSTIQUE

ACOUSTICS WEEK IN CANADA 2019 – Edmonton AB

October 9-11, 2019
Sutton Place Hotel Edmonton

Welcome to Edmonton!

Edmonton looks forward to welcoming delegates to the 2019 Acoustics Week in Canada. Acoustics researchers, professionals, educators, and students from across the country are welcomed to Alberta's Capital for 3 days of plenary lectures and technical sessions. The Canadian Acoustical Association Annual General Meeting will be held in conjunction with the conference, along with the Acoustical Standards Committee Meeting, the conference banquet, and an exhibition of acoustical equipment and services.

Plenary Lectures/Technical Sessions

Acoustics Week in Canada 2019 will feature three plenary lectures covering current acoustical topics, and highlighting regional expertise and situations. Technical sessions will cover all major areas of acoustic interest, including Hearing Loss Prevention, Acoustical Standards, Architectural Acoustics, Noise Control, Shock and Vibration, Hearing and Speech Sciences, Musical Acoustics, Underwater Acoustics, Bioacoustics, and other topics.

Exhibition & Sponsorship

There will be an exhibition area for acoustical equipment, products, and services on Thursday October 10. If you or your company is interested in exhibiting, or if you would be interested in sponsoring a conference social event, technical session, coffee breaks, or student prizes, please contact the **Exhibition Coordinators.** The conference offers an excellent opportunity to showcase your company and products or services.

CANADIAN ACOUSTICAL ASSOCIATION
ASSOCIATION CANADIENNE D'ACOUSTIQUE

ACOUSTICS WEEK IN CANADA 2019 – Edmonton AB

Student Participation

Students (graduate and undergraduate) are enthusiastically encouraged to attend the conference. Travel subsidies and reduced registration fees will be available. Student presenters are also eligible to win prizes for best presentations.

Paper Submissions

The abstract deadline is June 14, 2019. Two-page summaries for publication in the proceedings of Canadian Acoustics are due by July 15, 2019. Please see further details on the conference website: http://awc.caa-aca.ca/

Contacts/Organizing Committee

Conference Chair	Benjamin V. Tucker, University of Alberta (benjamin.tucker@ualberta.ca)
Treasurer:	Corjan Buma, University of Alberta/ACI (meanu@ualberta.ca)
Technical Chairs:	Tara Vongpaisal, MacEwan University (saiken@dal.ca) Daniel Aalto, University of Alberta (aalto@ualberta.ca)
Exhibit/Sponsor Coordinators:	Philippe Moquin, Alberta Government (philippe.moquin@gov.ab.ca) Ellen Buchan, Alberta Government (ellen.buchan@gov.ab.ca)
Student Prizes and Subsidies:	Mary Ingraham, University of Alberta (maryi@ualberta.ca)

CONFERENCE WEBSITE:
https://awc.caa-aca.ca/

CANADIAN ACOUSTICAL ASSOCIATION
ASSOCIATION CANADIENNE D'ACOUSTIQUE

ACOUSTICS WEEK IN CANADA 2019 – Edmonton AB

Du 9 au 11 octobre 2019
Sutton Place Hotel Edmonton

Bienvenue à Edmonton !

Edmonton se réjouit d'accueillir les délégués de la Semaine canadienne d'acoustique 2019. Des chercheurs en acoustique, des professionnels, des éducateurs et des étudiants de partout au pays sont invités à la capitale de l'Alberta pour trois jours de séances plénières et de sessions scientifiques. L'assemblée générale annuelle de l'Association canadienne d'acoustique aura lieu en conjonction avec le congrès, ainsi que la rencontre du comité de normalisation en acoustique, le banquet du congrès, et une exposition d'équipements et de services acoustique. Le congrès se tiendra à l'hôtel Sutton Place Hotel Edmonton.

Séances plénières et sessions scientifiques

La Semaine canadienne d'acoustique 2019 mettra en vedette trois présentations plénières dans des domaines actuels d'intérêt en acoustique et mettant en évidence l'expertise et le cadre régional. Des sessions scientifiques porteront sur tous les domaines principaux d'intérêt en acoustique, y compris la prévention des pertes auditives, la normalisation, l'acoustique architecturale, le contrôle du bruit, les chocs et les vibrations, l'audition et les sciences de la parole, l'acoustique musicale, l'acoustique sous-marine, la bioacoustique marine, et d'autres sujets.

Expositions et commandites

Il y aura un espace d'exposition pour l'équipement en acoustique, les produits et les services le jeudi 10 octobre. Si vous ou votre entreprise êtes intéressé à exposer, ou si vous êtes intéressé à commanditer un événement social du congrès, une session scientifique, des café pauses, ou des prix d'étudiants, veuillez contacter **le coordonnateur de l'exposition.** Le congrès offre une excellente occasion de présenter votre entreprise et vos produits ou services.

CANADIAN ACOUSTICAL ASSOCIATION
ASSOCIATION CANADIENNE D'ACOUSTIQUE

ACOUSTICS WEEK IN CANADA 2019 – Edmonton AB

Participation des étudiants

Les étudiants de premier cycle et des cycles supérieurs sont chaleureusement encouragés à participer au congrès. Des subventions de voyage et les frais d'inscription réduits seront disponibles. Les présentateurs étudiants sont également admissibles à gagner des prix pour les meilleures présentations.

Soumissions

La date limite pour les résumés est le 14 juin, 2019. Des articles de deux pages pour publication dans les actes de congrès sont dues le 15 juillet, 2019. Veuillez voir plus de détails sur le site de la conférence:
http://awc.caa-aca.ca/

Contacts / Comité d'organisation

Présidents:	Benjamin V. Tucker, Université de l'Alberta (benjamin.tucker@ualberta.ca)
Trésorier:	Corjan Buma, University of Alberta/ACI (meanu@ualberta.ca)
Directeurs scientifiques:	Tara Vongpaisal, L'Université MacEwan (saiken@dal.ca) Daniel Aalto, Université de l'Alberta (aalto@ualberta.ca)
Coordinateur aux commandites:	Philippe Moquin, gouvernement de l'Alberta (philippe.moquin@gov.ab.ca) Ellen Buchan Moquin, gouvernement de l'Alberta (ellen.buchan@gov.ab.ca)
Prix étudiants et subventions:	Mary Ingraham, University of Alberta (maryi@ualberta.ca)

SITE WEB DU CONGRÈS
https://awc.caa-aca.ca/

7-11 july 2019

ICSV26 MONTRÉAL

26th International Congress on Sound & Vibration

The annual congress of the International Institute of Acoustics and Vibration (IIAV)

WELCOME TO ISCV26, MONTRÉAL, QC, CANADA

The International Institute of Acoustics and Vibration (IIAV) and the Canadian Acoustical Association (CAA) are pleased to invite scientists and engineers from all over the world to attend the 26th International Congress on Sound and Vibration (ICSV26) to be held in Montréal 7–11 July 2019.

This congress is a leading event in the area of acoustics and vibration and provides an important opportunity for scientists and engineers to share their latest research results and exchange ideas on theories, technologies and applications in these fields. The congress will feature a broad range of high-level technical papers from across the world: distinguished plenary lectures will present recent developments in important topics of sound and vibration and include discussions about future trends.

Montréal is an exciting, vibrating and welcoming destination. It's a city where delegates can enjoy a rich diversity of culture, museums, art galleries, night-life, gastronomy, shopping and sport, not to mention the International Jazz Festival right before the conference. Cosmopolitan Montréal offers something to suit every delegate!

THE CONGRESS VENUE: HOTEL BONAVENTURE

The congress venue will be the Hotel Bonaventure Montréal located in the heart of downtown Montréal. The Hotel Bonaventure Montréal is a true Garden of Eden overlooking the bustling streets of the city and easily connected to the underground city, central station and the business district, Old Montréal, and major attractions. A block of highly discounted rooms have been secured for ICSV26, and participants are invited to consider staying at the conference hotel to make their stay in Montréal a memorable experience! Details on accommodation at the congress venue and other hotels can be found on the ICSV26.org website.

CONGRESS SECRETARIAT ICSV26

École de technologie supérieure
1100 Notre-Dame West
Montréal (Québec)
H3C 1K3, Canada
info@icsv26.org

KEY DATES

For Registration	
Deadline for Early-Bird Registration	31 December 2018
Deadline for Early Registration	31 March 2019
Deadline for Late Registration	31 May 2019
Submission of Abstracts and Full Papers	
Abstract Deadline	1 December 2018
Deadline for Full-Length Paper Submission	31 March 2019

ORGANISED BY

International Institute of Acoustics and Vibration

In cooperation with

CANADIAN ACOUSTICAL ASSOCIATION
ASSOCIATION CANADIENNE D'ACOUSTIQUE

Jointly with

irsst
Institut de recherche Robert-Sauvé en santé et en sécurité du travail

CANADIAN ACOUSTICS ANNOUNCEMENTS - ANNONCES TÉLÉGRAPHIQUES DE L'ACOUSTIQUE CANADIENNE

Looking for a job in Acoustics?

There are many job offers listed on the website of the Canadian Acoustical Association!

You can see them online, under http://www.caa-aca.ca/jobs/

August 5th 2015

ICSV26 to be held in Montreal, July 2019

The 26th International Congress on Sound and Vibration (ICSV26) will held in Montreal, Canada, from 07 - 11 July 2019 at Hotel Bonaventure.

This conference is co-sponsored by the Canadian Acoustical Association. - Deadline for abstract submission is January 31st, 2019! - - You can also check out our website at www.icsv26.org - - Jeremie Voix (conference-chair@icsv26.org) - Franck Sgard (technical-chair@icsv26.org) -

October 12th 2017

ICA 2019

The ICA 2019 congress will be held 9-13 September 2019 in Aachen, Germany. It is promising to be an interesting and exciting event. - The deadline for Abstracts is 1 February 2019. Go to http://www.ica2019.org/authors/ for the online submission. - - - -

The ICA (with the support of the Acoustical Society of America and the German Acoustical Society) has established the ICA-ASA-DEGA Young Scientist Conference Attendance Grants Programme to help young acousticians attend ICA 2019. Each grant is currently up to 500 EUR from which a portion will be used to cover the conference registration and the remainder provided at the time of the conference. Candidates must be under 35 years on the day of the opening ceremony of the Congress and may be either undergraduate or postgraduate students, postdoctoral or young acousticians. Special attention will be given to applicants from developing countries. The deadline for applications for a ICA YS Grant is 1 February 2019. Go to http://icacommission.org/YSgrants.html for more information and application forms -

January 16th 2019

International Symposium on Room Acoustics - ISRA2019

The "International Symposium on Room Acoustics" in Amsterdam. ISRA 2019 is a satellite symposium to the ICA conference that takes place September 15 – 17 2019.

- You are cordially invited to participate in the conference and to submit your contributions. The agenda features interesting structured sessions but all submissions on the topic of room acoustics are very much appreciated. The existing session cover the following topics: - - Developments in prediction techniques - Experimental methods in room acoustics - Music rehearsal rooms and stage acoustics - Performer's adaptation to room acoustics - Room acoustic simulations as a tool for performance-based design - Room acoustic perception - Curved Architecture in Acoustics - Design fundamentals and strategies for concert halls and large auditoria - Metrics vs. Quality – What are we missing? - It goes without saying that distinguished keynote lectures and a concert in Concertgebouw Amsterdam are a central part of the conference's agenda. - - You can find detailed information at www.isra2019.eu. -

February 15th 2019

Acoustics Week in Canada 2019

We are pleased to announce that the 2019 Acoustics Week in Canada meeting will be in Edmonton, Alberta on October 9-11, 2019.

- We are pleased to announce that the 2019 Acoustics Week in Canada meeting will be in Edmonton, Alberta on October 9-11, 2019. Abstract submission is now open with abstracts due on June 14, 2019. We are also pleased to announce our three plenary speakers: - - -Hildegard Westerkamp (Soundscape Composition and Acoustic Ecology) - -Sonya Bird (Speech Acoustics and Indigenous Languages) - -Michelle Vigeant (Acoustics & Architectural Engineering) - - Please find the call for papers here <https://awc.caa-aca.ca/index.php/AWC/index/manager/files/AWC19/Call_for_papers_Combined.pdf>. More information can be found online at https://awc.caa-aca.ca/. - - We look forward to seeing you in Edmonton! - -

April 1st 2019

À la recherche d'un emploi en acoustique ?

De nombreuses offre d'emploi sont affichées sur le site de l'Association canadienne d'acoustique !

Vous pouvez les consulter en ligne à l'adresse http://www.caa-aca.ca/jobs/

August 5th 2015

International Symposium on Room Acoustics (ISRA 2019)

Le « Colloque International sur l'acoustique des salles» (plus connu sous le nom de « International Symposium on Room Acoustics » ou encore ISRA) qui aura lieu à Amsterdam du 15 au 17 septembre 2019 à la suite de la réunion de l'ICA (International Congress on Acoustics).

Vous êtes cordialement invités à nous soumettre vos contributions pour cette conférence. Des réunions intéressantes et structurées sont déjà au programme, mais tous les apports au thème de l'acoustique des salles sont les bienvenus. Les réunions couvrent les thèmes suivants : - - Developments in prediction techniques - Experimental methods in room acoustics - Music rehearsal rooms and stage acoustics - Performer's adaptation to room acoustics - Room acoustic simulations as a tool for performance-based design - Room acoustic perception - Curved Architecture in Acoustics - Design fundamentals and strategies for concert halls and large auditoria - Metrics vs. Quality – What are we missing? - - Le programme inclut aussi plusieurs allocations majeures sur le thème de l'acoustique, et offre la possibilité d'assister à un concert dans le hall principal du Concertgebouw. - Vous pouvez retrouver des informations détaillées sous le lien suivant : - http://www.isra2019.eu -

February 15th 2019

Semaine canadienne de l'acoustique 2019

La Semaine canadienne de l'acoustique 2019 se tiendra à Edmonton, en Alberta, du 9 au 11 octobre 2019.

Nous sommes heureux d'annoncer que la conférence de la Semaine canadienne de l'acoustique 2019 se tiendra à Edmonton, en Alberta, du 9 au 11 octobre 2019. La soumission des résumés est ouverte et les résumés doivent nous parvenir le 14 juin 2019. Nous avons également le plaisir d'annoncer nos trois conférenciers pléniers: - - -Hildegard Westerkamp (Soundscape Composition and Acoustic Ecology) - -Sonya Bird (Speech Acoustics and Indigenous Languages) - -Michelle Vigeant (Acoustics & Architectural Engineering) - - Veuillez trouver l'appel à contributions ici <https://awc.caa-aca.ca/index.php/AWC/index/manager/files/AWC19/Call_for_papers_Combined.pdf>. Plus d'informations peuvent être trouvées en ligne à https://awc.caa-aca.ca/. - -

April 1st 2019

INTERNATIONAL COMMISSION FOR ACOUSTICS ICA

The purpose of the ICA is to promote international development and collaboration in all fields of acoustics including research, development, education, and standardisation.

http://www.icacommission.org/

Contacts:
ICAPresident@icacommission.org
ICASecGen@icacommission.org
ICATreasurer@icacommission.org

To: ICA Member Societies
and International Affiliates

Dear Colleagues,

As you know, the International Commission for Acoustics has started preparations for the celebration of an International Year of Sound for the 2020 (IYS 2020). The IYS 2020 will not be included in the UNESCO and the UN's official list of International Years but will have a similar format, with events centrally organized by an IYS 2020 Liaison Committee, events organized by the ICA National Societies and International Affiliates and possibly events organized by the Week of Sound (WoS) a French non-governmental organization which had the initiative to approach to convince UNESCO to approve the Resolution 39 C/49 25 September 2017 “THE IMPORTANCE OF SOUND IN TODAY’S WORLD” . The IYS 2020 will make reference to the necessity for promoting best practices in the framework of this resolution and we have already informed UNESCO about that.

The ICA and the WoS will create a Liaison Committee to coordinate the IYS 2020. For the time being the ICA representatives are Michael Taroudakis (President) and Marion Burgess (Past President). In addition, an ICA/IYS 2020 steering committee will be formed to coordinate all the events to be organized by the ICA Member Societies and will have representatives from all the regions.

In order to prepare the events of the IYS 2020 in the most efficient way, we are asking each of the ICA Members and our International Affiliates to appoint one representative to be in direct contact with the ICA/IYS 2020 steering committee. The contact person will have the responsibility to communicate all the planned events by his/her organization to the ICA/IYS 2020 steering committee and also to convey and discuss with them any ideas or suggestions about the events and activities to be included in the IYS 2020.

The attached file describes the main idea of the events to be included in the IYS 2020.

Please send the name and contact details of your representative to the ICA Secretary General Mike Stinson (ICASecGen@icacommission.org). If you have any questions or comments, please contact me (ICAPresident@icacommission.org).

I hope that with your collaboration, the importance of sound in today's world will reach every part of our planet in 2020.

With my best regards

Michael Taroudakis
President of the ICA

INTERNATIONAL YEAR OF SOUND 2020

National/International Coordinators

Education and Outreach on Sound for Society and the World

Culture – Creativity – Nature – Health – Science – Technology

Development – Education – History

Outcome of the UNESCO Charter of Sound

MISSION

The International Commission for Acoustics has decided to declare the Year 2020 as the International Year of Sound (IYS 2020). The IYS 2020 will not take the form of an official International year sponsored by UNESCO and the UN, but will have a structure similar to such an official International Year with many events to be organized centrally by the IYS 2020 steering committee or regionally by the ICA members Societies and the Week of Sound, which will be a partner to ICA in his celebration.

The International Year of Sound follows naturally as an important contribution to the UNESCO Charter of Sound. The year will be a global initiative to highlight the importance of sound in all aspects of life on earth and will work towards an understanding of sound-related issues at the international level.

ACTIVITIES/EVENTS IYS 2020

These will fall into three main categories:

- Centrally organized broad area events/outcomes funded by ICA and sponsors.
- Those organized and funded by ICA Member societies and organisations.
- Those organized by the Week of Sound (WoS) funded in the normal manner by the WoS (also referred to as La Semaine du Son).

LIAISON AND STEERING COMMITTEES

The ICA and the WoS will create a Liaison Committee to coordinate the IYS 2020. For the time being the ICA representatives are Michael Taroudakis (President) and Marion Burgess (Past President).

Also, an ICA IYS 2020 Steering Committee will be formed to coordinate all the activities of the IYS 2020, which will include events managed by ICA Member Societies and supporting Organisations. Members of this Committee will be representatives from all the ICA Regions.

STRUCTURE FOR ICA MEMBER ORGANISATIONS ACTIVITIES/EVENTS

Each member organisation/society is asked to nominate a coordinator to be the primary contact with the ICA IYS steering committee

The coordinator will discuss with the organization/society the events/activities that can be undertaken during 2020 and will help to promote one or more aspects of acoustics.

Once the activities are decided upon, the coordinator will provide a concise summary plus dates to the IYS steering committee for endorsement as an official IYS activity.

Each activity endorsed will have the authority to use the IYS 2020 logo and be included in the official IYS 2020 website calendar and other promotion.

All funding for the event/activity must be provided for the activity by the member society or organization and no central funding will be provided

The steering committee will provide some promotional material to the coordinator. The steering committee will also promote the activity internationally as appropriate.

At the completion of the activity, the coordinator will be responsible for providing a concise report plus photos and links to supplementary material. This will be loaded onto the IYS 2020 website as a future resource.

TYPES OF ICA MEMBER ORGANISATIONS ACTIVITIES/EVENTS

All activities that relate to the mission of the IYS 2020 would be relevant. While commercial sponsorship is encouraged, and hence there would be some advertisement, the coordinator is responsible to ensure that the activity is not solely aimed to promote the company or particular products.

This IYS 2020 is the opportunity to promote to the world the importance of sound to all aspects of our life. Organisations are encouraged to consider outreach activities and to be innovative.

The following are some suggestions but it is up to each organisation to consider what may be appropriate for their region/resources

Activities related to the annual meeting or conference.

Activities related to relevant "days" throughout the year such as

- International Noise Awareness Day - Wednesday, 29 April 2020.
- World Hearing Day - 3 March 2020.
- International Mother Language Day - Friday 21 February 2020.

Activities related to education.

These will naturally take longer but the outcome will be long lasting.

The package of activities could include production of any material (digital/video/audio) addressing a particular topic or area or age group.

Also it could include specific events dedicated to teachers and students in collaboration with educational institutes and especially with priparay and secondary level schools.

Activities addressed to the general public

The activation of the Public Media is essential in conveying the message of the International Year of sound to the general public. The National Societies and International Affiliates are encouraged to use all possible means of communication with the community to explain the important of sound for our lives to all the citizens.

TYPES of ICA ORGANIZED AND CENTRALLY FUNDED EVENTS:

The following is a provisional list of centrally organized events for the IYS 2020

- Design of promotional material (posters and leaflets) to be distributed electronically to ICA members and International Organizations. The ICA members will include this material in their web-sites. After printing, these leaflets will be available for distribution to all the events related to the IYS. Banners for the IYS 2020 will be produced to be displayed in the IYS 2020 focal events as well any other events of the ICA and The Week of Sound.
- Organization of the opening ceremony of the IYS 2010 in Paris in 2020. The details and the program of the opening event will be set later this year.
- Organization of world-wide competitions for students of primary and secondary schools respectively. The subject of the competitions will be decided by the IYS 2020 Liaison Committee.
- Development of a video to promote the objectives of the IYS 2020. The film should be of short duration, 5 min max, and will be shown to all conferences and events coordinated by ICA, and its Member Societies and associations as well as to the events of The Week of Sound. This film can also be used as promotional material for the IYS 2020.
- Development of a video for use in education on the importance of sound in our world and to provide guidance on the career opportunities.

MAJOR INTERNATIONL CONFERENCES ASSOCIATED WITH THE IYS 2020

The organisers of at least the following major events during 2020 will be asked to include some form of activity/event in recognition of IYS 2020. Additional International Conferences on Acoustics may be added in this list based on the approval of the ICA Steering Committee.

- FORUM ACUSTICUM (the EAA main conference) Lyon, France, 20-24 April 2020.
- 179th Meeting of the ASA Chicago, Illinois 11-15 May 2020.
- ICSV 27, Prague, Czech Republic, July 2020.
- Internoise 2020, Seoul, Korea, 23-26 August 2020.
- FIA 2020 - 12° Iberoamerican Congress on Acoustics, Florianopolis, Brazil, 27-20 September 2020.
- 180th Meeting of the ASA Cancun, Mexico 9-13 November 2020.

Why publish in Canadian Acoustics?


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of the Canadian Acoustical Association - Journal de l'Association Canadienne d'Acoustique

SEPTEMBRE 2

Volume -- Numé

Because, it is...

- A respected scientific journal with a 40-year history uniquely dedicated to acoustics in Canada
- A quarterly publication in both electronic and hard-copy format, reaching a large community of experts worldwide
- An Open Access journal, with content freely available to all, 12 months from time of publication
- A better solution for fast and professional review providing authors with an efficient, fair, and constructive peer review process.

Pourquoi publier dans Acoustique canadienne ?

Parce que, c'est...

- Une revue respectée, forte de 40 années de publications uniquement dédiée à l'acoustique au Canada
- Une publication trimestrielle en format papier et électronique, rejoignant une large communauté d'experts à travers le monde
- Une publication "accès libre" dont le contenu est disponible à tous, 12 mois après publication
- Une alternative intéressante pour une évaluation par les pairs, fournissant aux auteurs des commentaires pertinents, objectifs et constructifs

Canadian Acoustical Association
Association canadienne d'acoustique

Application for Membership

CAA membership is open to all individuals who have an interest in acoustics. Annual dues total $120.00 for individual members and $50.00 for student members. This includes a subscription to ***Canadian Acoustics***, the journal of the Association, which is published 4 times/year, and voting privileges at the Annual General Meeting.

Subscriptions to *Canadian Acoustics* *or* Sustaining Subscriptions

Subscriptions to ***Canadian Acoustics*** are available to companies and institutions at a cost of $120.00 per year. Many organizations choose to become benefactors of the CAA by contributing as Sustaining Subscribers, paying $475.00 per year (no voting privileges at AGM). The list of Sustaining Subscribers is published in each issue of ***Canadian Acoustics*** and on the CAA website.

Please note that online payments will be accepted at http://jcaa.caa-aca.ca

Address for subscription / membership correspondence:

Name / Organization ______________________________
Address ______________________________
City/Province ______________ Postal Code __________ Country ______________
Phone ______________ Fax ______________ E-mail ______________

Address for mailing Canadian Acoustics, if different from above:

Name / Organization ______________________________
Address ______________________________
City/Province ______________ Postal Code __________ Country ______________

Areas of Interest: (Please mark 3 maximum)

1. Architectural Acoustics
2. Engineering Acoustics / Noise Control
3. Physical Acoustics / Ultrasound
4. Musical Acoustics / Electro-acoustics
5. Psychological / Physiological Acoustic
6. Shock and Vibration
7. Hearing Sciences
8. Speech Sciences
9. Underwater Acoustics
10. Signal Processing / Numerical Methods
11. Other

For student membership, please also provide:

______________ ______________ ______________________________
(University) *(Faculty Member)* *(Signature of Faculty Member)* *(Date)*

I have enclosed the indicated payment for:
[ ] CAA Membership $ 120.00
[ ] CAA Student Membership $ 50.00

Corporate Subscriptions (4 issues/yr)
[ ] $120 including mailing in Canada
[ ] $128 including mailing to USA,
[ ] $135 including International mailing

[ ] Sustaining Subscription $475.00
(4 issues/yr)

Please note that the preferred method of payment is by credit card, online at http://jcaa.caa-aca.ca

For individuals or organizations wishing to pay by check, please register online at *http://jcaa.caa-aca.ca* and then mail your check to:

Executive Secretary, Canadian Acoustical:
Dr. Roberto Racca
c/o JASCO Applied Sciences
2305–4464 Markham Street
Victoria, BC V8Z 7X8 Canada

Association Canadienne d'Acoustique
Canadian Acoustical Association

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