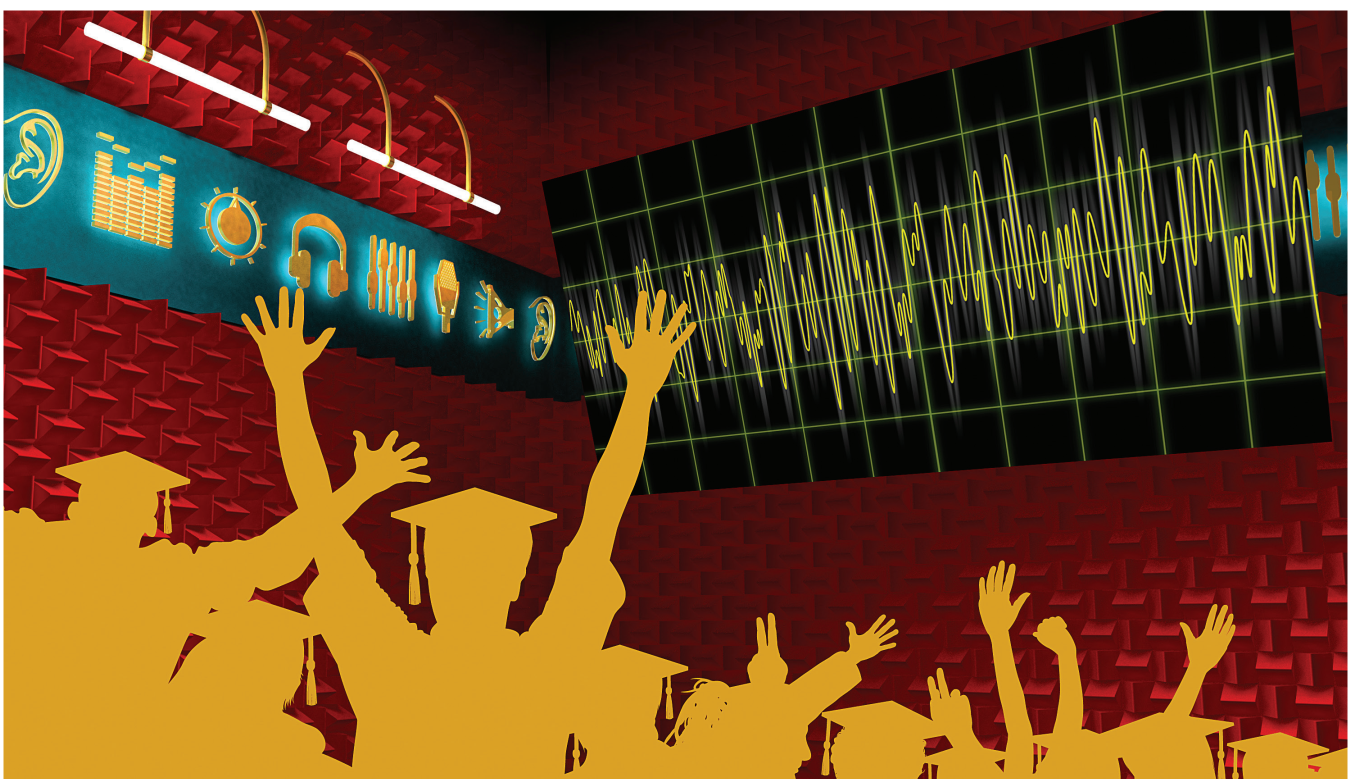
ISSN 0711-6659

canadian acoustics
acoustique canadienne

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

SEPTEMBER 2013 SEPTEMBRE 2013
Volume 41 -- Number 3 Volume 41 -- Numéro 3



canadian acoustics

acoustique canadienne

THE CANADIAN ACOUSTICAL ASSOCIATION
P.O. BOX 1351, STATION "F"
TORONTO, ONTARIO M4Y 2V9

L'ASSOCIATION CANADIENNE D'ACOUSTIQUE
C.P. 1351, SUCCURSALE "F"
TORONTO, ONTARIO M4Y 2V9

CANADIAN ACOUSTICS publishes refereed articles and news items on all aspects of acoustics and vibration. Articles reporting new research or applications, as well as review or tutorial papers and shorter technical notes are welcomed, in English or in French. Submissions should be sent directly to the Editor-in-Chief. Complete instructions to authors concerning the required camera-ready copy are presented at the end of this issue.

CANADIAN ACOUSTICS is published four times a year - in March, June, September and December. Copyright on articles is held by the author(s), who should be contacted regarding reproduction. Annual subscription: $40 (student); $90 (individual, institution); $400 (sustaining - see back cover). Back issues (when available) may be obtained from the CAA Secretary - price $25 including postage. Advertisement prices: $350 (full page- $1200 for four issues); $200 (half page - $700 for four issues); $150 (quarter page - $500 for four issues). Contact the Associate Editor (advertising) to place advertisements. Canadian Publication Mail Product Sales Agreement No. 0557188.

ACOUSTIQUE CANADIENNE publie des articles arbitrés et des informations sur tous les domaines de l'acoustique et des vibrations. On invite les auteurs à soumettre des manuscrits, rédigés en français ou en anglais, concernant des travaux inédits, des états de question ou des notes techniques. Les soumissions doivent être envoyées au rédacteur en chef. Les instructions pour la présentation des textes sont exposées à la fin de cette publication.

ACOUSTIQUE CANADIENNE est publiée quatre fois par année - en mars, juin, septembre et décembre. Les droits d'auteur d'un article appartiennent à (aux) auteur(s). Toute demande de reproduction doit leur être acheminée. Abonnement annuel: $40 (étudiant); $90 (individuel, société); $400 (soutien - voir la couverture arrière). D'anciens numéros (non-épuisés) peuvent être obtenus du Secrétaire de l'ACA - prix: $25 (affranchissement inclus). Prix d'annonces publicitaires: $350 (page pleine - $1200 pour quatre publications); $200 (demi page - $700 pour quatre publications); $150 (quart de page - $500 pour quatre publications). Contacter le rédacteur associé (publicité) afin de placer des annonces. Société canadienne des postes - Envois de publications canadiennes - Numéro de convention 0557188.

EDITORIAL / EDITORIAL

The September issue of Canadian Acoustics is normally the proceedings issue of Acoustics Week in Canada. However, given the joint meeting earlier this year of the Canadian Acoustical Association and the Acoustical Society of America (ASA) under the aegis of the International Commission for Acoustics, proceedings have been published in the ASA's Proceedings of Meetings on Acoustics (Volume 19). In its place, I am pleased to present a special issue dedicated to research by new Scholars. All lead authors published herein are within 10 years of the terminal degree. We are fortunate to be witnessing a period of continued growth in all areas of acoustics. This growth is fueled by new scholars who are working to advance established subfields as well as to create new ones.

The current issue captures a representative sample of this growth spanning bio-acoustics, psychological acoustics, underwater acoustics, noise control, and speech sciences.
The focus on new scholars is timely given the renewal that the journal has undergone recently. In December of 2012, the editorial board was renewed and past issues of the journal became available online at jcaa.caa-aca.ca. Since that time there has been an increase in the rate of submissions to the journal. To stay ahead of these increases, we have phased in an electronic manuscript submission system and reduced the time it takes to reach an editorial decision (8 weeks currently). Access to the journal is also open with the exception of issues published within the most recent calendar year. These changes are helping to increase the visibility of the journal and to disseminate its contents more widely. Looking forward, the renewal at the journal will continue with Jérémie Voix taking over my role as Editor effective March of 2014.

Frank Russo
Editor-in-Chief

Le numéro du mois de septembre de l'Acoustique Canadienne est normalement consacré aux actes de conférence de la Semaine canadienne d'acoustique. Or, en raison de la réunion conjointe de l'Association Canadienne d'Acoustique et la Acoustical Society of America (ASA) qui a eu lieu un peu plus tôt cette année sous les auspices de la Commission internationale d'acoustique, les actes de conférence ont paru dans le journal Proceedings of Meetings on Acoustics (volume 19) de l'ASA. Je suis donc heureux de vous présenter ce numéro spécial portant sur les travaux de nouveaux chercheurs. Tous les auteurs principaux des articles publiés dans ce numéro ont obtenu leur dernier diplôme universitaire au cours des dix dernières années. Nous sommes chanceux d'être témoins d'une période de croissance continue dans tous les domaines de l'acoustique. Cette croissance est alimentée par les nouveaux chercheurs qui contribuent à l'avancement de sous-disciplines établies de même qu'à la création de nouvelles. Ce numéro présente donc un échantillon représentatif de cette croissance, avec des articles portant sur la bioacoustique, la psycho-acoustique, l'acoustique sous-marine, le contrôle du bruit et la science de la parole.

Cette emphase sur les travaux des nouveaux chercheurs coïncide avec des nouveautés au sein du journal. En effet, en décembre 2012, le comité de rédaction a été renouvelé et les anciens numéros du journal sont devenus disponibles en ligne au jcaa.caa-aca.ca. Depuis ce temps, il y a eu une hausse du taux de soumissions au journal. Pour répondre à cette hausse, nous avons mis sur pied un système électronique pour la soumission de manuscrits et réduit le temps nécessaire pour les décisions éditoriales (présentement à 8 semaines). De plus, l'accès au journal est ouvert à l'exception des numéros publiés dans la dernière année. Ces changements contribuent à la visibilité du journal et à une plus grande diffusion. Enfin, Jérémie Voix prendra la relève en tant que rédacteur, en mars 2014.

Frank Russo
Rédacteur en chef

WHAT'S NEW in Canada ??

Promotions
Deaths
New jobs
Moves
Retirements
Degrees awarded
Distinctions
Other news

Do you have any news that you would like to share with Canadian Acoustics readers? If so, send it to:

QUOI DE NEUF en Canada??

Promotions
Décès
Offre d'emploi
Déménagements
Retraites
Obtention de diplômes
Distinctions
Autres nouvelles

Avez-vous des nouvelles que vous aimeriez partager avec les lecteurs de l'Acoustique Canadienne? Si oui, écrivez-les et envoyer à:

Jéremie Voix - Email: voix@caa-aca.ca

EFFECTS OF CONSTRUCTION NOISE ON THE COOK INLET BELUGA WHALE (*DELPHINAPTERUS LEUCAS*) VOCAL BEHAVIOR

Lindsey Saxon Kendall[1], Ana Širović[1, 2], Ethan H Roth[3]

1-Alaska Pacific University, 4101 University Drive, Anchorage, AK 99508, USA
2-current address: Scripps Institution of Oceanography, University of California San Diego, 9500 Gilman Drive MC 0205, La Jolla, CA 92093-0205, USA
3-School of Ocean and Earth Science and Technology, University of Hawai'i at Manoa, 1000 Pope Road, Honolulu, HI 96822, USA

ABSTRACT

Cook Inlet beluga whales (*Delphinapterus leucas*) are listed as endangered under the US Endangered Species Act. Potential threats to this population include anthropogenic noise and coastal zone development. The Port of Anchorage Marine Terminal Redevelopment (MTR) Project, taking place in the Knik Arm of Cook Inlet, Alaska, involves multiple construction activities including dredging, gravel fill and pile driving. The impacts of construction noise on beluga vocalizations were investigated in this study. Passive sonobuoys were deployed in a four mooring array during 20 d in August and September 2009 near the MTR Project. Data were recorded in real-time at a shore-based observation station. No beluga whistles or noisy vocalizations were recorded during this period; however, beluga echolocation clicks were frequently detected. An energy summation method was used to automatically detect echolocation clicks. Times with and without construction noise (*i.e.*, dredging and pile driving) were determined from long-term spectral averages. The detected hourly click rate was higher during times without (429 detected clicks/h) than with (291 detected clicks/h) construction activity; however, the difference was not statistically significant ($t_{(24)} = -0.56$, $P = 0.58$). Lower frequency beluga whale vocalizations (*e.g.*, whistles) were potentially masked, there may be have been an overall reduction in beluga vocalizations, or it is possible belugas were avoiding the area during construction activity.

RÉSUMÉ

Le béluga (*Delphinapterus leucas*) de Cook Inlet est en voie de disparition selon le Loi sur les Espèces en Voie de Disparition des EE.UU. Ses animaux ont le potentiel d'être menacé par des bruits d'origine anthropique et le développement du secteur côtier. Le projet de Réaménagement de Terminal Marine (RTM) du Port de Anchorage, qui aura lieu à Knik Arm de Cook Inlet, Alaska, consiste de plusieurs travaux, comme le dragage, remplissage du gravier et de battage des pieux. Dans cette étude, on a investigué les effets du bruit des travaux sur les vocalises des bélugas. Bouées acoustiques ont été déployées dans un réseau de quatre mouillages pendant 20 jours en Août et Septembre 2009, près du projet RTM. Les données ont été recueillies en temps réel à une station d'observation côtière. Les sifflets ou vocalisations bruyantes des bélugas n'ont pas été enregistrées pendant cette période, mais les clics d'écholocation ont été détectés fréquemment. La somme de l'énergie a été utilisée pour détecter d'une manière automatique des clics d'écholocation. Les temps avec et sans bruit des travaux (c'est-à le dragage et battage) ont été déterminés par l'examen des spectrogrammes comprimé. Le taux de clic détecté était plus élevé pendant les périodes sans travaux (429 clics détectés / h) qu'avec (291 détecté clics / h), mais la différence n'était pas statistiquement significatif (t (24) = 0,56, P = 0,58). Le vocalises des bélugas de la fréquence basse (par exemple, sifflets) ont été potentiellement masqués, il peut y avoir eu une générale réduction des vocalisations des bélugas, ou il est possible que les bélugas évitaient la domaine pendant l'activité de construction.

1. INTRODUCTION

Cook Inlet beluga whales (*Delphinapterus leucas*) are geographically isolated and genetically distinct from other US beluga whale stocks (O'Corry-Crowe *et al.* 1997, Laidre *et al.* 2000, O'Corry-Crowe *et al.* 2002). In 2008, the population was listed as endangered under the US Endangered Species Act (NMFS 2008*a*). The population, currently estimated at 312 individuals (Hobbs *et al.* 2012), was expected to increase 2-6% per year following increased restrictions on the subsistence harvest of beluga in 1999 (Hobbs *et al.* 2008). However, population trends since harvest restrictions indicate a continued decline of 1.3% per year (Hobbs *et al.* 2012). Many factors are identified as potential threats to the Cook Inlet beluga whale, including coastal zone development and anthropogenic noise (NMFS 2008*b*). Known effects of noise on cetaceans include behavioral changes, avoidance or displacement from important habitat, masking of important sounds and changes to acoustic behavior (Richardson *et al.* 1995, Lesage *et al.* 1999, McDonald *et al.* 2006).

Beluga whales have highly developed hearing and vocal abilities. Their hearing is most sensitive from 10-100 kHz (Awbrey *et al.* 1988, Johnson *et al.* 1989, Richardson *et al.* 1995) which is related to their use of high frequencies for echolocation and communication (Richardson *et al.* 1995). Beluga whales were one of the first cetaceans to be recorded underwater and they were found to produce a variety of sounds (Schevill and Lawrence 1949). Beluga whale whistles range between 0.26-20 kHz, pulsed tones between 0.4-12 kHz, noisy vocalizations between 0.5-16 kHz (Schevill and Lawrence 1949, Sjare and Smith 1986*a*, *b*, Richardson *et al.* 1995) and their echolocation clicks have been recorded up to 120 kHz (Au *et al.* 1985). Whistles, noisy vocalization and pulsed sounds at lower frequencies are generally associated with social behaviors (Sjare and Smith 1986*b*, Faucher 1988, Karlsen *et al.* 2002, Belikov and Bel'kovich 2006, 2007, 2008), while high frequency echolocation clicks are generally associated with navigation and foraging (Au *et al.* 1985, Au *et al.* 1987, Faucher 1988, Turl and Penner 1989, Turl 1990).

Beluga whale vocalizations have been studied in stocks found in Cunningham Inlet (Sjare and Smith 1986*a*, *b*), Churchill River (Chmelnitsky and Ferguson 2012) and St. Lawrence Estuary, Canada (Faucher 1988), Bristol Bay, Alaska (Angiel 1997), Svalbard, Norway (Karlsen *et al.* 2002) and the White Sea in Russia (Belikov and Bel'kovich 2006, 2007, 2008), as well as in captive animals (Au *et al.* 1985, Au *et al.* 1987, Turl and Penner 1989, Lammers and Castellote 2009). Similarities in whistles, pulsed sounds and noisy vocalizations among these stocks include frequency band, contour types, duration of contour types and the production of multicomponent whistles (Sjare and Smith 1986*a*, Karlsen *et al.* 2002, Belikov and Bel'kovich 2006, 2007, 2008). Echolocation clicks have been examined in captive belugas (Au *et al.* 1985, Au *et al.* 1987, Turl and Penner 1989, Lammers and Castellote 2009), but have not been compared between wild stocks. Belugas emit two distinct pulses in a single echolocation click (Lammers and Castellote 2009) and their click trains can be separated into three categories based on their distinctly different interclick interval patterns (Au *et al.* 1987). Additionally, beluga clicks may vary in frequency and bandwidth depending on the ambient noise levels (Au *et al.* 1985). Currently, there are no peer-reviewed studies on the vocal repertoire of the Cook Inlet beluga whale.

The presence of anthropogenic noise can affect marine mammals behaviorally, acoustically and physiologically (Nowacek *et al.* 2007). Beluga whale behavioral responses in the presence of anthropogenic noise (*e.g.*, watercraft, aircraft and pile driving) include changes in swimming speed, diving patterns, direction, behavioral states (Patenaude *et al.* 2002), avoidance (Blane and Jaakson 1994, Erbe and Farmer 2000) and vocalizations (Lesage *et al.* 1999, Scheifele *et al.* 2005). Changes in beluga vocalizations include a reduction in call rate, increase in the production of tonal and pulsed calls, shift in frequency band (Lesage *et al*. 199) and the Lombard vocal response (Scheifele *et al.* 2005). In addition, documented beluga responses in the presence of pile driving activity include changes in sighting duration, behavior (*e.g.*, traveling and diving), group composition and group formation (*e.g.*, densely packed or dispersed; Kendall 2010).

A way to increase our understanding of the effects of anthropogenic noise on marine mammals is to use passive acoustic monitoring studies. Passive acoustic monitoring is an innovative technique that is increasingly used for cetacean surveys (Mellinger *et al.* 2007). Traditional visual surveys require daylight and good weather conditions, often resulting in low detection rates (Mellinger *et al.* 2007), while passive acoustic monitoring can continue throughout the night and in poor weather conditions (Barlow and Taylor 2005; Mellinger *et al.* 2007). Sonobuoy hydrophones are relatively inexpensive and have been used successfully for a variety of passive acoustic studies, including documenting the presence and locations of calling animals at high latitudes in challenging environmental conditions (Clark and Ellison 1988, McDonald and Moore 2002, Laurinolli *et al.* 2003, Širović *et al.* 2006).

The Port of Anchorage (POA) Marine Terminal Redevelopment (MTR) Project in the Knik Arm of Cook Inlet, Alaska, takes place in an area frequented by beluga whales (Rugh *et al.* 2000, Hobbs *et al.* 2005). The MTR Project involves several types of construction activities including dredging, gravel fill and pile driving. The combination of these construction activities increases underwater noise levels that could interfere with beluga whale communication and echolocation (Richardson *et al.* 1995, NMFS 2008*c*). We investigated the presence of different beluga whale vocalizations in these recordings and evaluated the impact of construction noise adjacent to the MTR Project on beluga whale echolocation using a fixed array of sonobuoys. Data were manually examined for beluga vocalizations in real-time during data collection and then again by examining long-term spectral averages (LTSA).We used an automatic detector to determine the presence of echolocation clicks in 20 d of recorded data. We determined time periods with and without construction noise and then calculated the detected hourly click rate to determine if there are differences in the rate of detected beluga whale clicks with and without construction activity near the MTR Project.

2. METHODS

2.1 Study Design

The study was conducted in the Knik Arm of Upper Cook Inlet, adjacent to the MTR Project near Anchorage, Alaska, close to in-water construction activities (Figure 1). Four moored lines were deployed in a rhomboid formation on 1 August and were left in the water until 7 October, 2009 (Figure 1). Each mooring was anchored with approximately 270 kg of railroad rail sections and attached to a 45-55 m line with a surface float. These moorings allowed quick re-deployment of multiple sonobuoys in the array throughout the survey. After each sonobuoy deployment, observers at the Cairn Point Station (CPS) on Joint Base Elmendorf-Richardson monitored and recorded signals received from the sonobuoys in real-time. The location of the moorings was chosen based on proximity to the construction activity at the MTR Project, favorable bathymetric conditions, and relative safety from dredging and shipping operations. The time period of this study (late summer and early fall) was chosen to correspond with times when beluga whales are most frequently observed in the area (Rugh *et al.* 2000, Hobbs *et al.* 2005). The days and times of sonobuoy deployments and acoustic data collection were driven by tides and weather conditions, limiting the ability to launch the deployment boat, which could not be done during low tide.

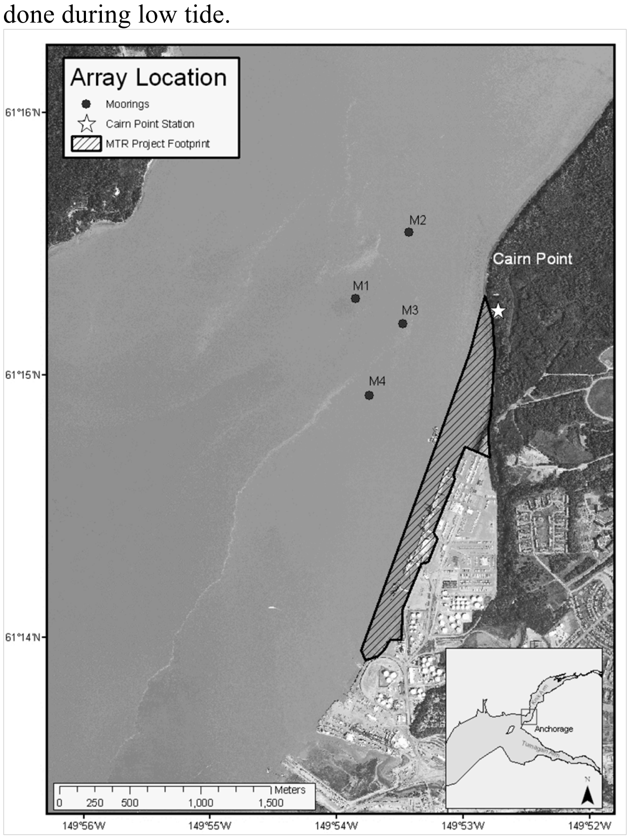


Figure 1. The location of the fixed array of 4 moored lines (black dots), placed between 400 and 700 m apart and approximately 600 m off Cairn Point. Passive sonobuoys were attached to the moorings during each day of acoustic monitoring. The Marine Terminal Redevelopment (MTR) Project footprint is outlined and crosshatched and Cairn Point Station is denoted by the star.

Passive sonobuoys are relatively inexpensive, expendable electronic devices that consist of a hydrophone, surface float, radio transmitter, antenna and salt-water battery. Omnidirectional sonobuoys, AN/SSQ-57B, used in this study have a calibrated broadband frequency response from 10-20,000 Hz, but can effectively detect signals up to 30 kHz (Horsley 1989). Signals received by the omnidirectional hydrophone are amplified and conducted up a cable to the radio transmitter and antenna, which are housed in the surface float.

Prior to each deployment, the sonobuoys were modified to withstand the high tidal current conditions of Knik Arm. Each sonobuoy was stripped from its original housing and placed in a plastic canister attached to a life ring. The life ring provided additional structural support and buoyancy against the fast moving currents, allowing the sonobuoy surface float to remain in a vertical position on the surface for sufficient signal transmission to the CPS. Twenty-seven m (90 ft) of cable and the clumped weight, preamplifier and hydrophone were passed through an opening on the bottom of the canister, which allowed the hydrophone and cable to suspend in the water column. A life ring with one sonobuoy was attached to each mooring float at the beginning of each day of acoustic observations. Previously deployed sonobuoys were collected each time before the deployment of new sonobuoys. The deployment location was recorded on each day of acoustic observations using a handheld Garmin GPS to verify the location of the moorings. The daily position of each mooring was compared to its deployment location to verify the moorings did not move during the study. Once deployed, the sonobuoys continuously transmitted their radio signal to the observers at the CPS until scuttling 8-10 h later. In the case of a non-operational sonobuoy, the deployment team immediately recovered the failed sonobuoy and deployed another one. Due to restrictions in the ability to launch a boat for sonobuoy deployment, most data collection started on the slack high tide and proceeded during the ebb flow.

Two omnidirectional Diamond D130J Super Discone antennae were mounted on the observational platform at the CPS to receive radio signals from the sonobuoys. A set of custom electronics and software was used to record and analyze the acoustic data. The antennae passed the signals to four software-controlled ICOM scanner radio receivers (IC-PCR 100 or IC-PCR1500 models), each tuned to receive individual FM signals transmitted by the sonobuoy array. Each radio was connected to a computer, which was connected to a MOTU Traveler mk2 that acquired the analog signal and provided a digitized output to another computer running the software program *Ishmael* (Mellinger 2001). Sample rates were initially adjusted to test electronics' capability and maximize recording capacity. On 3 August, data were sampled at 44 kHz, from 4-18 August the sampling rate was 48 kHz and from 20 August-30 September the sampling rate was 88.2 kHz. Data were saved as .WAV files.

During the daily acoustic observation period at CPS following sonobuoy deployments, construction and environmental data were collected and preliminary acoustic analysis was manually conducted. Data collected during the observation period included: deployment date, time, latitude, longitude and transmission channel for each sonobuoy as reported by the deployment team;

beginning and end of the acoustic observation period; start and end time of vocalizations (if detected), the species detected, and the channel(s) with vocalizations; environmental conditions; type of construction activity (*e.g.*, impact pile driving [IPD] or vibratory pile driving [VPD]); and duration of construction activity. Construction activities were defined as any anthropogenic activities associated with the construction of the MTR Project. All anthropogenic activities within the study area were also documented during daily observation efforts. Events were categorized as: no activity, IPD, VPD, dredging, in-water gravel fill placement, and aircraft and vessel activities. The duration of each activity was recorded. Data were entered into *Microsoft Excel* for *Windows*.

2.3 Data Analysis

Sonobuoy recordings were manually examined for beluga whale social vocalizations in real-time during data collection by listening to incoming recordings and visually scrutinizing scrolling spectrograms using the software program *Ishmael* (Mellinger 2001). In post-processing, an energy summation algorithm was used for the automatic detection of echolocation clicks. An energy detector was selected as an automatic detection method due to the short duration and broadband frequency of beluga whale clicks. To reduce the number of false detections, the ratio between the energy in the frequency band of interest (*i.e.* echolocation click) and that in an adjacent band of noise not containing the sound of interest was used. The frequency band used for the calculation of signal energy was 23-25 kHz, which was compared to the energy in the adjacent "noise" frequency band from 18-20 kHz. Due to the initial variation in sampling rate from 3-18 August, the energy summation parameters were adjusted to account for the difference in sampling rate (44 kHz and 48 kHz). Files from 3 August were manually scanned for echolocation clicks. Detections for 4-18 August were based on the energy ratio between the energy in the signal band from 23-23.9 kHz and the noise band from 15-18 kHz. When *Ishmael* signaled a detection, 2 s of the signal before and after the detection were saved into an individual .WAV file. Each file was visually verified for the presence of beluga whale echolocation clicks and false detections were removed from subsequent analysis.

Long-term spectral averages (LTSAs; Wiggins and Hildebrand 2007, Wiggins *et al.* 2010), were used to manually review the data for beluga social vocalizations and to determine times with and without construction activity (Figure 2). LTSAs were calculated with 10 s time bins and 500 Hz frequency resolution from the original .WAV files using *Triton*, a *MatLab* (MathWorks, Natick, MA) based customized sound analysis program developed by Wiggins *et al.* (2010). Only data where clicks were detected were used in the analysis on the effect of noise on echolocations. Each LTSA was manually scanned for the start and end of construction activity. Manual classification, rather than a more objective, automated classification was necessary because of the constantly varying effects of tides and currents on the overall sonobuoy signal strength, which was difficult to quantify and implement in an automatic framework. All construction activities (IPD, VPD, dredging) were pooled because they frequently overlapped and were not easily distinguishable in the LTSA. Gravel fill did not take place during the study, and therefore, was not included in the analysis. Times when pile driving (IPD or VPD) or dredging took place were considered time periods "with" construction activity. All other time periods were considered "without" construction activity. Although time periods without construction activity may have included other sources of anthropogenic noises such as air- or watercraft, they were considered control conditions because they were unaffiliated with construction activities. Construction activity had to continue for > 5 min in order to classify the time period as "with" construction activity. The total time with and without construction activity was calculated for each day of observation.

The detected hourly click rate during time periods with and without construction was calculated for each day of observations. To avoid counting the same click twice, only clicks from the sonobuoy with the longest recording were counted if more than one sonobuoy detected clicks on a particular day. An independent samples t-test was used to determine if there was a statistical difference in the rate of detected beluga whale clicks during periods with and without construction activity. The alpha level was set at $P < 0.05$.

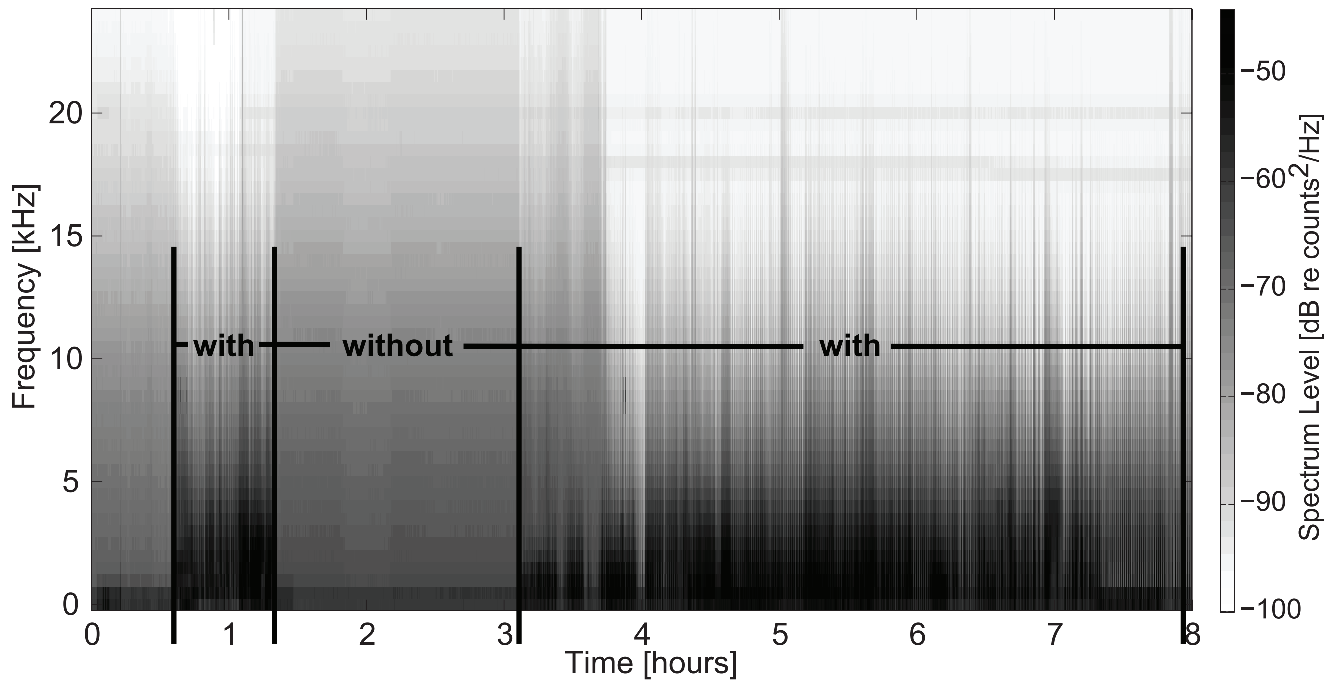


Figure 2. A long-term spectral average (LTSA) for 20 August 2009. The LTSA provides an overall picture of acoustic activity at the Marine Terminal Redevelopment Project on a daily basis. Example times "with" and "without" construction activity are marked.

3. RESULTS

Acoustic observations were conducted for more than 148 h over 20 d (mean of 7:25 ± 0:29 h of observation/d) in August and September 2009. Eighty-six sonobuoys were deployed during the study, 8 of which failed (failure rate 9.3 %). A total of 373 h of recordings were collected from all moorings. The VHF signal reception from sonobuoys varied with tidal stage. Occasionally, a signal from a sonobuoy was lost during high flood or ebb tides because the sonobuoy transmitter was submerged. The signal resumed once the sonobuoy resurfaced after approximately 20-60 min. During the recovery of sonobuoys in subsequent days, the hydrophone was often detached from the sonobuoy cable, likely due to the fast moving currents. Occasionally, this resulted in abbreviated daily sampling effort; however, more often the hydrophone detached after the daily sampling period ended.

Echolocation clicks were frequently produced by beluga whales in the vicinity of the MTR Project, but no other types of vocalizations (*e.g.*, whistles or other social signals) were detected with the sonobuoy array. A total of 63,392 clicks were detected during 14 d (out of 20) of the passive acoustic study, although some of those clicks were likely the same clicks detected on multiple sonobuoys in the array. The false detection rate of the automated detector was 35.5 %. Most of the acoustic energy received from beluga whale clicks recorded near the MTR Project construction site was above 15 kHz. Due to the sample rate, the full frequency range and the frequency of peak energy of clicks could not be observed. Beluga whale clicks were detected most commonly on mooring M1, the westernmost mooring.

Construction activity took place approximately 76 % of the time during the 14 d beluga whale clicks were detected, resulting in a total of approximately 71 h of recordings with and approximately 22 h without construction activity (Table 1). The detected click rate was higher without (429 detected clicks/h) than with (291 detected clicks/h) construction activity; however, the difference was not significant ($t_{(24)} = -0.56$, $P = 0.58$; Figure 3).

4. DISCUSSION

4.1 Effects of Construction Noise on Beluga Vocalizations

Construction activity took place during the majority of the acoustic survey (3/4 of the time). While no beluga whistles and noisy vocalizations were detected during the survey, it is possible that persistent noise associated with construction activity at the MTR Project masked beluga vocalizations. The frequency band of noise associated with activity near the MTR Project was generally below 10 kHz; however, the frequency band recorded from IPD extended to 20 kHz. Majority of the beluga whale whistles and noisy vocalizations are within the frequency band taken up by the construction activity noise (Richardson *et al.* 1995). VPD or dredging, in particular, could potentially mask beluga whale vocalizations because in addition to frequency overlap, they are also longer in duration.

Alternatively, to avoid interference from continuous construction noise, beluga whales may not use whistles or noisy vocalizations when they are near the MTR Project. Beluga whales may change their behavior to avoid masking from the construction noise or the construction noise may deter them from engaging in social activities when they are in the vicinity of the MTR Project. Therefore, behavioral changes or the lack of social activity in general could also explain the absence of whistles or noisy vocalizations in the study area.

Table 1. Sonobuoy sampling effort, total time, total number of detected echolocation clicks and detected hourly click rate with and without construction activity during the 14 d beluga whale clicks were detected.

Date	Sonobuoy Sampling Effort (hh:mm)	Total Time WITH (hh:mm)	Total Time WITHOUT (hh:mm)	No. of Clicks WITH[a]	No. of Clicks WITHOUT[b]	Detected Click Rate WITH (clicks/h)	Detected Click Rate WITHOUT (clicks/h)
4-Aug-09	3:46	3:46	0:00	29	−	8	−
13-Aug-09	8:17	8:17	0:00	1,283	−	155	−
18-Aug-09	7:25	4:07	3:18	31	0	8	0
20-Aug-09	7:36	5:56	1:40	10	0	2	0
22-Aug-09	6:48	3:49	2:59	4,380	4,239	1,147	1,422
25-Aug-09	5:11	3:12	1:59	14	7	4	4
1-Sep-09	6:36	3:54	2:42	185	1,182	47	438
4-Sep-09	6:58	5:20	1:38	134	43	25	26
8-Sep-09	3:41	2:20	1:21	61	36	26	27
10-Sep-09	6:10	5:46	0:24	1,094	0	190	0
20-Sep-09	4:58	3:12	1:46	400	177	125	100
23-Sep-09	7:52	6:59	0:53	5,775	481	827	547
25-Sep-09	8:47	7:28	1:19	630	155	84	117
27-Sep-09	9:10	7:05	2:05	10,109	5,122	1,428	2,463
Total	93:15:00	71:11:00	22:04:00	24,135	11,442	291[c]	429[c]

[a] The number of clicks used in the analysis for each day corresponds to the total number of clicks detected on the sonobuoy that had the longest recording during the respective day.
[b] On 4 and 13 August, there were no recorded periods without construction activity; therefore, "−" represents that no clicks could be detected "without" construction activity on those days.
[c] These values are the mean detected click rates.

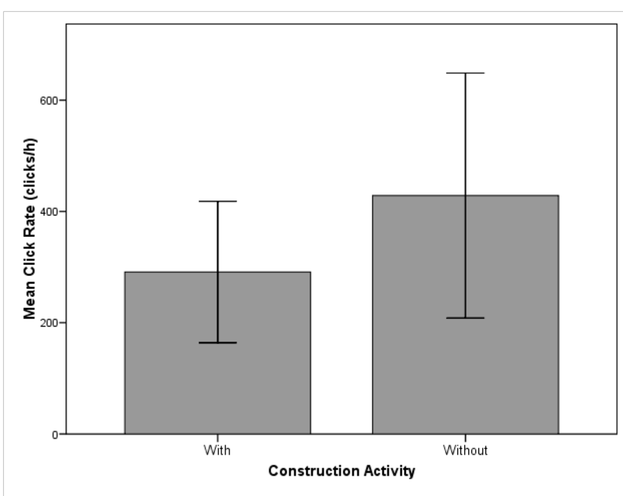


Figure 3. Detected hourly beluga whale echolocation click rates with and without construction activity near the Marine Terminal Redevelopment (MTR) Project during the 14 d beluga whale clicks were detected between 1 August and 30 September, 2009.

Conversely, because the type of vocalizations used by beluga whales is likely determined by the behavioral state of the whale (Sjare and Smith 1986b, Au *et al.* 1985, Panova *et al.* 2012), they may be engaged primarily in echolocation (Richardson *et al.* 1995) as they travel through the study area (Cornick and Kendall 2008*a*, *b*, Cornick *et al.* 2010). Echolocation could be particularly important to beluga whales for navigating in the turbid waters of Cook Inlet where whales cannot rely on eyesight for navigation. As a result, echolocation could be the primary type of vocalization utilized by beluga whales when traveling through the study area. This final explanation is consistent with the fact that we recorded no whistles even during periods without construction; however, a more detailed study of the association of behavioral states and call production would be needed to test that hypothesis.

In addition to the absence of whistles and noisy vocalizations used by beluga whales in the study area, click rate was higher without construction activity. Although the difference was not significant, we had a relatively small sample size and a large variance in the number of detected clicks between days. The lower detected click rate with construction activity could be another possible indication of a reduction in vocal activity by the beluga whales in the study area during construction. Masking is not likely a concern when producing echolocation clicks because most of the acoustic energy in the beluga whale click extended above the frequency band recorded for the construction activity at the MTR Project. However, it is possible beluga whales may shift the frequency in echolocation clicks in response to construction (Au *et al.* 1985), producing clicks we did not detect, thus the observed reduced click rate could result from our relatively low sample rate. Alternatively, the reduction in click rate with construction activity could indicate a reduction in the number of beluga whales in the area. Similar responses have been observed for harbor porpoises (*Phocoena phocoena*) during the installation of offshore wind turbines, suggesting that the reduction in echolocation clicks was a result of the reduction in the number of harbor porpoises present in the area (Carstensen *et al.* 2006, Brant *et al.* 2011). A reduction of beluga whales in the study area could suggest avoidance of the area near the construction site.

Beluga whales were not equally detected across our array, but there was a spatial pattern to their detections. The echolocation clicks were more commonly detected offshore near the deep channel in Knik Arm (moorings M1 and M2) rather than adjacent to the shoreline (M3 and M4). This may indicate beluga whales use areas offshore more frequently than originally believed (Moore *et al.* 2000). Over the past several years, the visual observers for the MTR project (Scientific Marine Mammal Observers [MMO]), observed beluga whales more often along the shoreline and adjacent to the MTR Project footprint than offshore (Markowitz and McGuire 2007, Cornick and Kendall 2008*a*, *b*, Cornick *et al.* 2010). However, sightings are directly related to the location and elevation of the observation station from the beluga whales, therefore, beluga whales at greater distances from the observation station are more likely missed (Buckland *et al.* 2001, Markowitz and McGuire 2007). If acoustic detections were primarily west of the moorings, belugas may be using a more energetically efficient method of travel by taking advantage of the fast-moving current in the deep channel located in the center of Knik Arm (Smith *et al.* 2005). Alternatively, the location of acoustically detected beluga whales near the central channel of Knik Arm may indicate disturbance or avoidance from the nearshore construction activity.

Though the noise from the construction activity may cause behavioral disturbance to the beluga whales, they may choose to travel through the area despite the consequences because the habitat beyond the construction area is extremely important to their existence (Goetz *et al.* 2012, NMFS 2011). Knik Arm is designated critical habitat for the Cook Inlet beluga whale (NMFS 2011). The construction area, located at the entrance of Knik Arm has been exempt from the critical habitat designation (NMFS 2011). Beluga whales must either travel through or adjacent to the construction area to get to the upper reaches of the Arm. Critical habitat provides areas for summer foraging, calving, molting, and predator avoidance as well as known fall and wintering areas (NMFS 2011). Beluga whales have been documented year round in Knik Arm (Hobbs *et al.* 2005), using it as a known summer foraging area (NMFS 2011), as well as potential nursery and predator avoidance area (Huntington 2000, NMFS 2011). The MTR Project Scientific MMOs documented a decrease in the total time beluga whales were in view of visual observers within the study area since the MTR Project began (Cornick and Kendall 2008*a*, *b*, Cornick *et al.* 2010, Kendall 2010). However, if disturbance from the construction activity outweighed the benefits of traveling through the construction area to important habitat, avoidance or displacement from the area could occur (Goetz *et al.* 2012). The use of the central channel observed during the acoustic survey and the increased use of the western shoreline near Port MacKenzie documented by the Scientific MMOs (Cornick and Kendall 2008*a*, *b*, Cornick *et al.* 2010, Kendall 2010) imply possible avoidance of the construction area by beluga whales.

Carstensen *et al.* (2006) observed harbor porpoises returned to a construction area between pile driving events; however, the return time often took several days. Brandt *et al.* (2011) observed the reduction of harbor porpoise activity and density at a construction area over the entire 5 mo period pile driving took place. They also documented increased use of areas 20 km away from the construction site. Considering that the Cook Inlet beluga whale's range has been contracting over the past three decades (NMFS 2008*b*, Rugh *et al.* 2010), avoidance or displacement of the Cook Inlet beluga whale from the upper reaches of Knik Arm could be detrimental to the population's recovery.

4.2. Study Limitations and Challenges

In general, passive acoustic monitoring offers numerous advantages over visual surveys of cetaceans (Mellinger *et al.* 2007), but there are numerous challenges associated with studying beluga whales in Cook Inlet using passive acoustics due to environmental and technological constraints. First of all, the Knik Arm of Cook Inlet is a difficult environment to conduct any type of passive acoustic monitoring. Bottom-mounted autonomous recorders, more typically used for passive acoustic monitoring, were not chosen for this study because of the concerns that the heavy sediment load carried in the water would cover the instrument and make it impossible to retrieve. Also, there was a high potential for damage to the instruments due to the strong tides and currents carrying debris. The tides and currents, with speeds over 7 knots (Smith *et al.* 2005), occasionally inhibited signal transmission or damaged the equipment used during this study; however, the relative inexpensiveness of sonobuoys, enabling repeated deployment after any fouling event, made them the most practical choice for this study.

Sonobuoy deployments were conducted in an array formation to enable sound source localization of beluga whale social vocalizations. However, since we did not record any social vocalizations, and echolocation clicks propagated over much shorter distance (approximately 400 m) and thus were never detected on three sonobuoys at the same time, localization was not possible. The use of sonobuoys, also limited our recording bandwidth. Beluga whale clicks extend well above the frequency response of the sonobuoys (Au *et al.* 1985) and we were not able to detect echolocation clicks above 30 kHz, which limited the number and types of clicks we detected.

Extreme tides were another environmentally constraining condition, as they limited the ability to launch the boat to deploy sonobuoys. The tidal constraints may have created a bias in the data because beluga whales are highly dependent on the tidal stages for traveling throughout Cook Inlet (Moore *et al.* 2000) and our data were mostly collected around high tides.

Surprisingly, flow noise was not an issue during our study considering the strong currents in the area; construction noise, on the other hand, was the most prevalent source of underwater sound. Background noise levels measured in the area range from 113-133 dB re 1 μPa (Blackwell and Greene 2002, Blackwell 2005, Širović and Kendall. 2009). Sound levels measured during pile driving activity (IPD or VPD) ranged from 162-196.9 dB re 1 μPa with varying distance from the source and pile size (Blackwell 2005, Širović and Kendall 2009). Dredging sound levels measured in the area at 156.9 dB re 1 μPa at 30 m (SFS 2009). Noise associated with construction was nearly continuous at times. If pile driving was not taking place, dredging occurred or vice versa. Because of frequent overlaps, the construction data were pooled. Periods without construction activity mostly consisted of only brief moments (~5 min) when construction ceased, therefore, most of the times considered "without" construction activity were simply prolonged breaks in construction activity.

While our recordings indicate beluga whales may not be using whistles and noisy vocalizations when traveling near the MTR Project, they may decrease click rates or otherwise modify their echolocation clicks in the presence of construction noise, or there may be a decrease in the number of beluga whales traveling through the area. Of course, it does not necessarily mean beluga whales were not present during times when we did not detect beluga vocalizations; they may just be silent as they move through the area. To fully understand the impacts of noise associated with construction activity on the Cook Inlet beluga whale, we need to understand Cook Inlet beluga whale vocalizations under different behavioral states. Since cetacean detection rates vary between acoustic and visual survey methods (Clark *et al.* 1985, McDonald and Moore 2002, Širović *et al.* 2006, O'Boisseau *et al.* 2007, Kimura *et al.* 2009), it is important to integrate both survey methods in order to effectively monitor belugas in harsh environments such as Knik Arm. By improving our understanding of the behavioral context of calling, we may also increase our ability to evaluate the impact of noise on belugas and perhaps improve our understanding of factors causing the population decline.

4.3 Conclusions

There were four major findings and issues of importance in this study. 1) No beluga whale whistles or noisy vocalizations were detected in the vicinity of the MTR Project during the study, which is unusual behavior for highly vocal beluga whales (Schevill and Lawrence 1949). 2) We observed a decreasing trend in the hourly click rate between times without and with construction activity which may be an indication of disturbance. 3) There is limited information on construction impacts on beluga whales in particular and marine mammals in general. This study adds to the body of knowledge regarding construction impacts on this endangered population. 4) Upper Cook Inlet is a major urban area that contains half of Alaska's population, yet it provides a very challenging environment for conducting research. There are many ongoing and upcoming coastal zone development projects in Upper Cook Inlet, especially in Knik Arm, where beluga whales are frequently observed. For successful management of this population as well as continuing urban development, it is imperative to use all available sources of information to increase our understanding of the impacts from coastal zone development and the associated noise on this population.

ACKNOWLEDGEMENTS

We would like to thank the US Department of Transportation Maritime Administration, the POA, ICRC and the At-Sea Processors Association for funding this project. A special thanks to Lyn Dokoozian, Laurie Butler and Sam Cunard at ICRC for logistical support. Thanks to John Hildebrand at the Scripps Institution of Oceanography for providing the sonobuoys. Thanks to all the acoustic observers at APU for field support throughout the project. Thanks to Marie Roch for helping translate the abstract to French. Leslie Cornick (APU)

and Mike Williams (NMFS) provided valuable input on this manuscript which was part of LSK's Master's thesis.

REFERENCES

Angiel, N. M. 1997. The vocal repertoire of the beluga whale in Bristol Bay, Alaska. MS Thesis, University of Washington, Seattle, WA.

Au, W. W. L., D. A. Carder, R. H. Penner and B. L. Scronce. 1985. Demonstration of adaptation in beluga whale echolocation signals. Journal of Acoustic Society of America 77: 726-730.

Au, W. W. L, R. H. Penner and C. W. Turl. 1987. Propagation of beluga echolocation signals. Journal of Acoustic Society of America 82: 807-813.

Awbrey, F. T., J. A. Thomas, R.A. Kastelein. 1988. Low-frequency underwater hearing sensitivity in belugas, *Delphinapterus leucas*. Journal of Acoustic Society of America 84: 2273-2275.

Barlow, J. and B. Taylor. 2005. Estimates of sperm whale abundance in the northeastern temperate pacific from a combined acoustic and visual survey. Marine Mammal Science 21:429-445.

Belikov, R. A., and V. M. Bel'kovich. 2006. High-pitched tonal signals of beluga whales (*Delphinapterus leucas*) in a summering assemblage off Solovetskii Island in the White Sea. Acoustical Physics 52:125-131.

Belikov, R. A., and V. M. Bel'kovich. 2007. Whistles of beluga whales in the reproductive gathering off Solovetskii Island in the White Sea. Acoustical Physics 53:528-534.

Belikov, R. A., and V. M. Bel'kovich. 2008. Communicative pulsed signals of beluga whales in the reproductive gathering off Solovetskii Island in the White Sea. Acoustical Physics 54:115-123.

Blackwell, S.B. and C.R. Greene Jr. 2002. Acoustic measurements in Cook Inlet, Alaska during August 2001. Greeneridge Report 271-2. Report from Greeneridge Sciences, Inc., Santa Barbara for National Marine Fisheries Service, Anchorage, Alaska. 41 p.

Blackwell, S.B. 2005. Underwater measurements of pile driving sounds during Port MacKenzie Dock Modifications 13-16 August 2004. Report 328-1. Report from Greeneridge Science, Inc., Goleta, CA, and LGL Alaska Research Associates, Inc. Anchorage AK, in association with HDR Alaska, Inc., for Knik Arm Bridge and Toll Authority, Anchorage, AK, Department of Transportation and Public Facilities, Anchorage, AK, and Federal Highway Administration, Juneau, AK. 33p.

Blane, J. M. and R. Jaakson. 1994. The impact of ecotourism boats on the St. Lawrence beluga whales. Environmental Conservation 21(3): 267-269.

Brandt, M. J., A. Diederichs, K. Betke and G. Nehls. 2011. Responses of harbor porpoise to pile driving at Horn Rev II offshore wind farm in the Danish North Sea. Marine Ecology Progress Series. 421:205-216.

Buckland, S. T., D. R. Anderson, K. P. Burnham, J. L. Laake, D. L. Borchers and L. Thomas. 2001. Introduction to distance sampling-Estimating abundance of biological populations: Oxford University Press.

Carstensen, J., O. D. Henriksen and J. Teilman. 2006. Impacts of offshore wind farm construction on harbor porpoises: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs). Marine Ecology Progress Series 321:295-308.

Chalmnitsky, E. G. and S. H. Ferguson. 2012. Beluga whale, *Delphinapterus leucas*, vocalizations from the Churchill River, Manitoba, Canada. Journal of the Acoustical Society of America 131: 4821-4835.

Clark, C. W., W. T. Ellison and K. Beeman. 1985. Acoustic tracking of migrating bowhead whales. Oceans '86 Conference Record: Science-Engineering-Adventure: Conference 86:341-346.

Clark, C. W. and W. T. Ellison. 1988. Numbers and distributions of bowhead whales, *Balaena mysticetus*, based on the 1985 acoustic study off Pt. Barrow, Alaska. Report for International Whaling Commission 38: 365-370.

Cornick, L. A. and L. S. Kendall. 2008*a*. Distribution, habitat use, and behavior of Cook Inlet beluga whales in Knik Arm, Fall 2007. Prepared for Integrated Concepts and Research Corporation. Prepared by Alaska Pacific University. Anchorage, Alaska. 29 pp.

Cornick, L. A. and L. S. Kendall. 2008*b*. Distribution, habitat use and behavior of Cook Inlet Beluga Whales and other marine mammals at the Port of Anchorage Marine Terminal Redevelopment Project June-November, 2008. Prepared for U.S. Department of Transportation Maritime Administration, Port of Anchorage and Integrated Concepts and Research Corporation. Prepared by Alaska Pacific University. Anchorage, Alaska. 29 pp.

Cornick, L. A., L. S. Kendall and L. Pinney. 2010. Distribution, habitat use and behavior of the Cook Inlet beluga whales and other marine mammals at the Port of Anchorage Marine Terminal Redevelopment Project, May-November 2009. Scientific Marine Mammal Monitoring Program 2009 Annual Report. Prepared for U.S. Department of Transportation Maritime Administration, the Port of Anchorage and Integrated Concepts and Research Corporation. Prepared by Alaska Pacific University. Anchorage, Alaska. 40 pp.

Croll, D. A., C. W. Clark, J. Calambokidis, W. T. Ellison and B.R. Tershy. 2001. Effects of anthropogenic low-freuency noise on foraging ecology *Balaenoptera* whales. Animal Conservation 4:13-27.

Erbe, C. and D. M. Farmer. 2000. Zones of impact around icebreakers affecting beluga whales in the Beaufort Sea. Journal of Acoustic Society of America 108:1332-1340.

Faucher, A. 1998. The vocal repertoire of the St. Lawrence Estuary population of beluga whale (*Delphinapterus leucas*) and it behavior, social and environmental contexts. MS Thesis, Dalhousie University, Halifax, Nova Scotia.

Frantzis, A. (1998) Does acoustic testing strand whale? Nature 392: 29.

Goetz, K. T., R. A. Montgomery, J. M. Ver Hoef, R. C. Hobbs and D. S. Johnson. 2012. Identifying essential summer habitat of the endangered beluga whales *Delphinapterus leucas* in Cook Inlet, Alaska. Endangered Species Research 16: 135-147.

Greene Jr., C. R., M W. McLennan, R. G. Norman, T. L. McDonald, R. S. Jakubaczak and W. J. Richardson. 2004. Directional frequency and recording (DIFAR) sensors in seafloor recorders to locate calling bowhead whales during their fall migration. Journal of Acoustic Society of America 116: 799-813.

Hobbs, R. C., K. L. Laidre, D. J. Vos, B. A. Mahoney and M. Eagleton. 2005. Movement and area use of belugas, *Delphinapterus leucas*, in subarctic Alaskan estuary. Arctic. 58: 331-340.

Hobbs, R. C., K. E. W. Shelden, D. J. Rugh and S. Norman. 2008. 2008 status review and extinction risk assessment of Cook Inlet belugas (*Delphinapterus leucas*). AFSC Processed Rep. 2008-002, 116 p. Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, Seattle, WA.

Hobbs, R.C., C.L. Sims, and K.E.W. Shelden. 2012. Estimated abundance of belugas whales in Cook Inlet, Alaska, from aerial surveys conducted in June 2012. NMFS, NMML Unpublished Report. 7pp.

Horsley, L. E. 1989. Modification and deployment techniques for hand-deployed arctic long-life sonobuoys. IEEE Journal of Oceanic Engineering 14: 211-220.

Huntington, H. P. 2000. Traditional knowledge of the ecology of the belugas*, Delphinapterus leucas*, in Cook Inlet, Alaska. Marine Fisheries Review 62(3): 134-140.

Jepson, P. D., M. Arbelo, R. Deaville, *et al.* 2003. Gas-bubble lesions in stranded ceataceans – was sonar responsible for a spate of whale deaths after an Atlantic military exercise? Nature 425: 575-576.

Johnson, C. S., M. W. McManus and D. Skaar. 1989. Masked tonal hearing thresholds in beluga whale. Journal of Acoustic Society of America 85:2651-2654.

Karlsen, J. D., A. Bisther, C. Lydersen, T. Haug and K. M. Kovacs. 2002. Summer vocalizations of adult male white whales (*Delphinapterus leucas*) in Svalbard, Norway. Polar Biology 25:808-817.

Kendall, L. S. 2010. Behavior and distribution of the Cook Inlet beluga whales (*Delphinapterus leucas*) pre- and during pile driving activity at the Port of Anchorage Marine Terminal Redevelopment Project, 2005-2009. MS Thesis. Alaska Pacific University. Anchorage, Alaska. 88 pp.

Kimura, S., T. Akamatsu, K. Wang, D. Wang, S. Li, S. Dong and N. Arai. 2009. Comparison of stationary acoustic monitoring and visual observation of finless porpoises. Journal of Acoustic Society of America 125: 547-553.

Laidre, K. L., K. E. W. Shelden, D. J Rugh and B. A. Mahoney. 2000. Beluga, *Delphinapterus leucas*, Distribution and Survey Efforts in the Gulf of Alaska. Marine Fisheries Review 6 (3):27-36.

Lammers, M. O. and M. Castellote. 2009. The beluga whale produces two pulses to form its sonar signal. Biology Letters 5: 297-301.

Laurinolli, M. H., A. E. Hay, F. Desharnais and C. T. Taggart. 2003. Localization of North Atlantic right whale sounds in the Bay of Fundy using a sonobuoy array. Marine Mammal Science 19: 708-723.

Lesage, V., C. Barrette, M. C. S. Kingsley and B. L. Sjare. 1999. The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence River estuary, Canada. Marine Mammal Science 15: 65-84.

Ljungblad, D. K., B. Würsig, S. L. Swartz and J. M. Keene. 1988. Observations on the behavioral response of bowhead (Baleena Mysticetus) to active geophysical vessels in the Alaskan Beaufort Sea. Arctic 41:183-194.

Markowitz, T. M. and T. L. McGuire. 2007. Temporal-spatial distribution, movements and behavior of beluga whales at the Port of Anchorage, Alaska. Report prepared by LGL Alaska Research, Inc., Anchorage, AK, for Integrated Concepts and Research Corporation and the U.S. Department of Transportation Maritime Administration. 93 pp.

McDonald, M. A. and S. E. Moore. 2002. Calls recorded from North Pacific right whales (*Eubalaena japonica*). Journal of Cetacean Research and Management 4: 261-266.

McDonald, M. A., J. A. Hildebrand and S. Wiggins. 2006. Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California. Journal of Acoustic Society of America 120: 711-718.

Mellinger, D. K. 2001. Ishmael 1.0 User's Guide. NOAA Tech. Memo. OAR-PMEL-120, NOAA Pacific Marine Environmental Laboratory, Seattle, WA 26 pp.

Mellinger, D. K., K. M. Stafford, S. E. Moore, R. P. Dziak and H. Matsumoto. 2007. An overview of fixed passive acoustic observation methods for cetaceans. Oceanography 20: 36-45.

Moore, S. E., K. E. W. Shelden, L. K. Litzky, B. A. Mahoney and D. J. Rugh. 2000. Beluga, *Delphinapterus leucas*, Habitat Associations in Cook Inlet, Alaska. Marine Fisheries Review 62(3): 60-80.

National Marine Fisheries Service (NMFS). 2008*a*. Endangered and Threatened Species; Endangered Status for the Cook Inlet Beluga Whale. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. 50 CFR Part 224. 73(205): 62919-62930 (73 FR 62919).

National Marine Fisheries Service (NMFS). 2008*b*. Conservation Plan for the Cook Inlet beluga whale (*Delphinapterus leucas*). National Marine Fisheries Service, Juneau, Alaska. 122 pp.

National Marine Fisheries Service (NMFS) (2008c) Small Takes of Marine Mammals Incidental to Specified Activities; Port of Anchorage Marine Terminal Redevelopment Project, Anchorage, Alaska. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. 73(53): 14443-14453 (73 FR 14443).

National Marine Fisheries Service (NMFS). 2011. Endangered and Threatened Species: Designation of Critical Habitat for Cook Inlet Beluga Whale. 50 CFR Part 226. 76(69): 20180-20214 (76 FR 20180).

National Oceanic and Atmospheric Administration (NOAA) Fisheries Service. 2011. NOAA Fisheries News Release. Alaska Regional Office. National Marine Fisheries Service. Juneau, AK. Available from: < <http://www.fakr.noaa.gov/newsreleases/2012/cibelugas010912.htm> (accessed March 27, 2012).

National Research Council (NRC). 2003. Ocean Noise and Marine Mammals: National Academies Press, Washington, D.C.

Nowacek, D. P., L. H. Thorne, D. W. Johnson and P. L. Tyack. 2007. Responses of cetaceans to anthropogenic noise. Marine Mammal Review 37 (2): 81-115.

O'Boisseau, J. M., D. Gillespie, C. Lacey, A. Moscrop and N. El Ouamari. 2007. A visual and acoustic survey for harbor porpoise off North-West Africa: further evidence of a discrete population. African Journal of Marine Science 29(3): 403-410.

O'Corry-Crowe, G. M., R. S. Suydam, A. Rosenberg, K. J. Frost and A. E. Dizon. 1997. Phylogeography, population structure and dispersal patterns of the beluga whale *Delphinapterus leucas* in the western Nearctic revealed by mitochondrial DNA. In: Molecular Ecology 6: 955-970.

O'Corry-Crowe, G. M., A. E. Dizon, R. S. Suydam and L. F. Lowry. 2002. Molecular genetic studies of population structure and movement patterns in a migratory species: The beluga whale, *Delphinapterus leucas*, in the western Nearctic, p.53-64. In C. J. Pfieffer (editor), Molecular and cell biology of marine mammals. Malabar, Florida: Krieger Publishing Company.

Panova, E. M., R. A. Belikov, A. V. Agafonov and V. M. Bel'kovich. 2012. The relationship between the behavioral activity and the underwater vocalization of the beluga whale (*Delphinapterus leucas*). Oceanology 52: 79-87.

Patenaude, N., W. J. Richardson, M. A. Smultea, W. R. Koski, G. W. Miller and B. Würsig. 2002. Aircraft sound and disturbance to bowhead and beluga whales during spring migration in the Alaskan Beaufort Sea. Marine Mammal Science 18: 309-335.

Richardson, W. J., C. R. Greene Jr., C. I. Malme and D. H. Thomson. 1995. Marine Mammals and Noise: Academic Press.

Rugh, D. J., K. E. W. Shelden and B. A. Mahoney. 2000. Distribution of belugas, *Delphinapterus leucas*, in Cook Inlet, Alaska, during June/July 1993-2000. Marine Fisheries Review 62(3): 6-21.

Rugh, D. J., K. E. W. Shelden and R. C. Hobbs. 2010. Range contraction in a beluga whale population. Endangered Species Research 12: 69-75.

Scheifele, P. M., S. Andrew, R. A. Cooper, M. Darre, F. E. Musiek and L. Max. 2005. Indication of a Lombard vocal response in the St. Lawrence River beluga. Journal of Acoustic Society of America 117: 1486-1492.

Schevill, W. E. and B. Lawrence. 1949. Listening to the white whale porpoise, *Delphinapterus leucas*. Science 109: 143-144.

Scientific Fishery Systems, Inc. (SFS). 2009. 2008 Underwater Nose Survey during Construction Pile Driving at the Port of Anchorage Marine Terminal Redevelopment Project. Prepared by Scientific Fishery Systems, Inc. in support of Alaska Native Technologies, LLC., Anchorage, Alaska, prepared for the US Department of Transportation Maritime Administration, the Port of Anchorage and Integrated Concepts and Research Corporation, Anchorage, Alaska.

Širović, A., J. A. Hildebrand and D. Thiele. 2006. Baleen whales in the Scotia Sea during January and February 2003. Journal of Cetacean Research and Management 8: 161–171.

Širović, A. and L.S. Kendall. 2009. Passive acoustic monitoring of beluga whales. Analysis Report. Prepared by Alaska Pacific University, Anchorage, Alaska, prepared for the US Department of Transportation Maritime Administration, Port of Anchorage and Integrated Concepts and Research Corporation, Anchorage, Alaska.

Smith, O. P., A. Khokholov and M. Zieserl. 2005. Water property, sediment, tide, and current measurement analyses in the vicinity of the proposed Knik Arm Bridge. Contract report for URS Corporation and HDR Alaska, Inc., Anchorage, AK. Prepared for Knik Arm Bridge and Toll Authority, the Alaska Department of Transportation and Public Facilities and the Federal Highway Administration, Anchorage, Alaska.

Sjare, B. L. and T. G. Smith. 1986*a*. The vocal repertoire of white whales, *Delphinapterus leucas*, summering in Cunningham Inlet, Northwest Territories. Canadian Journal of Zoology 64: 407-415

Sjare, B. L. and T. G. Smith. 1986*b*. The relationship between behavioral activity and underwater vocalizations of the white whale, *Delphinapterus leucas*. Canadian Journal of Zoology 64: 2824-2831.

Smultea, M. A., J. R. Mobley, D. Fertl and G. L. Fulling. 2007. An unusual reaction and other observation of sperm whales near fixed-wing aircraft. Gulf and Carribean Research 20: 75-80.

Turl, C. W. and R. H. Penner. 1989. Differences in echolocation click patterns of the beluga whale (*Delphinapterus leucas*) and the bottlenose dolphin (Tursiops trucatus). Journal of Acoustic Society of America 86: 497-502.

Turl, C. W. 1990. Echolocation abilities of the beluga whale, *Delphinapterus leucas*: a review and comparison with the bottlenose dolphin, Tursiops trucantus. In: T Smith, D St. Aubin, and J Gerci [ed.] Advances in research on the beluga whale *Delphinapterus leucas*. Canadian Bulletin of Fisheries and Aquatic Science 224:119-128.

Wiggins, S. and J. A. Hildebrand. 2007. High-Frequency Acoustic Recording Package (HARP) for broad-band, long-term marine mammal monitoring. UT07+SSC07, Tokyo, Japan, 17-20 April 2007. 551-557.

Wiggins, S., M. Roch, J. A. Hildebrand. 2010. TRITON software package: analyzing large passive acoustic monitoring data sets using MATLAB. Journal of Acoustic Society of America 128: 2299.

Würsig, B., C. R. Greene Jr. and T. A. Jefferson. 2000. Development of an air bubble curtain to reduce underwater noise of percussive piling. Marine Environmental Research 49:79-93.


SVS
SOUND & VIBRATION SOLUTIONS CANADA Inc.
Dynamic Products from Industry Leaders
p. 519-853-4495
w. svscanada.ca
e. andy@svscanada.ca
The most complete Sound Level Meter on the market today!
Specialists in Acoustic Measurement Instrumentation
Integrated Solutions from World Leaders
Precision Measurement Microphones
Intensity Probes
Outdoor Microphones
Sound Level Meters Type 1
Ear Simulation Devices
Speech Simulation Devices
Calibrators
Array Microphones
Sound Quality
Sound Intensity
Sound Power
Room Acoustics
Noise Monitoring
Dynamic Signal Analyzers
Electro Dynamic Shaker Systems
Doppler Laser Optical Transducers
Laser Vibrometers
Multi-Channel Dynamic Analyzer/Recorder
Soundbook™
Designed for You:
2-4-8 Channel √
IEC conform √
PTB Aproved √
User friendly √
General purpose √
Tough (MIL) √
Reliable √
G.R.A.S.
SOUND & VIBRATION
CRYSTAL
instruments
Norsonic
SINUS
Messtechnik GmbH

THEORETICAL ANALYSIS OF LINED-DUCT SOUND ATTENUATION

Chris Bibby and Murray Hodgson
Acoustics and Noise Research Group, University of British Columbia
3rd Floor, 2006 East Mall, Vancouver, BC, Canada V6T1Z3
[chrisbibby@gmail.com; murray.hodgson@ubc.ca]

ABSTRACT

This paper investigates theoretically how duct geometry and liner thickness affect the attenuation of fundamental-mode sound propagation in a lined duct. The study was done to satisfy the need for a greater understanding of interior natural-ventilation openings and of silencers implemented to improve the acoustical performance ('ventilators'), and to provide engineers and architects with optimal-design guidelines. It assumed ventilators of the simplest form – straight, acoustically-lined ducts of rectangular cross-section. An analytical solution is presented for the attenuation of the fundamental mode in such a duct. Duct-liner thickness does not affect high-frequency performance; however, it limits low-frequency performance. A 25-mm liner is likely not thick enough to be effective, but a 100-mm liner may be excessive. Increasing the duct height reduces the attenuation at all frequencies; in order to provide effective attenuation through the 4000-Hz band, the height should not exceed 100 mm. If the cross-sectional aspect ratio of a duct is greater than 10, or the duct is only lined on two opposing surfaces, the attenuation of its fundamental mode is in effect identical to that of a 2D lined duct. Provided that the duct liner and height are such that the silencer is effective at absorbing sound at a given frequency, reducing the aspect ratio towards unity will result in large attenuation gains.

RÉSUMÉ

Cet article étudie l'influence théorique de la géométrie d'un conduit et de l'épaisseur d'un revêtement acoustique sur l'atténuation acoustique du mode fondamental. L'étude vise une meilleure compréhension des ouvertures dans les cloisons internes et des silencieux conçus pour améliorer la performance acoustique, afin d'informer les ingénieurs et les architectes des conceptions optimales. Elle fait l'hypothèse de silencieux de formes simples: un conduit rectangulaire avec un revêtement acoustique interne. Une solution analytique est présentée pour l'atténuation du mode fondamental de ce type de conduit. L'épaisseur du revêtement n'influence pas sur les performances à hautes fréquences; cependant, elle limite celles à basses fréquences. Un revêtement d'une épaisseur de 25 mm n'est pas efficace, mais 100 mm peut être excessif. Augmenter la hauteur du conduit réduit l'atténuation pour toutes les fréquences; dans le but d'obtenir une atténuation efficace aux fréquences supérieures à 4000 Hz, la hauteur ne devrait pas dépasser 100 mm. Si le rapport des dimensions latérales du conduit est supérieur à 10, ou si seulement deux surfaces opposées portent un revêtement, l'atténuation du mode fondamental est égale à celle d'un conduit 2D. Tant que le revêtement et les dimensions du conduit sont tels que le silencieux 2D absorbe efficacement le son à une fréquence particulière, une réduction du rapport résultera en une atténuation plus importante.

1. INTRODUCTION

This paper investigates theoretically how duct geometry and liner thickness affect the attenuation of fundamental-mode sound propagation in a lined duct. While the results are generally applicable, the work was done as part of larger study [1] to satisfy the need for a greater understanding of interior natural-ventilation openings and of silencers implemented to improve the acoustical performance ('ventilators'), and to provide engineers and architects with optimal-design guidelines.

Natural ventilation is increasingly employed to make buildings more sustainable [2]. It works by using wind- or buoyancy-induced pressure differentials (stack effect) to drive ventilation air through a building. Typically these pressures are small compared to those available in a mechanically-ventilated building. In order for this low pressure to drive a sufficient volume of air, it is necessary to have low airflow resistance throughout the building. To achieve this, large openings are created in internal partitions, which prove detrimental to the noise isolation between the spaces. There is a clear need for a greater understanding of interior natural-ventilation openings and of silencers implemented to improve their acoustical performance, in order to provide engineers and architects with optimal design techniques.

This paper assumes silencers of the simplest form – a straight, lined duct of rectangular cross-section. An analytical solution exists for the attenuation of the fundamental model in such a duct [3, 4]. In straight sections of lined silencers, the attenuation of the fundamental mode generally governs the performance, because it is the least attenuated [4]. This paper presents the analytical solution and uses it to investigate the effect of silencer geometry on the resulting attenuation.

2. GENERAL CARTESIAN SOLUTION

In rectangular ducts, since the geometries are made of planes defined by simple Cartesian coordinates, it is useful to use the wave equation in Cartesian coordinates. The linear wave equation for sound pressure p can be written as:

$$\nabla^2 p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$

where c is the sound speed. Using separation of variables to find solutions, the pressure can be expressed as the product of three spatially-dependent functions and a time-dependent function:

$$p(r,t) = p_x(x)p_y(y)p_z(z)T(t)$$

By inserting this assumption into the wave equation, the spatially-dependent variables can be separated from the time-dependent variable, creating multiple ordinary differential equations from the single partial differential equation:

$$ODEs: \begin{cases} p_x''(x) - s_x \dfrac{p_x(x)}{c^2} = 0 \\ p_y''(t) - s_y \dfrac{p_y(y)}{c^2} = 0 \\ p_z''(z) - s_z \dfrac{p_z(z)}{c^2} = 0 \\ p_t''(t) - s p_t(t) = 0 \end{cases}$$

where $s_x + s_y + s_z = s$. Differential equations of this form can take the following solutions:

$$p_{x,y\,or\,z}(x, y\,or\,z) = \begin{cases} A_1 e^{\sqrt{\frac{s_x}{c^2}}x} + A_2 e^{-\sqrt{\frac{s_x}{c^2}}x} & if\ s_x > 0 \\ A_1 + A_2 x \quad if\ s_x = 0 \\ A_1 e^{j\sqrt{\frac{-s_x}{c^2}}x} + A_2 e^{-j\sqrt{\frac{-s_x}{c^2}}x} & if\ s_x < 0 \end{cases}$$

$$p_t(t) = \begin{cases} A_1 e^{\sqrt{s}t} + A_2 e^{-\sqrt{s}t} & if\ s_t > 0 \\ A_1 + A_2 t \quad if\ s_t = 0 \\ A_1 e^{j\sqrt{-s}t} + A_2 e^{-j\sqrt{-s}t} & if\ s_t < 0 \end{cases}$$

Our interest is in the harmonic solution, for which $s_{x,\,t} < 0$. It is convenient and informative to introduce the wave number k and angular frequency ω. Letting $-s_x = k_x^2 c^2$ and $-s = \omega^2$, the general Cartesian solution can be written as:

$$p = p_x(x)p_y(y)p_z(z)p_t(t)$$

$$\text{where}: \begin{cases} p_x(x) = A_1 e^{jk_x x} + A_2 e^{-jk_x x} \\ p_y(y) = A_3 e^{jk_y y} + A_4 e^{-jk_y y} \\ p_z(z) = A_5 e^{jk_z z} + A_6 e^{-jk_z z} \\ p_t(t) = A_7 e^{j\omega t} + A_8 e^{-j\omega t} \\ k_x^2 + k_y^2 + k_z^2 = k^2 = \dfrac{\omega^2}{c^2} \end{cases}$$

This solution represents waves, with some amplitudes and wave numbers, propagating in the positive and negative directions along each axis, and propagating in both directions with respect to time.

3. RIGID-WALLED DUCT

In an infinite-length duct, or equivalently in a duct with an anechoic termination, waves will not propagate in the $-z$ direction. Waves travel forward with unit amplitude as time increases. With these restrictions, the general solution becomes:

$$p_z(z) = A_5 e^{-jk_z z}$$
$$p_t(t) = e^{j\omega t}$$

Taking the cross-section of the duct to extend from 0 to L_x in x, and 0 to L_y in y, the Neumann condition is applied to the rigid duct walls:

$$\frac{dp_x(x)}{dx} = 0 \quad at\ x = 0\ and\ x = L_x$$
$$\frac{dp_y(y)}{dy} = 0 \quad at\ y = 0\ and\ y = L_y$$

Using these boundary conditions, and the general solution, a modal solution can be presented as:

$$p = A\cos(k_l x)\cos(k_m y)e^{j(\omega t - k_z z)}$$
$$k_l^2 + k_m^2 + k_z^2 = \frac{\omega^2}{c^2}$$
$$where \begin{cases} k_l = \dfrac{l\pi}{L_x} & l = 0,1,2,3\ldots \\ k_m = \dfrac{m\pi}{L_y} & m = 0,1,2,3\ldots \end{cases}$$

By letting $k_l^2 + k_m^2 = k_{lm}^2$, and solving for the wave number in z, some properties of the system become apparent:

$$k_z = \sqrt{\frac{\omega^2}{c^2} - k_{lm}^2}$$

For relatively high frequencies, or ducts of large cross-section with respect to a given mode, the pressure fluctuates sinusoidally with z:

$$\frac{\omega^2}{c^2} - k_{lm}{}^2 > 0$$

$$p = A\cos(k_l x)\cos(k_m y)e^{j\omega t}e^{-j\sqrt{\frac{\omega^2}{c^2}-k_{lm}{}^2}z}$$

When the frequency becomes low, or the duct is small with respect to a given mode, the wave number becomes complex, resulting in a pressure that decays exponentially with increasing z. This defines the cut-off frequency for a mode in a duct. The only mode that does not have a cut-off frequency is the plane-wave mode ($l = 0$, $m = 0$):

$$\frac{\omega^2}{c^2} - k_{lm}{}^2 < 0$$

$$p = A\cos(k_l x)\cos(k_m y)e^{j\omega t}e^{-\sqrt{k_{lm}{}^2-\frac{\omega^2}{c^2}}z}$$

4. NON-RIGID-WALLED DUCT

If a duct does not have rigid walls, the Neumann boundary condition becomes invalid. If the normal-incidence surface impedance is known, then the boundary condition can be replaced with:

$$Z_s = \frac{p}{u}$$

Applying Newton's second law to an element of fluid, the particle velocity can be related to pressure:

$$F = m\ddot{x}$$
$$\frac{\partial p_x}{\partial x} = -\rho_0 \frac{\partial u_x}{\partial t}$$
$$\frac{\partial p_y}{\partial y} = -\rho_0 \frac{\partial u_y}{\partial t}$$

Assuming that u_x and u_y have solutions that vary sinusoidally with time, it follows that:

$$u_x = \frac{-1}{j\rho_0\omega}\frac{dp_x}{dx} = \frac{-k_x}{\rho_0 kc}\left(A_1 e^{jk_x x} - A_2 e^{-jk_x x}\right)$$
$$u_y = \frac{-1}{j\rho_0\omega}\frac{dp_y}{dy} = \frac{-k_y}{\rho_0 kc}\left(A_3 e^{jk_y y} - A_4 e^{-jk_y y}\right)$$

Solving for the impedance at the duct walls (h_x, $-h_x$, h_y, $-h_y$):

$$Z_{s,x}(h_x) = \frac{A_1 e^{jk_x h_x} + A_2 e^{-jh_x}}{\frac{-k_x}{\rho_0 kc}\left(A_1 e^{jh_x} - A_2 e^{-jh_x}\right)}$$
$$Z_{s,x}(-h_x) = \frac{A_1 e^{-jk_x h_x} + A_2 e^{jh_x}}{\frac{-k_x}{\rho_0 kc}\left(A_1 e^{-jh_x} - A_2 e^{jh_x}\right)}$$
$$Z_{s,y}(h_y) = \frac{A_3 e^{jk_y h_y} + A_4 e^{-jk_y h_y}}{\frac{-k_y}{\rho_0 kc}\left(A_3 e^{jk_y h_y} - A_4 e^{-jk_y h_y}\right)}$$
$$Z_{s,y}(-h_y) = \frac{A_3 e^{-jk_y h_y} + A_4 e^{jk_y h_y}}{\frac{-k_y}{\rho_0 kc}\left(A_3 e^{-jk_y h_y} - A_4 e^{jk_y h_y}\right)}$$

If the impedances of opposite walls are equal, the simplifying assumption can be made that the propagating modes will be either symmetric or antisymmetric [3]. For symmetric-mode propagation:

$$A_1 = A_2$$
$$A_3 = A_4$$
$$\frac{Z_{s,x}(h_x)}{Z_0} = \frac{-Z_{s,x}(-h_x)}{Z_0} = \frac{-k}{jk_x}\cot(k_x h_x)$$
$$\frac{Z_{s,y}(h_y)}{Z_0} = \frac{-Z_{s,y}(-h_y)}{Z_0} = \frac{-k}{jk_y}\cot(k_y h_y)$$

For antisymmetric-mode propagation:

$$-A_1 = A_2$$
$$-A_3 = A_4$$
$$\frac{Z_{s,x}(h_x)}{Z_0} = \frac{-Z_{s,x}(-h_x)}{Z_0} = \frac{k}{jk_x}\tan(k_x h_x)$$
$$\frac{Z_{s,y}(h_y)}{Z_0} = \frac{-Z_{s,y}(-h_y)}{Z_0} = \frac{k}{jk_y}\tan(k_y h_y)$$

Re-written, the system of equations for a duct in which opposite walls have the same impedance is:

$$\left.\begin{aligned} k_x\tan(k_x h_x) &= \frac{jkZ_0}{Z_{s,x}} \\ k_y\tan(k_y h_y) &= \frac{jkZ_0}{Z_{s,y}} \\ k_x{}^2 + k_y{}^2 + k_z{}^2 &= k^2 \end{aligned}\right\}\text{ symmetric}$$
$$\left.\begin{aligned} k_x\cot(k_x h_x) &= \frac{-jkZ_0}{Z_{s,x}} \\ k_y\cot(k_y h_y) &= \frac{-jkZ_0}{Z_{s,y}} \\ k_x{}^2 + k_y{}^2 + k_z{}^2 &= k^2 \end{aligned}\right\}\text{ antisymmetric} \qquad (1)$$

These two sets of equations can be solved numerically to find k_z as a function of k (k is directly related to frequency). A numerical-iteration scheme, such as the Newton-Raphson method, can be used to find the roots of, and solutions to, these equations.

One important observation from this analysis is that, if the wall impedance is not infinite, the wavenumbers will be complex. If the wavenumber in z is complex, the pressure variation p_3 with respect to the duct length can be written:

$$p_3(z) = A_5 e^{j\,\mathrm{Re}(k_z)z} e^{-\mathrm{Im}(k_z)z}$$

This result shows that the modal pressure decays exponentially along the length of the duct. The attenuation can be conveniently expressed in decibels as:

$$\text{Attenuation} = 20\,\mathrm{Im}(k_z)z\log(e) = 8.686\,\mathrm{Im}(k_z)z \text{ dB}$$

4.1 Defining the Surface Impedance

A solution for the plane-wave attenuation in a lined duct has been presented; however, the surface impedance of the absorptive liner must be known. The transfer-function method is presented here as a simple method for converting an absorptive material's characteristic impedance and wave number into a surface impedance. A brief background is also given on absorptive materials, to describe how the propagation impedance and wavenumber are determined.

4.1.1 Transfer-function method

In order to use the propagation impedance and wavenumber for design in typical applications, they must be converted into an equivalent surface impedance [5, 6]. The transfer-function method is convenient for this purpose. It starts by defining the pressure and velocity at positions $x = 0$ and $x = d$ as functions of the forward and backward propagating waves. These four equations are then rearranged to relate the pressure and velocity at $x = d$ to those at $x = 0$ by a general 'transfer function':

$$p_x(0) = A_1 + A_2$$

$$u_x(0) = \frac{(A_1 - A_2)}{\rho\omega}$$

$$p_x(d_x) = A_1 e^{-jk_x d_x} + A_2 e^{jk_x d_x}$$

$$u_x(d_x) = \frac{k_x\left(A_1 e^{-jk_x d_x} - A_2 e^{jk_x d_x}\right)}{\rho\omega}$$

Subscript x indicates the component of the variable in the x direction. Combining these equations gives:

$$p_x(0) = p(d_x)\cos(k_x d_x) + ju(d_x)\frac{\rho\omega}{k_x}\sin(k_x d_x)$$

$$u_x(0) = \frac{jk_x p(d_x)}{\rho\omega}\sin(k_x d_x) + u(d_x)\cos(k_x d_x)$$

which can be equivalently expressed in matrix form as:

$$\begin{bmatrix} p(0) \\ u(0) \end{bmatrix} = [T]\begin{bmatrix} p(d_x) \\ u(d_x) \end{bmatrix}$$

$$[T] = \begin{bmatrix} \cos(k_x d_x) + j\dfrac{\rho\omega}{k_x}\sin(k_x d_x) \\ \dfrac{jk_x}{\rho\omega}\sin(k_x d_x) + \cos(k_x d_x) \end{bmatrix}$$

$[T]$ is the transfer matrix for a finite-thickness layer. Transfer matrices can be defined for many simple geometries, and are multiplied together to find the total transfer functions of compound layers and geometries. Here, we see that, if we let the surface impedance at $x = d$ be $Z_{s,x}(d_x)$, we can solve for the surface impedance at $x = 0$, $Z_s(0)$:

$$Z_{s,x}(0) = \frac{Z_{s,x}(d_x)\cot(k_x d_x) + jZ_0\dfrac{k}{k_x}}{j\dfrac{Z_s,x(d_x)k_x}{Z_0 k} + \cot(k_x d_x)}$$

If the layer is backed by a rigid surface, then $Z_{s,x}(d_x)$ is effectively infinite and the surface impedance can be simplified to:

$$Z_{s,x}(0) = -jZ_0\frac{k}{k_x}\cot(k_x d_x) \qquad (2)$$

This result can be used, in combination with Eqs. (1), to define the surface impedance of a duct, provided the propagation impedance and wavenumber, Z_0 and k respecttively, are known for the porous absorber. For clarity, from here on the characteristic impedance and wavenumber of the porous absorber are identified as Z_w and k_w. The symmetric equations are:

$$\left.\begin{aligned} &-jZ_w\frac{k_w}{k_{w,x}}\cot(k_{w,x}d_x) = j\cot(k_x h_x)\frac{jkZ_0}{k_x} \\ &-jZ_w\frac{k_w}{k_{w,y}}\cot(k_{w,y}d_y) = j\cot(k_y h_y)\frac{jkZ_0}{k_y} \\ &k_x^{\,2} + k_y^{\,2} + k_z^{\,2} = k^2 \end{aligned}\right\} \qquad (3)$$

This formulation allows for arbitrary incidence angle; however, $k_{w,x}$ must be found using Snell's law, as refraction occurs due to the difference in wave speeds in air and in a porous absorber. With ψ and φ being the incident and transmitted angles, $k_{w,x}$ is [5]:

$$k_{x,w} = k_w\sqrt{1-\sin(\phi)} = \sqrt{k_w^{\,2} - k^2\sin(\psi)}$$

In practice, the wave speeds in many porous materials are much smaller than in air; thus the waves propagate nearly normal to the surface [7]. Considering this effect, $k_{w,x} \approx k_w$. Materials in which sound will only propagate normal to the surface are referred to as 'locally reacting'. The surface impedance of a rigidly-backed, locally-reacting absorber is:

$$Z_{s,x} = -jZ_w \cot(k_w d_x)$$

The local-reaction assumption is valid provided $R < 4$ [7], where R is the normalized flow resistance, given by:

$$R = \frac{\sigma d}{\rho_0 c}$$

in which σ is the flow resistivity in MKS Rayl/m.

4.1.2 Characterizing porous absorptive materials

Porous acoustical absorbers are materials that absorb sound energy passively by means of thermal dissipation. As sound waves propagate through the porous material, the shear forces due to no-slip conditions at the absorber surface convert the kinetic energy into heat. In addition, the high surface area in the porous material makes the compression process non-adiabatic.

Porous absorbers are, as shown above, most usefully described in terms of their acoustical propagation impedance and wavenumber. Many methods, both empirical and analytical, have been developed to determine the acoustical impedance, based on material properties [5, 7]. Analytical methods, based on models of the microscopic fluid domain, have proven successful; however, they are quite complicated compared to empirical methods. Empirical methods, such as the well-known Delaney-Bazley model [5], provide a simple method for calculating the impedance from easily measured properties.

The Delaney-Bazley model is based on a data curve-fit of many samples of fibrous acoustical absorbers with different flow resistivities; therefore, it should not be expected to give accurate results for non-fibrous absorbers, such as open-cell foams. The acoustical impedance and wavenumber of a fibrous porous absorber are [5]:

$$\frac{Z_w}{Z_0} = 1 + 0.0571X^{-0.754} - j0.087X^{-0.732}$$

$$k_w = \frac{\omega}{c_0}\left(1 + 0.0978X^{-0.700} - j0.189X^{-0..595}\right)$$

X is a function of the flow resistivity σ and frequency f:

$$X = \frac{\rho_0 f}{\sigma}$$

The Delaney-Bazley model is a single log-linear curve fit of the real and imaginary components of the impedance and wavenumber, to represent all fibrous absorbers. It is valid when [5]:

- ε (porosity) ≈ 1
- $0.01 < X < 1.0$
- $1000 < \sigma < 50{,}000$ MKS Rayl/m.

5. RESULTS

To investigation plane-wave attenuation in a lined duct, it is necessary to define realistic liner properties. For this analysis, a liner was defined to have properties similar to the material used in laboratory-measured cross-talk silencers [2]. Once a lining material was established, the effect of geometry on attenuation was investigated.

5.1 Duct-Liner Properties

To use the Delaney-Bazley method of describing the porous material, it is necessary to define the material's flow resistivity. This was done by selecting a flow resistivity that, using the Delaney-Bazley model and transfer-function methods, defines a material with a similar normal-incidence absorption coefficient a to that of the liner used in laboratory measurements [1]. Using the pressure-reflection coefficient r, the normal-incidence coefficient can be calculated from the surface impedance:

$$a = 1 - |r|^2$$

$$r = \frac{Z_s - \rho_0 c}{Z_s + \rho_0 c}$$

The normal-incidence absorption coefficient of a 25-mm-thick OEM glass-fiber sample was measured using an impedance tube and a standardized measurement procedure [8]. A comparison between the measured glass-fiber material and Delaney-Bazley prediction for different flow resistivities is shown in Figure 1. Data above 2000 Hz could not be obtained, due to impedance-tube limitations.

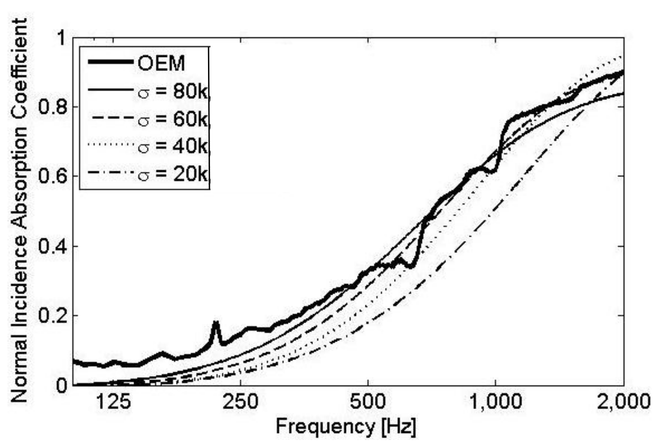


Figure 1: Absorption coefficient of 25-mm-thick OEM glass fiber as measured, and as predicted by the Delaney-Bazley model for different flow resistivities, σ in MKS Rayl/m.

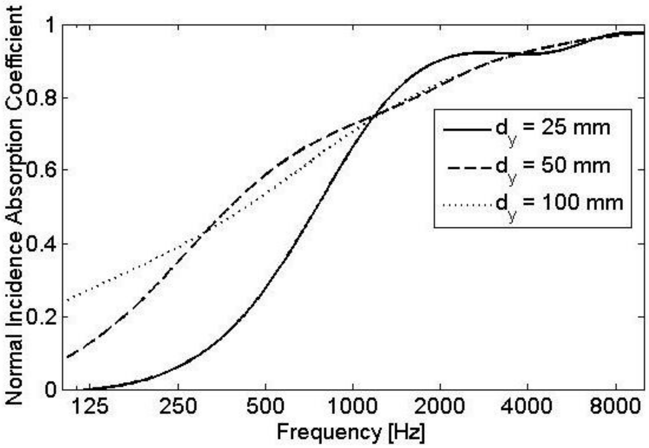


Figure 2: Variation of normal-incidence absorption coefficient for various liner thicknesses as predicted by the Delaney-Bazley model with σ = 60,000 MKS Rayl/m.

Above 500 Hz, the predicted absorption agrees best with the measurement when the flow resistivity is 60,000 MKS Rayl/m; however, below 500 Hz the Delaney-Bazley model under-predicts the measured absorption. Using a higher flow resistivity would slightly increase the low-frequency absorption; however, it would step outside of the range of validity of the local-reaction assumption. Direct measurements of the OEM glass fiber showed the flow resistivity to be 46,000 MKS Rayl/m [9]. In summary, reasonable normal-incidence-absorption agreement occurs for σ = 60k MKS Rayl/m.

The absorption is also strongly dependent on the liner thickness. Using a material with a flow resistivity of 60,000 MKS Rayl/m, the Delaney-Bazley model was used to calculate the absorption coefficient of a layer of glass fiber with varying thickness. The results are shown in Figure 2. All liner thicknesses generally provide increased absorption with increasing frequency. Above 1 kHz, all three liners have high absorption. Decreasing liner thickness results in decreased absorption at low frequency. The 25-mm liner is effectively incapable of absorbing in the 125-Hz octave band; only modest absorption is achieved in the 125-Hz band with a 100-mm liner.

5.2 Cross-Sectional Dimensions

To optimize the performance of a straight section of lined duct, one must consider the effect of the silencer flow-path dimensions, lining thickness and the acoustical proper-

Figure 3: Silencer dimensions.

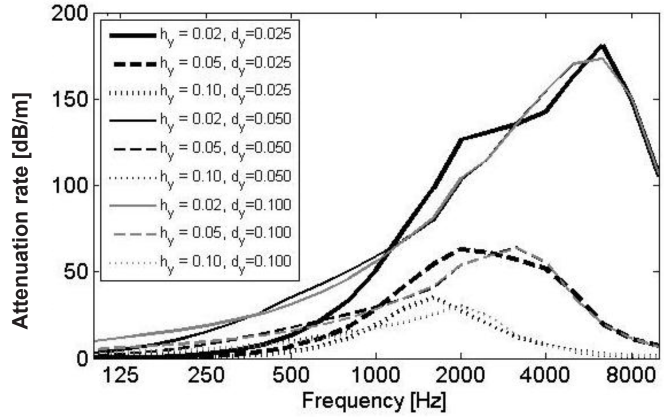


Figure 4: Predicted attenuation rate for various duct heights (h_y) and liner thicknesses (d_y).

ties of the liner. The height and width of the flow cavity in the silencer both have great effects on the acoustical attenuation; the cross-sectional geometry was examined by looking at the effects of flow-path height and aspect ratio, and how the behaviour depended on liner thickness. As required for Eqs. (3), the silencer height was equal to $2h_y$, and the liner thickness was d_y (Figure 3). The plane-wave attenuation was determined by solving Eqs. (1) and (2) using the Newton-Raphson numerical-iteration scheme.

5.2.1 Flow-path height

To examine the effect of flow-path height, a 2D silencer was studied. Attenuation of the fundamental mode in a 2D silencer is identical to that in a 3D silencer with: a. the same height, and with width much larger than the height; b. the same height and any width, but lined only on the top and bottom surfaces.

Figure 4 shows the attenuation rate in dB/m of the first-order mode in a duct with varying height and absorber thickness, plotted against frequency. If the attenuation rate (already a logarithm of power) is plotted on a logarithmic

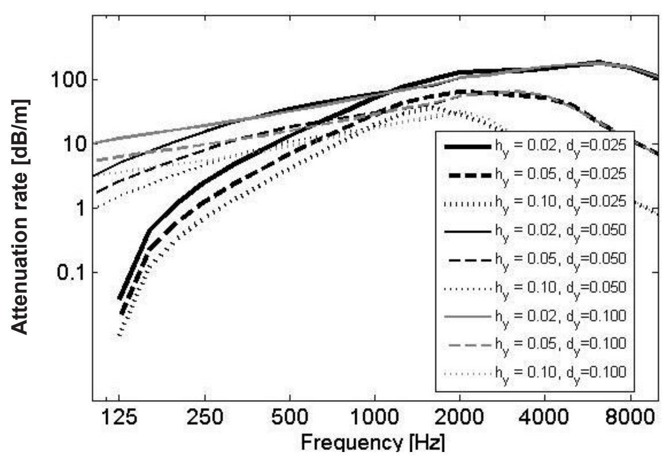


Figure 5: Predicted attenuation rate for various duct heights (h_y) and liner thicknesses (d_y), with attenuation rate plotted on a logarithmic scale.

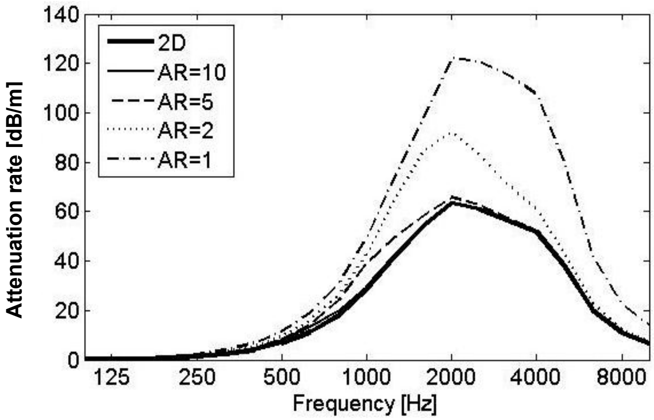


Figure 6: Predicted attenuation rate for various duct aspect ratios (AR): h_y=50 mm, h_x=$h_y \cdot$AR, d_y=d_x=25 mm.

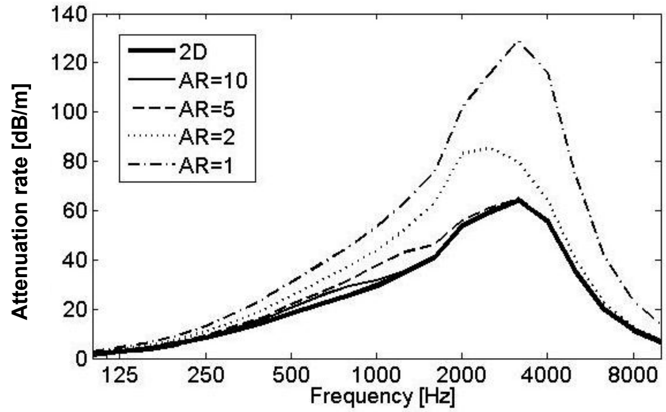


Figure 7: Predicted attenuation rate for various aspect ratios (AR): h_y=50 mm, h_x=$h_y \cdot$AR, d_y=d_x=50 mm.

scale with respect to frequency, the relationships are better illustrated (see Figure 5).

It is apparent that, at low frequencies, the attenuation rate is governed by the absorber thickness. Below 1000 Hz the performance of the silencer with a 25-mm liner falls off relative to those of the 50- and 100-mm liners. Likewise, below 250 Hz the attenuation with 50-mm liner falls off with respect to that of the 100-mm-thick liner. This result is consistent with the normal-incidence absorption-coefficient results shown in Figure 2.

Above 250 Hz, for the 50-mm liner, and above 1000 Hz for the 25-mm liner, the attenuation rate is not governed by the thickness of the liner (although it may be affected by the flow resistivity). In this region the attenuation rate is limited by the rate at which energy in the fundamental mode diffracts into the absorptive material. In all cases, the frequency at which the attenuation is maximized is very close to the frequency at which the wavelength is equal to the duct height (2*h*).

5.2.2 Flow-path aspect ratio

In the previous section the relationship between duct height and attenuation was investigated. To calculate the fundamental-mode attenuation, a 2D duct, equivalent to a duct with infinite width or a duct only lined on two opposing surfaces, was investigated. This section investigates the effect on the attenuation of the fundamental mode of a duct of varying the aspect ratio, with all four walls acoustically lined. Figure 6 shows the effect of varying the aspect ratio of a lined duct with a 0.1-m total internal height, and all four walls lined with 25-mm-thick absorptive material. As expected, if the aspect ratio is large (AR>10), the result is effectively identical to that of the 2D solution. As the aspect ratio decreases, there is an increase in attenuation. The increase in attenuation due to a reduction in AR appears to be directly related to the original attenuation – that is, if the 2D silencer has negligible attenuation, reducing the AR will not result in significant attenuation. If a 2D silencer has significant attenuation at a given frequency, a silencer with the same height, but AR = 1, will have greatly increased attenuation. Figures 7 and 8 show the same result for ducts with 50- and 100-mm-thick absorptive liners. The same results are observed for all liner thicknesses; however, as before, the attenuation rates are more pronounced at lower frequencies for thicker liners.

The increase in the attenuation of a lined duct with a small aspect ratio should be expected. With a 2D duct the wavefront will form a 2D arc as it diffracts into the liner. Because the length of an arc increases in proportion to the arc radius, the maximum energy-attenuation rate is inversely proportional to the radius. In a 3D duct with AR = 1, the wavefront will approximate the spherical end of a 3D cone as it diffracts into the liner. The area of a sphere increases in proportion to the radius squared; therefore the maximum attenuation is inversely proportional to the radius squared. As attenuation rate is expressed on a logarithmic scale, the attenuation rate in a duct with an aspect ratio of 1 is twice that in a 2D duct (or, equivalently, with AR>10) with the same height. Figures 6, 7 and 8 suggest that the attenuation rate with AR = 1 is indeed nearly twice the 2D value for any duct configuration and frequency.

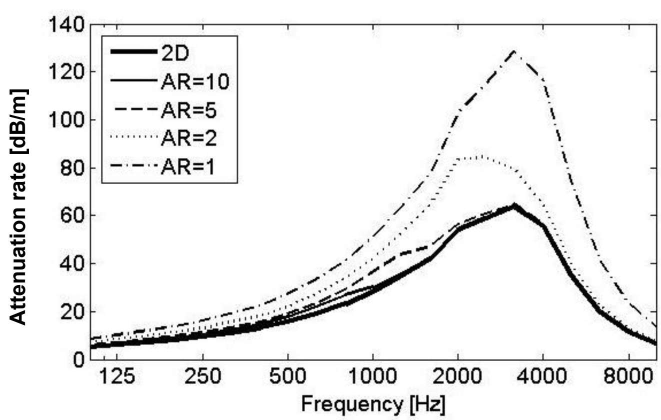


Figure 8: Predicted attenuation rate for various aspect ratios (AR): h_y=50 mm, h_x=$h_y \cdot$AR, d_y=d_x=100 mm.

6. CONCLUSION

Through comparison of the absorption coefficients, it was determined that a fibrous material with a flow resistivity of 60,000 MKS Rayl/m, as defined by the Delaney-Bazley model, has similar acoustical performance to the glass-fiber liner used in laboratory measurements [1]. Using this material, with an analytical solution for plane-wave attenuation in a lined duct, the effects of varying the duct's cross-sectional dimensions have been analyzed, providing information about how liner thickness, duct height and duct aspect ratio affect attenuation.

Duct-liner thickness does not affect high-frequency performance; however, it limits low-frequency performance. The performance of a 25-mm liner falls off below 1000 Hz; that of a 50-mm liner falls off below 250 Hz. From ventilation-opening laboratory measurements [1], it was observed that the performance of natural-ventilation-opening silencers is often limited by the 500-Hz frequency band. This result was based on the assumption that the sound that natural-ventilation-opening silencers are required to attenuate is speech. As a result, a 25-mm liner is likely not thick enough to be effective; however, a 100-mm liner may be excessive. Increasing the duct height reduces attenuation at all frequencies; however, if the frequency is high enough, or the duct is large enough that the wavelength is shorter than the duct height, the attenuation decreases rapidly. In order to provide effective attenuation through the 4000-Hz band, the duct height should not exceed 100 mm. In the case of using ducts as silencers in natural-ventilation openings to control the propagation speech sounds, smaller duct heights may be more appropriate than in the case of ducts silencers controlling lower-frequency mechanical-ventilation noise.

If the aspect ratio of a duct is greater than 10, or it is only lined on two opposing surfaces, the attenuation of its fundamental mode is, in effect, identical to that of a 2D duct.

Provided the duct liner and dimensions are such that the 2D silencer is effective at absorbing sound at a given frequency frequency, reducing the aspect ratio to near unity results in large attenuation gains. The attenuation rate of a lined duct with AR=1 is approximately twice that of a 2D lined duct.

REFERENCES

[1] C. Bibby, "Investigation of the acoustical and airflow performance of interior natural ventilation openings", M.A.Sc. (Mechanical Engineering) Thesis, University of British Columbia (Dec 2011).

[2] F. Allard and M. Santamouris, Natural Ventilation in Buildings: A Design Handbook, London: James and James Ltd., 1998.

[3] M. McCormick, "The attenuation of sound in lined rectangular ducts containing uniform flow," *J. Sound Vib.,* vol. 39, no. 1, 1975, pp. 35-41.

[4] M. L. Munjal, Acoustics of ducts and mufflers with application to exhaust and ventilation system design. Wiley-InterScience, 1987.

[5] T. Cox and P. D'Antonio, Acoustic Absorbers and Diffusers: Theory Design and Application, 2nd ed., London and New York: Taylor and Francis, 2009.

[6] H. Kuttruff, Acoustics: An Introduction. New York: Taylor and Francis, 2007.

[7] K. U. Ingard, Notes on Sound Absorption Technology, New York: Noise Control Foundation, 1994.

[8] ASTM Standard C384-04, "Standard test method for impedance and absorption of acoustical materials by impedance tube method", ASTM International, West Conshohocken, PA, USA, 2004.

[9] S. Daltrop, M. Gosselin and M. Hodgson, "Measurement and prediction of the airflow and acoustical characteristics of porous materials," Technical Report, Acoustics and Noise Research Group, University of British Columbia, 2011.

PERCEPTUAL INTEGRATION OF VISUAL EVIDENCE OF THE AIRSTREAM FROM ASPIRATED STOPS

Connor Mayer
Department of Computer Science, University of British Columbia, Vancouver, British Columbia

Bryan Gick
Department of Linguistics, University of British Columbia, Vancouver, British Columbia
Haskins Laboratories, New Haven, Connecticut

Tamra Weigel
School of Audiology and Speech Sciences, University of British Columbia, Vancouver, British Columbia

D. H. Whalen
Haskins Laboratories, New Haven, Connecticut
Program in Speech-Language-Hearing Sciences, City University of New York, New York, New York

ABSTRACT

This study investigates whether indirect visual evidence of aspiration can influence speech perception as previously found for tactile information. Participants were shown video of a speaker producing the sequence "pom" and "bomb" in a noisy setting. In some tokens, a candle was visibly perturbed by aspiration. All participants were more likely to correctly identify “pom” and incorrectly identify “bomb” in the presence of visible perturbation, indicating that perceptual integration was taking place. This effect was stronger for participants who reported being consciously aware of the candle as a predictor. This indicates that ambient information can be incorporated in speech perception even when presented via an indirect modality, and that active attention can amplify this effect.

RÉSUMÉ

Cette étude observe si une preuve d’aspiration visuelle et non directe peut influencer la perception de la parole comme cela a été démontré dans le cas d’une information tactile. Les participants ont visionné des extraits vidéo dans lesquelles un locuteur produisait des séquences “pom” et “bomb” dans un environnement bruyant. Dans certains extraits, la flamme d’une bougie était visiblement perturbée par l’aspiration. En présence de l’indication visuelle de perturbation, les participants étaient plus susceptibles d’identifier correctement “pom” et de moins bien reconnaître les séquences “bomb.” Cet effet était d’autant plus fort, lorsque les participants étaient conscients du facteur prédictif de la bougie. Ainsi, une information ambiante peut être incorporée à la perception de la parole, même présentée sous la forme d’une modalité indirecte; cet effet peut être amplifié par une attention active.

1 INTRODUCTION

Perceivers of speech integrate visual and acoustic information from articulator movements, resulting in both interference (e.g., McGurk and MacDonald 1976) and enhancement (e.g., Sumby and Pollack 1954) of auditory perception. Only a few studies have investigated the role of other types of information in speech perception. Fowler and Dekle (1991) and Gick et al. (2008) observed that tactile feedback from the “Tadoma” method of speechreading was integrated even by those who had just learned the system. Gick and Derrick (2009) found that during auditory speech perception, perceivers integrated tactile information in the form of light air puffs. These puffs, delivered cutaneously on the hand or neck, were designed to resemble speech aspiration (Derrick, Anderson, Gick, and Green 2009). When puffs were present, aspirated stops were more often correctly identified as being aspirated, and unaspirated stops were more often misidentified as aspirated, showing that listeners integrate tactile information in auditory perception in much the same way as visual information. Light taps in the same location, without direct relevance to speech, produced no effect.

The goal of the present study was to examine the influence of a related form of information on speech perception: indirect visual evidence of speech aspiration. This type of information is novel in several important respects: while previous studies have found perceptual integration of direct results of articulation (e.g., visible or palpable articulator movements, audible fluctuations in air pressure), the information studied here relies on the influence of speech production on an entity other than the speaker (e.g., aspiration moving a candle, hair, fabric, etc.). In addition to this greater degree of remove from the information source, speakers have likely had less experience with this type of information, which may make it less likely to be integrated. It is worth mentioning, however, that Derrick and Gick (2013) found integration for puffs of air received on the ankle, a situation that perceivers presumably encounter even less frequently than on the neck or hand. Finally, there are potential issues related to timing: the strength of integration increases as stimuli become more synchronous, as shown for both audio-visual (Munhall et al. 1996) and audio-tactile (Gick et al. 2010) integration. The processing of visual information is relatively slow compared to acoustic information because of the time required for the photochemical processes in the rods and cones of the eye (Welch and Warren 1986) and the greater amount of neural processing required for vision (Levine and Shefner 2000: 347). Thus, the latency in the visual modality coupled with the delay introduced between the production of aspiration and the motion of the candle flame could prove too long for the indirect information to affect the percept.

We considered three possibilities: perceivers could exhibit similarly automatic integration to that shown in previous studies, they could show strategic incorporation which relies on actively attending to the indirect information and incorporating it in post-perceptual judgements, or they could show no use of indirect information at all.

2 METHODS

2.1 Stimuli

Stimuli were produced by a 23-year-old female native speaker of west coast Canadian English saying the words "pom" (short for "pomegranate") and "bomb", and recorded using a Sony Mini-DV Handicam and a Sennheiser MK66 short shotgun microphone. There were a total of nine conditions in the experiment, based on the presence or absence of a candle, the definiteness of the acoustic information (clear or ambiguous) and matching of audio and video speech information (matched or mismatched). The conditions were separated into three different groups for analysis. Conditions *no-candle-pom-ambiguous* and *no-candle-bomb-ambiguous* used the video from conditions *no-candle-pom-matched* and *no-candle-bomb-matched*, described below, but with ambiguous audio between “pom” and “bomb” created by morphing audio of randomly selected pairs of the two words from conditions *no-candle-pom-matched* and *no-candle-bomb-matched* using the program STRAIGHT, with equal weighting on each word (Kawahara 2003). Because morphing resulted in half the original sound files, both the “pom” videos and “bomb” videos in these conditions used the same audio. This condition was intended to factor out the unlikely possibility of facial cues disambiguating the sounds (e.g., Owen and Blazek, 1985). The previous two conditions make up the first group: a one-way design. Conditions *candle-pom-matched* and *candle-bomb-matched* had a candle placed approximately 18 cm in front of the speaker: in *candle-pom-matched*, the speaker said “pom”, visibly perturbing the candle by the aspiration of the /p/, while in *candle-bomb-matched* the speaker said “bomb”, and the candle was not perturbed because of the lack of aspiration of /b/. Conditions *candle-pom-mismatched* and *candle-bomb-mismatched* used the same video as conditions *candle-pom-matched* and *candle-bomb-matched*, but with mismatched audio: in condition *candle-pom-mismatched*, perceivers saw a video “bomb” accompanied by an auditory “pom”, while in condition *candle-bomb-mismatched* they saw the opposite. The above four conditions make up the second group: a 2 x 2 x 2 factorial design. Conditions *no-candle-pom-matched* and *no-candle-bomb-matched* were identical to *candle-pom-matched* and *candle-bomb-matched* except that the candle was placed to the side of the speaker, and thus was not perturbed. The previous two conditions make up the final group: a 2 x 2 x 2 factorial design. Condition *training* featured the candle to the side as in conditions *no-candle-pom-matched* and *no-candle-bomb-matched*, but with perturbation of the candle flame occurring at times not corresponding to the effects of the airstream. This condition was designed primarily for training purposes: perceivers were shown 10 tokens of it at the beginning of the experiment to downplay the significance of the flickering candle, decreasing the likelihood of a strategic response. Additional efforts were made to distract attention from the candle, such as placing a variety of props on the bar (chips, beer, etc.) and actors in the background. Aside from condition *training*, all conditions had 20 repetitions, resulting in a total of 170 tokens. Each token was approximately one second in length.

2.2 Participants

A total of 39 native North American English listeners participated. No participants had any training in linguistics nor any reported language or hearing problems.

2.3 Procedure

Participants were seated in a soundproof room and shown short video clips of the speaker producing the sequence "pom" and "bomb" in a noisy bar setting with multi-talker babble. The babble was mixed into the video signal and set to such a volume that correct auditory-only identification of the sounds was about 70% (based on a pilot study of ten listeners). This signal-to-noise ratio was kept constant across participants. Participants listened through a pair of headphones.

Participants were told to assume the role of the bartender and that the speaker was ordering a drink. They were given a forced-choice task to identify whether they heard "pom" or "bomb" in each video clip by pressing the left and right arrows on a keyboard. Aside from the initial presentation of condition *training* for training purposes, stimuli were presented in random order including all conditions. Half the participants pushed left for "pom", the other half pushed right. Stimuli were presented and input recorded using Psyscope B53 on an iMac. When the experiment was completed, participants were asked if there were any aspects of the video that helped inform their responses. If they responded negatively, they were then asked whether they had been consciously aware of the candle flickering and whether they had used it in any conscious strategy to disambiguate the sounds. Although several participants who did not mention the candle in their initial response reported being aware of the candle after being prompted by the experimenters, all of them claimed not to have used it as a conscious decision strategy, and so were included in the negative response group. A total of 13 participants claimed to have incorporated the candle in their decision-making process while 26 did not. Data from the training condition were not included in the analysis.

3 RESULTS

Participants showed an overall bias towards "bomb" responses in all conditions (see fig. 1 and table 1). A paired t-test showed no difference in response between conditions *no-candle-pom-ambiguous* (67% "pom") and *no-candle-bomb-ambiguous* (66% "pom") across all participants [t(38) = 0.0336; p = 0.74]. This indicates that facial information alone was not sufficient for participants to distinguish between the productions. Tokens with ambiguous audio were therefore excluded from further analysis. The bias towards "pom," which contrasts with the general trend in the data, may indicate that the ambiguous audio was more similar to acoustic "pom" than "bomb."

Looking only at data where the candle was in the airstream, a 2 ("pom" vs. "bomb" audio; within factor) x 2 ("pom" vs. "bomb" video; within factor) x 2 (noticed vs. not noticed candle; between factor) repeated measures ANOVA on response across conditions *candle-pom-matched, candle-bomb-matched, candle-pom-mismatched* and *candle-bomb-mismatched* showed a significant effect of audio [F (1, 37) = 33.744; p < 0.001]; "bomb" was more accurately identified than "pom." There were significant interactions between audio and video [F (1, 37) = 26.9392; p < 0.001], and between audio, video, and whether the participant noticed the candle [F (1, 37) = 8.047; p < 0.01]. The percentages correct by listener group for all conditions with the candle in the airstream are shown in table 1. This latter interaction indicates that having seen the candle as a useful perceptual cue affected participants' responses, suggesting that strategic responding may have occurred in participants who noticed the candle: we thus conducted separate analyses on participants who noticed the candle and participants who did not.

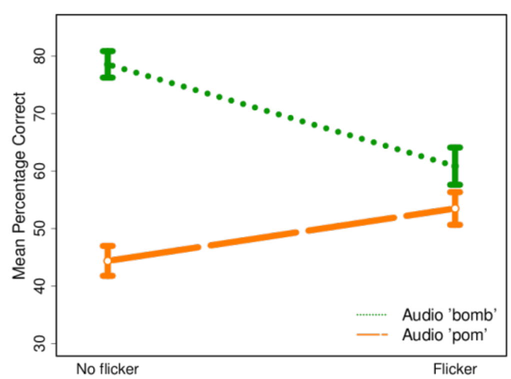


Figure 1: Interaction graphs with standard error bars across all participants in conditions with the candle present. Participants were more likely to respond correctly if the audio and video matched. Conditions *candle-pom-matched, candle-pom-mismatched, candle-bomb-matched* and *candle-bomb-mismatched*).

For participants who did not notice the candle, a 2 ("pom" vs. "bomb" audio) x 2 ("pom" vs. "bomb" video) repeated measures ANOVA showed significant effects for audio [F (1, 25) = 30.96; p < 0.001] and a significant interaction between video and audio [F (1, 25) = 14.1; p < 0.001], but no effect for video [F (1, 25) = 2.056; p = 0.164].

Audio	Video	Noticed candle	Did not notice candle
ba	ba	78%	79%
ba	pa	51%	66%
pa	ba	41%	46%
pa	pa	60%	50%

Table 1: Percentage of tokens correctly identified for conditions where the candle was in the airstream.

For participants who did notice the candle, a 2 x 2 repeated measures ANOVA showed a near-significant effect for audio [F (1,12) = 4.535; p = 0.0546] and a significant interaction between audio and video [F (1, 12) = 13.54; p < 0.01] but no effect of video [F (1, 12) = 0.429; p = 0.525].

For both groups of participants, the flickering candle induced more "pom" responses (see fig. 1). The "pom" visual signal both increased correct responses for audio "pom" (*candle-pom-matched*) and reduced correct responses for audio "bomb" (*candle-bomb-mismatched).* This effect was larger, however, for participants who were aware of the candle, explaining the interaction between noticing the candle, audio and video seen in this group.

A 2 ("pom" production vs. "bomb" production) x 2 (noticed vs. not noticed candle) ANOVA on conditions *no-candle-pom-matched* and *no-candle-bomb-matched* across all participants showed a significant effect for word being produced [F (1, 37) = 92.099; p < 0.001], with "bomb" being correctly identified (76%) more often than "pom" (44%). There was no significant effect for whether the participant noticed the candle [F (1, 37) = 0.747; p = 0.393] nor any interaction between the production and whether the candle was noticed [F (1, 37) = 0.025; p = 0.876]. This indicates that people were indeed responding to the candle and not facial cues.

4 DISCUSSION

Participants showed a bias towards "bomb" responses: indeed, the responses to "pom" audio are close to chance (see Table 1). This may be due to the Ganong effect (Ganong 1980): when presented with a stimulus that is ambiguous between a word and a non-word, listeners are more likely to choose the classification that results in a word. While "bomb" is a common word in English, "pom" is much rarer. This question could be studied in more detail by reproducing this experiment but having participants choose between "palm" (for those speakers who do not pronounce the /l/) and "bomb" instead.

All participants showed an increase in "pom" responses in the presence of a flickering candle. Depending on whether participants reported being consciously aware of it, however, the presence or absence of the candle in the airstream created by stop aspiration had different effects on their responses. Participants who reported being aware of the candle showed stronger integration and interference effects: although the increase in "pom" responses in the presence of a flickering candle held across all participants, those who reported being aware of it showed a higher rate of correct identifications of "pom" and incorrect identifications of "bomb." This suggests that this kind of indirect evidence is still close to enough to the source to be unconsciously integrated in perception, but is also removed enough to be used as a strategic cue if listeners are consciously aware of it.

It is also noteworthy that the difference in correct classification between matched and mismatched video is more pronounced for the conditions with audio "pom" than those with audio "bomb" for all participants (see Table 1). This might indicate a difference in the use of positive and negative evidence: a flickering candle is stronger evidence for an aspirated stop than a steady flame is for an unaspirated one.

Despite no participants having linguistic training, the direction of the influence shows the correct association between a candle flicker and aspiration. This indicates that some implicit awareness of speech aerodynamics influenced perceivers' interpretation of what a flickering candle should entail, regardless of whether they were consciously aware of its significance. Indeed, no participants who reported being aware of the candle were able to provide reasons for why aspiration and the flickering candle were associated, but only that they were. Neither group showed a difference between visual "pom" and "bomb" coupled with identical ambiguous audio, suggesting that participants were not able to use facial cues in differentiation; this accords with a lack of perceptual use of differences in face posture for distinguishing /p/ and /b/ (though /p/ and /m/ were distinguished) (Abel et al. 2011).

Previous studies have shown that both direct and indirect consequences of articulation, whether auditory, visual, or tactile, can influence perception. The present study supports and expands upon these results, showing that integration can be caused not only by primary sensory input but also by the secondary effects of speech on an external entity. Further research is needed to determine more clearly the limits of unconscious integration, the role of attention in multimodal speech perception, the differing roles of positive and negative evidence, and the extent of perceivers' implicit understanding of those physical systems – factors that inform strategic incorporation of useful environmental information in speech perception.

ACKNOWLEDGEMENTS

Thanks to Donald Derrick, Mark Scott, Molly Babel, Naomi Francis, Denise Tom, Bénédicte Schoepflin, and the members of the UBC Interdisciplinary Speech Research Lab. This project was funded by an NSERC Discovery Grant to the second author and by NIH Grant DC-002717 to Haskins Laboratories.

REFERENCES

Abel, J., Barbosa, A.V., Black, A., Mayer, C., and Vatikiotis-Bateson, E. (**2011**). "The Labial Viseme Reconsidered: Evidence from Production and Perception," *Proceedings of the 9th International Seminar on Speech Production (ISSP 2011)*. Montreal, Quebec, Canada. http://www.cogsys.ubc.ca/401/files/2011/05/issp2011-labials_final.pdf

Derrick, D., Anderson, P., Gick, B., and Green, S. (**2009**). "Characteristics of air puffs produced in English `pa': Experiments and simulations," J. Acoust. Soc. Am. 125(4), 2272-2281.

Derrick, D., and Gick, B. (**2013**). "Full body aero-tactile integration in speech perception," Multisensory Research. In press.

Fowler, C.A., and Dekle, D.J. (**1991**). "Listening with eye and hand: Cross-modal contributions to speech perception," Journal of Experimental Psychology: Human Perception and Performance 17, 816-828. http://www.haskins.yale.edu/sr/SR107/SR107_04.pdf

Ganong, W. F. (**1980**). "Phonetic categorization in auditory perception," Journal of Experimental Psychology: Human Perception and Performance 6, 110–125.

Gick, B., and Derrick, D. (**2009**). "Aero-tactile integration in speech perception," Nature 462, 502-504.

Gick, B., Ikegami, Y. and Derrick, D. (**2010**). "The temporal window of audio-tactile integration in speech perception," J. Acoust. Soc. Am. 128(5), EL342-EL346.

Gick, B., Jóhannsdóttir, K., Gibraiel, D., and Muehlbauer, J. (**2010**) "Tactile enhancement of auditory and visual speech perception in untrained perceivers, J. Acoust. Soc. Am. 123(4), EL72-76.

Kawahara, H., and Matsui, H. (**2003**). "Auditory morphing based on an elastic perceptual distance metric in an interference-free time-frequency representation," ICASSP V.1 Hong Kong, 256–259. http://www.wakayama-u.ac.jp/~kawahara/PSSws/kwhrv2.pdf

Levine, M. W. (**2000**). *Levine and Shefner's Fundamentals of Sensation and Perception* (Oxford University Press, New York).

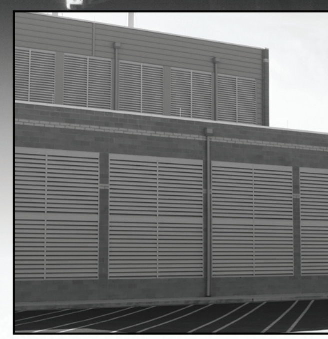
McGurk, H., and MacDonald, J.W. (**1976**). "Hearing lips and seeing voices," Nature 264, 746-748.

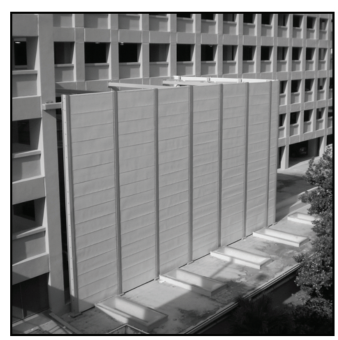
Munhall, K.G., Gribble, P., Sacco, L., and Ward, M. (**1996**). "Temporal constraints on the McGurk effect," Perception and Psychophysics 58(3), 351-362. http://gribblelab.org/publications/1996_PercepPsychophys_munhall.pdf

Owens, E., and Blazek, B. (**1985**). "Visemes observed by hearing-impaired and normal-hearing adult viewers," Journal of Speech and Hearing Research 28, 381-393.

Sumby, W. H., and Pollack, I. (**1954**). "Visual contribution to speech intelligibility in noise," J. Acoust. Soc. Am. 26, 212-215.

Welch, R. B., and Warren, D.H. (**1986**). "Intersensory interactions," in *Handbook of Perception and Human Performance*, edited by K. Boff, L. Kaufman, and J. Thomas (Wiley, New York).






For Digital Recorders
Introducing
For USB A/D Systems
PHANTOM POWER
7052PH
Measurement Mic System
7052H Type 1.5TM
Titanium Diaphragm
3Hz to >20 kHz
<20 dBA > 140 dBSPL
MK224 (<14 dBA to >134 dBSPL) Optional
4048 Preamp
Superior
IEC 1094 Type 1
Long-term Stability
Temperature and Humidity
Performance
Now in Stock
Phantom
to IEPE/ICP
Adaptor
Supplies 3-4 mA
Power
Accelerometers
Microphones
ICP1248
ACOustics
Begins with ACO
TM
MATTtm
Family
MATT TM
Mic
Attenuator
Handle Higher Sound Pressure Levels
ACO Pacific, Inc., 2604 Read Ave., Belmont, CA 94002
Tel:(650) 595-8588 FAX: (650) 591-2891 E-Mail: sales@acopacific.com
Web Site: www.acopacific.com

Validation of the CSA Z107.56 Standard Method for the Measurement of Noise Exposure from Headsets

Gabe Nespoli, Alberto Behar & Frank Russo
Department of Psychology, Ryerson University, Toronto, Ontario

ABSTRACT

The CSA Standard CAN/CSA-Z107.56-06 (R2011) "Procedures for the Measurement of Occupational Noise Exposure" deals with noise exposures found in industrial settings, where in most situations, the noise source is in the far field. The Standard also provides procedures for the measurement in situations where the noise sources include sources in the near field, which is the case with headsets. The procedures involve the use of sophisticated equipment and techniques that are generally difficult to implement in the workplace. However, the Standard also provides a simple calculation method that only requires the measurement of the background noise level using a sound level meter or a dosimeter. The calculation method assumes a signal-to-noise ratio (S/N) of 15 dBA, to ensure the most comfortable listening level for speech understanding. The noise exposure level of the ear under the headset is thus obtained as the sum of the background noise level (corrected for headset attenuation and duration of the signal) plus 15 dBA for the S/N. The objective of the present study was to assess the validity of the calculation method under different background noise conditions. Three different background noises were played at three sound levels. The noise exposure level under two headsets with different attenuations was assessed using a speech in noise paradigm. Participants were asked to adjust the signal level to comfortably understand the speech. The increase in sound level was measured for each combination of parameters using an artificial ear.

RÉSUMÉ

La norme CSA CAN/CSA-Z107.56-F06 (C2011) «Procédures relatives à la mesure de l'exposition au bruit au travail» traite de l'exposition au bruit trouvés dans les milieux industriels, où, dans la plupart des cas, la source de bruit est dans le champ lointain. La norme décrit également les procédures pour la mesure dans des situations où les sources de bruit incluent sources dans le champ proche, ce qui est le cas avec les casques. Les procédures impliquent l'utilisation de l'équipement et des techniques qui sont généralement difficiles à mettre en œuvre dans le milieu de travail sophistiqué. Cependant, la norme prévoit également un procédé de calcul simple qui ne nécessite que la mesure du niveau de bruit de fond en utilisant un appareil de mesure de niveau sonore ou d'un dosimètre. La méthode de calcul suppose un rapport signal-bruit (S/N) de 15 dBA, pour assurer le niveau sonore le plus confortable pour la compréhension de la parole. Le niveau d'exposition au bruit de l'oreille sous le casque est ainsi obtenue par la somme du niveau de bruit de fond (corrigée pour l'atténuation du casque et de la durée du signal), majoré de 15 dBA pour le rapport S/N. L'objectif de la présente étude était d'évaluer la validité de la méthode de calcul dans différentes conditions de bruit de fond. Trois différents bruits de fond ont été joués à trois niveaux sonores. Le niveau d'exposition au bruit sous deux casques avec différentes atténuations été évaluée en utilisant un discours de paradigme de bruit. Les participants ont été invités à ajuster le niveau du signal de comprendre facilement la parole. L'augmentation du niveau de bruit a été mesuré pour chaque combinaison de paramètres à l'aide d'une oreille artificielle..

1 INTRODUCTION

Noise exposure is a measure of the acoustical energy entering the ear of an exposed person, providing a basic index for risk of hearing loss. In Canada, the CAN/CSA Standard Z107.56 (Canadian Standards Association, 2002) provides procedures for the measurement of noise exposure. The standard focuses on measurement of exposure from noise sources located in the far field, such as those found in industrial environments. Another section of the same standard deals with measurement of exposure from noise sources located in the near field, such as communication headsets.

The standard presents several methods for this kind of measurement. They involve the use of specialized instruments and require skills not commonly found on the shop floor. There is, however, a much simpler procedure, called the "calculation method," that only requires the measurement of the background noise at the location where the headset is used. The objective of the present study was to assess the validity of the calculation method under different background noise conditions.

Communication headsets are used in a variety of workplaces such as retail stores, call centres, airport control towers, and other workplaces where the operator is exposed to background noise while communicating through a headset. There are a wide variety of headsets. Some can only be used for listening purposes, while others are equipped with microphones that allow for bidirectional communication. Headsets are available in single-earpiece and double-earpiece designs. Most headsets come with a headband worn over the head. Others can be attached to a hardhat or helmet when its use is required for safety reasons.

The noise exposure level under a communication headset can be obtained using the following formula:

$$L_{eq,T} = 10\log\left[10^{\frac{L-ATT}{10}} + \frac{t}{T}10^{\frac{S}{10}}\right] \qquad (1)$$

where $L_{eq,T}$ is the total noise exposure in dBA; L is the noise level of the background noise in dBA; ATT is the attenuation of the headset; t is the total duration of the signal during the workday in hours; T is the duration of the workday in hours; and S is the equivalent sound level of the signal in dBA.

The first component of the formula relates to the background noise attenuated by the headset's cup, while the second is the contribution of the signal, corrected by the ratio of the signal duration to the total duration of the exposure.

The calculation method in the Standard assumes that the most comfortable listening level for speech understanding requires a S/N ratio of 15 dBA. For normal hearing listeners, the most comfortable listening level leads to optimal word discrimination scores (Ullrich & Grimm, 1976).

The parameter investigated in this study was the noise exposure increase in the headset due to the speech signal. The calculation method described in Section 7 of the CSA Standard specifies an increase of the noise level under the headset by 15 dBA. As an example, if the background noise level is 70 dBA and the attenuation is not known, then the estimated noise level under the headset is 85 dBA. If the attenuation of the headset is known, then it is subtracted from the background noise level. Regardless of whether the attenuation of the headset is known, the final result must be corrected to take into account the total duration of the signal relative to the duration of the workday. No consideration is given to the nature and the spectral content of the background noise.

2 TESTING METHOD

Participants were asked to listen to speech signals (consisting of unrelated sentences) via the communication headsets under test. Simultaneously, background noise was reproduced at different levels over loudspeakers in the testing room. The participants' task was to increase the sound level of the speech signal using an attenuator until they reached the most comfortable listening level. Effort was made to ensure that participants were adjusting to the most comfortable listening level and not the threshold of hearing. Figure 1 illustrates the testing environment.

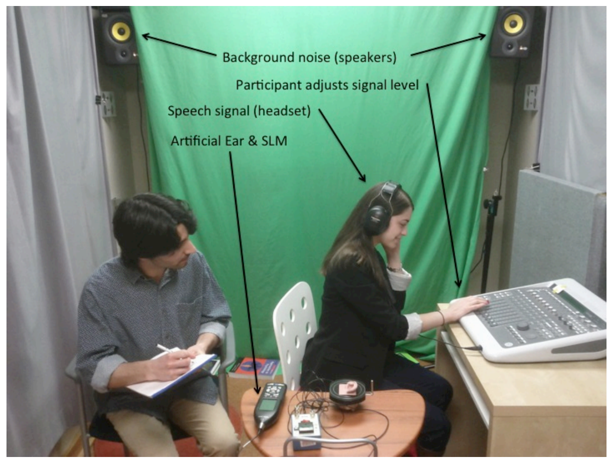


Figure 1. Background noise is played into the room via speakers, while the participant listens to the speech signal via headphones. She adjusts the signal to the most comfortable level for understanding. The experimenter then uses the Artificial Ear and Sound Level Meter to measure the noise exposure.

The CSA Standard concerns the measurement of occupational noise exposure over the duration of the workday. In our study the background noise and the speech signals had the same duration. Therefore the numerical values of noise exposure and noise level were identical.

2.1 Test site

Testing took place in a double-walled recording room (3.7m x 2.2m x 2.4m). The room is equipped with a double glazed observation window allowing for visual communication between the experimenter and the participant. The room also supports bi-directional aural communication between the participant and experimenter. The background noise level in the room was consistently lower than 40 dBA. No special precautions were taken regarding reverberation or diffusion of the background noise sound field inside the room.

2.2 Equipment

Headsets and speech signal presentation

Figure 2 is a photograph of the two headsets used in the experiment. Although both headsets entirely enclose the concha of the user, their attenuations are different. The 3M Peltor HTB79A headset was used to represent headsets with high attenuation. The Noise Reduction Rating (NRR) of the 3M headset as specified by the manufacturer is 26 dB. The Koss SB-40 communication headset was chosen to represent headsets with relatively low attenuation. Koss does not provide an NRR value for this headset. The attenuator used to control the levels of the speech signal was a slider on the hardware interface (DIGI003) of the Pro Tools 8 digital audio workstation.

Figure 2. Photograph of the headsets used for the experiment.

Background noise reproduction

The background noise was reproduced via two KRK Rockit 5 loudspeakers located in two corners of the room. The levels of the background noises were controlled using the software interface of the Pro Tools 8 digital audio workstation.

Sound level measurement

Measurements of sound levels were performed by connecting a Type 831 Larson Davis Sound Level Meter (SLM) to a G.R.A.S. Type 43AG Ear and Cheek Simulator. Use of the simulator for these measurements is consistent with the Australian/New Zealand Standard (Standards Australia & Standards New Zealand, 2005). Background noise measured with the simulator was found to be within +/- 1 dBA of the equivalent measurement obtained using the SLM on its own.

Audiometer

The air-conduction hearing threshold of each participant was obtained using a Grason-Stadler 61 Clinical Audiometer while seated in an IAC double-walled audiometric booth.

2.3 Sound signals

Background noise

Consistent with the standard, exposure levels were determined using dBA as the measuring unit. Three different background noises were used for the tests as follows:

a) multi-talker babble noise to simulate acoustical conditions found in call centers, airport control towers, etc.,
b) construction noise, and
c) industrial noise.

Each noise was played at 60, 65 and 70 dBA. Diagnostic testing of speaker output revealed distortions in the signal above 70 dBA, thus we did not use sound levels above this limit. Figure 3 shows the spectra of the three noises, played at 60 dBA, as recorded in the test room using the artificial ear.

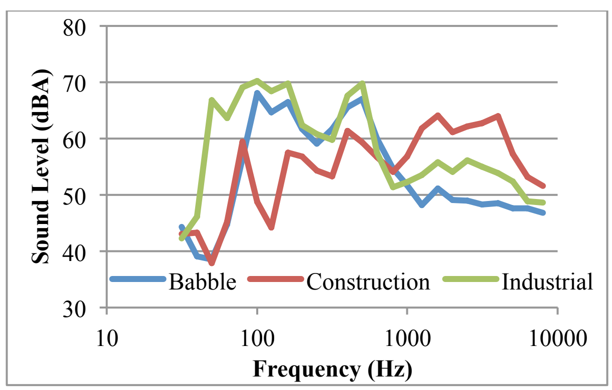


Figure 3. Spectra of the background noises used for the experiment.

Speech signals

Speech signals consisted of sentences from the revised Speech Perception In Noise test (SPIN-R; Bilger et al., 1984). The order of sentences was fixed across participants and sentences were never repeated in any two trials within the same block.

2.4 Participants

Twenty-two participants were recruited from the Ryerson University community (18 females). The average age of participants was 21.6 years with a Standard Deviation of 6.5 years.

All participants had normal hearing (threshold better than 25 dB HL) as measured by pure tone audiometric tests at the standard test frequencies (500, 1000, 2000, 4000 and 8000 Hz). Hearing thresholds were obtained after completing the study to avoid confusion between instructions for pure tones (threshold of hearing) and those for speech (most comfortable listening level). Participants were given course credit as compensation for their participation in the study.

The design of the experiment was approved by the Ryerson University Ethics Board under protocol # 2012-251. All participants gave informed consent to take part in the study.

3 PROCEDURE

3.1 Background noise calibration

The sound level of the three background noises was adjusted to 60, 65 and 70 dBA at the start of each session.

3.2 Testing

Participants were given instructions on how to operate the attenuator. Before the beginning of each trial the speech signal level was set to 0 dBA by the experimenter. Each background noise (multi-talker babble, industrial, and construction) was presented at each of three sound levels (60, 65, and 70 dBA). Participants were instructed to adjust the level of the speech signal to the most comfortable listening level of speech understanding. Once this level was achieved, the experimenter placed the right cup of the headphone on top of the Artificial Ear and measured the L_{eq} (speech plus background noise minus the headset attenuation) for 10 seconds. The order of trials was independently randomized for each participant.

4 MEASUREMENT RESULTS

The increase in noise exposure was obtained as the difference in sound level between the background noise and the combination of the background noise (reduced by the attenuation of the headset) and speech signal (adjusted by the participant), as measured by the artificial ear. To assess the reliability of these measurements, a subset of the participants completed a second block in the same session (see Appendix B).

All measurements from the first block were subjected to a 2 x 3 x 3 Analysis of Variance (ANOVA) with Attenuation (high vs. low), Noise Type (babble vs. construction vs. industrial) and Noise Level (60 vs. 65 vs. 70) as within-subject factors. Significant main effects were found for Attenuation ($F = 982.0$, $p < .001$) and Noise Type ($F = 38.6$, $p < .001$), as well as a significant interaction between Attenuation and Noise Type ($F = 10.1$, $p < .001$).

The high attenuation headset yielded smaller exposure increase values (mean = -7.6 dBA) than the low attenuation headset (3.9 dBA). This is to be expected since the increased attenuation creates a quieter environment inside the headset's cups, allowing the comfortable listening level to be lower. As expected, the resulting level under the headset's cup was lower than that of the background noise itself (as indicated by the negative values). These measurement results are summarized in Figures 4a and 4b.

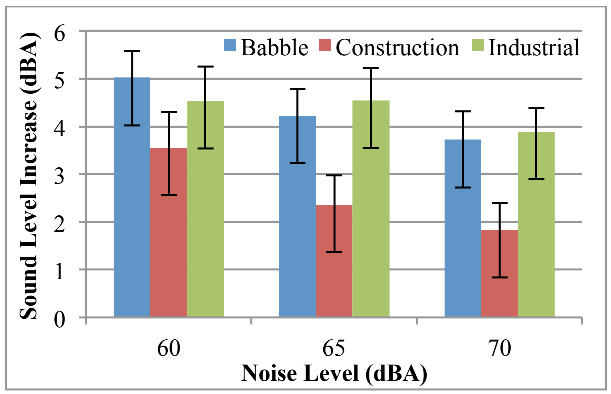


Figure 4a. Increase of sound level due to speech for the low attenuation headset. Error bars indicate standard error.

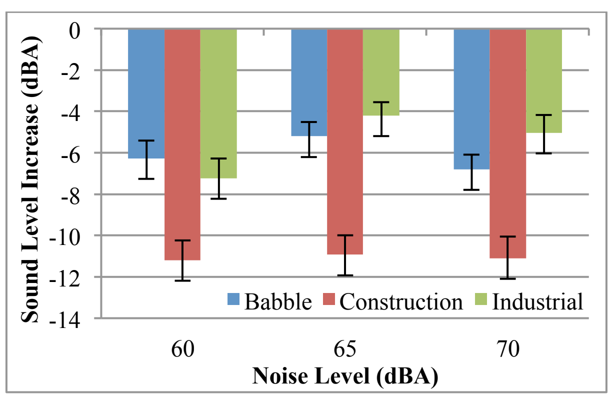


Figure 4b. Increase of sound level due to speech for the high attenuation headset. Note that all values are negative,

indicating a decrease in sound level. Error bars indicate standard error.

Bonferroni-corrected post-hoc tests revealed that construction noise yielded significantly smaller exposure increase values (mean = -4.1 dBA) compared to both babble (-0.91 dBA) and industrial noise (-0.55) across both attenuation conditions ($p < .001$).

The attenuation of construction noise compared to babble and industrial noise was different for each attenuation condition, as indicated by the significant interaction of Noise Type and Attenuation. For the low attenuation headset, exposure increase values for construction noise were 1.65 and 1.71 dBA smaller than babble and industrial noise, respectively. However, for the high attenuation headset, exposure increase values for construction noise were 4.81 and 5.46 dBA smaller than babble and industrial noise, respectively.

5 DISCUSSION

The main goal of the current study was to validate the calculation method described in the CSA Standard for measuring noise exposure due to communication headsets. The calculation method stipulates that 15 dB should be added to an environmental sound level measurement to account for sound coming from the headset. If the attenuation of the headset is known, the measurement should first be corrected to account for this. These results confirm that the exposure increase depends on the attenuation of the headset. However it also seems that the value of 15 dB is too high. The increase also depends on the type of background noise, something that is not addressed in the present Standard.

When using the high attenuation headset, participants were able to achieve a comfortable listening level that was quieter than the background noise, resulting in an average exposure increase of -7.6 dBA, which is drastically different from the 15 dBA stipulated in the Standard. Even for the low attenuation headset, participants only needed a 3.9 dBA increase in order to comfortably understand the speech signal.

The type of background noise also plays a role in the exposure increase due to headsets, and this is likely related to how they are differentially attenuated by the headset. Both headsets used in this study attenuated construction noise the most (see Appendix A), and correspondingly, exposure increase values were lowest for this type of noise source (see Figures 4a and 4b).

Interestingly, the difference in exposure increase between construction and other noises was larger for the high attenuation headset than the low one, as shown by the significant interaction. As seen in Figure 3, construction noise has a different spectral profile than babble or industrial noise, specifically one skewed towards higher frequencies. Given that higher frequencies are easier to attenuate than lower frequencies in hearing protector headsets (see Figure 3 in Berger, 2000), it makes sense that this type of noise was attenuated the most, and that the extent of attenuation was greatest in the high attenuation headset. This further strengthens the idea that the exposure increase due to headsets depends on both the attenuation of the headset and the type of background noise.

6 CONCLUSIONS

Results in our study cast doubt on the feasibility of having a single number to be added to the background noise level to obtain the noise level under a headset, because it is highly dependent on the type of noise in the environment Also, these results provide further validation for the advantage of high attenuation headsets, especially in high noise level environments.

ACKNOWLEDGEMENTS

We wish to acknowledge Tristan Loria for his invaluable assistance in all aspects of this project.

REFERENCES

Berger, E.H. (2000). Hearing Protection Devices. In Berger, E.H., Royster, L.H., Royster, J.D., Driscoll, D.P., & Layne, M. (Eds.), *The Noise Manual* (379-454). Fairfax, VA: American Industrial Hygiene Association.

Bilger, R.C., Nuetzel, J.M., Rabinowitz, W.M., & Rzeczkowski, C. (1984). Standardization of a Test of Speech Perception in Noise. *Journal of Speech and Hearing Research, 27,* 32-48.

Canadian Standards Association. (2002). *Hearing Protection Devices – Performance, Selection, Car and Use.* Canadian Standard CAN/CSA-Z94.2-02 (R2011). Canadian Standards Association, Toronto.

Standards Australia & Standards New Zealand. (2005). *Occupational Noise Management Part 1: Measurement and Assessment of Noise Immission and Exposure.* Australian/New Zealand Standard AS/NZS 1269-1:2005. Standards Australia, Sydney, and Standards New Zealand, New York.

Ullrich, K., & Grimm, D. (1976). Most comfortable listening level presentation versus maximum discrimination for word discrimination material. *Audiology, 15,* 338-347.

APPENDICES

Appendix A: Headsets' attenuation

The attenuation of both headsets was calculated as the difference between the noise levels measured in dBA with the Artificial Ear open and covered with the headset. These results are summarized in Figures A1 and A2.

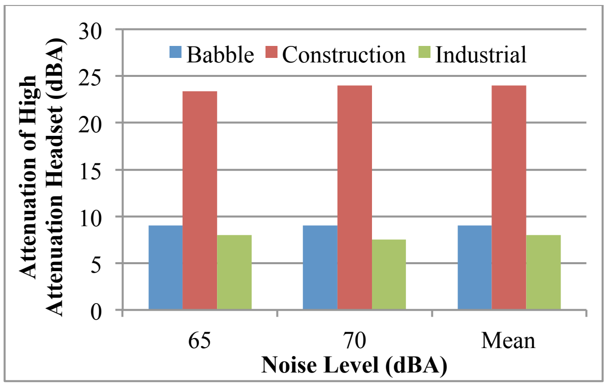


Figure A1: Attenuation of the high attenuation headset

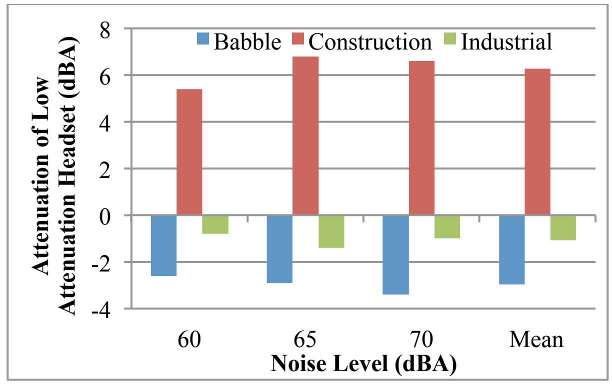


Figure A2: Attenuation of the low attenuation headset

Appendix B: Reliability analysis

Fifteen of the 22 participants completed the experiment twice in the same session (in two blocks) in order to conduct a reliability analysis. This was to ensure that participants were completing the task as instructed and not randomly setting the attenuation level. For each participant, exposure increase data for block 1 were correlated with those of block 2. The average Pearson correlation for all 15 participants was 0.86; all correlations were significant at least at the .001 level. As a result, data from block 2 were not included in the ANOVA that is reported in the results.

RECORDING TECHNIQUES AND THEIR EFFECT ON SOUND QUALITY AT OFF-CENTER LISTENING POSITIONS IN 5.0 SURROUND ENVIRONMENTS

Nils Peters[1], **Jonas Braasch**[2], **Stephen McAdams**[3]
[1] Centre for Interdisciplinary Research in Music Media and Technology, McGill University, nils@music.mcgill.ca
[2] School of Architecture, Rensselaer Polytechnic Institute, 110 8th St., Troy, NY 12180, braasj@rpi.edu
[3] Schulich School of Music, McGill University, 555 Sherbrooke St. W., Montreal, QC H3A 1E3, smc@music.mcgill.ca

ABSTRACT

Assessments of listener preferences for different multichannel recording techniques typically focus on the sweet spot, the spatial area where the listener maintains optimal perception of the reproduced sound field. The purpose of this study is to explore how multichannel recording techniques affect the sound quality at off-center (non-sweet spot) listening positions in medium-sized rooms. Listening impressions of two musical excerpts created by three different multichannel recording techniques for multiple off-center positions are compared with the impression at the sweet spot in two different listening room environments. The choice of a recording technique significantly affects the sound quality at off-center positions relative to the sweet spot, and this finding depends on the type of listening environment. In the studio grade listening room environment featuring a standard loudspeaker configuration, the two tested spaced microphone techniques were rated better at off-center positions compared to the coincident Ambisonics technique. For the less controlled room environment, the interaction between recording technique and musical excerpt played a significant role in listener preference.

SOMMAIRE

L' évaluation par des auditeurs de préférences entre différentes techniques d'enregistrement multi-canal se focalisent typiquement sur la zone idéale *(sweet spot)*, la région de l'espace où l'auditeur maintient une perception idéale du champ sonore reproduit. L'objectif de cette étude est de comprendre comment les techniques d'enregistrement multi-canal affectent la qualité sonore à des endroits hors de la zone idéale dans des salles de taille moyenne. Dans deux salles différentes, les impressions à l'écoute de deux extraits de musique créés par trois techniques d'enregistrement multi-canal à plusieurs endroits hors de la zone idéale sont comparées avec l'impression obtenue dans la zone idéale. Le choix d'une technique d'enregistrement affecte significativement la qualité sonore dans des zones non-idéales par rapport la zone idéale. Ce résultat dépend du type d'environnement d'écoute. Dans un studio d'écoute avec une configuration d'enceintes standard, les deux techniques utilisant des microphones espacés créent une moindre perception de dégradation sonore dans les zones non-idéales comparées à la technique Ambisonics. Dans un environnement moins contrôlé, l'interaction entre la technique d'enregistrement et l'extrait musical joue un rôle significatif dans la préférence des auditeurs.

1 INTRODUCTION

A concert hall is designed to enhance natural sound sources and produce a plurality of listening positions with perceptually good sound images of those sources [1]. In spatial audio reproduction, however, a best listening point is usually implied and limits quality surround-sound reproduction to small audiences. Although several types of microphone techniques exist for surround-sound recordings, and all techniques aim to give listeners the impression of *being there*, they favor the centralized listener and yield a degraded sound image for the others. Understanding the delivery of an improved sound image across the audience is critical. Off-center locations may be more representative of typical listening situations, and research on non-ideal listening positions "may provide significant information regarding the general performance of the [audio] system" [2].

In the past, listening tests have assessed the differences among surround microphone techniques primarily at the central listening position (e.g., [3, 4, 5, 6]) and excluded off-center positions. Also in a closely related field (the evaluation of sound reproduction environments), the effect of the listening position was primarily studied for localization errors (e.g., [7, 8]), neglecting all other perceptual dimensions. This paper investigates off-center listening, specifically, the degradation in sound quality as a function of the recording technique used for capturing a recording. Recording techniques generally differ in their strategy for creating phantom sources and for reducing undesired inter-channel correlation. Strategies may involve spacing of microphones and/or increasing the microphones' directivities. Griesinger [9] suggests that decorrelation of the loudspeaker feeds increases the listening area, which can be achieved, for instance, by spacing the microphones. To our knowledge, no formal listening tests have investigated Griesinger's hypothesis.

In the following section, we define the terms Center and Off-center Listening Position and identify acoustical properties in the spatial relationship of an off-center listener to the loudspeaker setup that cause a variety of perceptual artifacts. Our methodology and the experimental conditions are explained in Section 2. Listening experiments in two different listening rooms are analyzed in Sections 3 and 4. We conclude in Section 5 with a final discussion.

1.1 Center and Off-Center Listening Positions

Audio recording and reproduction techniques usually refer to a reference listening point, called the *sweet spot*, which draws from perceptual or geometric concepts. The perceptual concepts suggest a vague consensus that the sweet spot is the point in space where a listener is fully capable of hearing the intended audio recording, the spatial bubble of head positions where the listener maintains the desired perception. For scientific use, such a definition is imprecise, because the intended sound design is unknown to most listeners. The sweet spot has also been described as the point in space where the listener is equidistant from all speakers (or at least maximally distant from them if they do not form a circle).

To avoid the ambiguous meaning of the sweet spot, we will use the term *Central Listening Position* (CLP) to describe the reference listening point where all loudspeakers are equidistant and equally calibrated in Sound Pressure Level (SPL). An *Off-Center Listening Position* (OCP) refers to all other positions within the loudspeaker array. Our definition is compliant with ITU recommendation BS.1116-1 [10], which places the reference listening point in the center of the surround loudspeaker setup (Fig. 1). This recommendation also points to the least recommended listening positions.

1.2 Loudspeakers - Listener Relation

In spatial sound reproduction, speaker feeds from multiple directions create signals at the listener's ears, uniquely for each listening position. We will briefly introduce the underlying physical relationships.

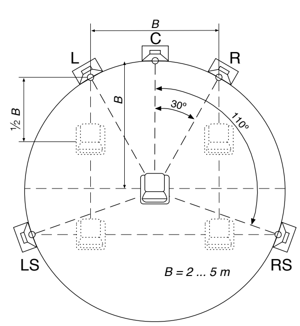


FIGURE 1 – ITU BS.1116-1. CLP (central seat) and worst case OCPs (dotted). The recommended listening area is within 0.7 m of the CLP.

Unbalanced Sound Pressure Level (SPL). A closer loudspeaker will produce a higher SPL than a loudspeaker that is farther away. For a conventional loudspeaker, the attenuation of the direct sound is ca. 6 dB SPL per doubled distance for the direct sound component. Thus, the SPL changes very quickly near a loudspeaker, which makes this effect most prominent at off-center positions in small speaker setups. Loudspeaker level differences at off-center positions also depend on room characteristics and on loudspeaker directivity due to the contribution of reflected sound energy. For uncorrelated sounds that contribute to envelopment the attenuation is closer to 3 dB SPL per doubled distance, which causes variations in off-center sound degradation across audio content [11].

Time-of-Arrival Differences (ToA). Loudspeaker feeds will arrive at an off-center position with different temporal delays due to distance differences. The maximal temporal delay is calculated from the distance of the closest and farthest loudspeakers and the speed of sound. The further away the off-center position is from the center, the greater the ToA differences.

Direction of Arriving Wavefronts. At the central listening position, a wavefront emitted by the right speaker (*R* in Fig. 1) arrives from a direction of 30°, whereas for a listener at the upper right dashed seat, the same wavefront impinges from the front.

1.3 Perceptual Artifacts

Localization. Depending on all three physical circumstances, the sound image might shift or even collapse toward the direction of the most prominent speaker feed. The Precedence Effect may explain this perception (see, e.g., [12] for a review). Although the Precedence Effect is primarily investigated for indoor localization (since it is related to localization processes in the presence of early reflections), it is also important in multichannel sound reproduction. An important distinction between these two scenarios is that a real sound source has one direct wavefront, from which directional information is decoded via summing localization and multiple (to-be-inhibited) early reflections. In multichannel audio, the location of a virtual sound source is perceived by the superposition of wavefronts emitted from several loudspeakers. At off-center positions, the auditory system may fuse and inhibit the wrong set of wavefronts. Each loudspeaker can also cause individual reflections in the listening room that will be superimposed upon the early reflections of the room in which the recording was made. Localization of reproduced sound over loudspeakers in listening rooms was specifically investigated by Olive and Toole and later by Bech. Olive and Toole [13] measured the energy of room reflections that is necessary to shift the image of the reproduced sound under three different room acoustic conditions. For early reflections (< 30 ms) this image-shift threshold was similar across all three conditions, but for reflections later than 30 ms, the reverberation time of the room had a strong influence, with the thresholds for the delayed reflection rising sharply with each move to a more reflective listening space. Bech [14] found that the amount of reflected spectral energy above 2 kHz contributes to audibility, and a strong first-order floor reflection can significantly affect spatial aspects of the reproduced sound field.

Image Stability. The perceived location of the reproduced sound source may change with pitch, loudness, or timbre. It may also change as a function of listener position, head rotation, or other normal movements. If these effects are small, the image will be stable [15]. Image Stability is one of three factors in the definition of Overall Spatial Quality by the IEC [16]. Other related spatial descriptors are Spatial Clarity, Readability, Locatedness, and Image Focus. For virtual sound sources, Lund [17] derived a localization-consistency score from the related descriptors Robustness, Diffusion, and Certainty of Angle.

Spatial Impression comprises Apparent Source Width (ASW) and Listening Envelopment (LEV). ASW describes the spatial extent of a sound source influenced by early lateral room reflections (up to 80 ms). ASW was found to be primarily generated by frequencies above 1 kHz and is correlated with the Inter-Aural Cross-correlation Coefficient (IACC) calculated from the early energy [18]. The authors of [19] found that for many, but not all sounds, the ASW is closely related to Image Stability. LEV describes the fullness of sound images around the listener due to late lateral reflections. LEV depends on the front/back energy ratio, the direction of the speakers' wavefronts, and the spectral content primarily below 1 kHz [20]. At off-center positions, the LEV can become unstable and compromises the envelopment illusion.

Timbral Effects. The relative importance of timbre and spatial aspects in audio reproduction was examined by Rumsey et al., [21]. Timbral fidelity has a weight of ca. 70% on the overall sound quality, whereas spatial factors accounted for ca. 30% of the variance. It was found that naive listeners valued surround spatial fidelity over frontal spatial fidelity, which was found to be the inverse for expert listeners [22]. Especially relevant for surround reproduction, Olive et al. [23] showed that listeners are less sensitive to the timbral effects of loudspeakers in multichannel setups compared to one-channel sound reproduction.

At off-center positions, the misalignment of the loudspeaker wavefronts (see ToA differences) can also lead to audible comb filtering [24]. The absolute threshold for an audible timbre change rises with increasing delays, whereas complex reflection patterns (responsible for ASW and LEV) and a binaural decoloration mechanism [25] can mask timbre changes. Rakerd [26] hypothesized that the auditory system may combine binaural and spectral cues for localization, so that a timbre change causes a localization change of an auditory event.

2 GENERAL METHODS

In two listening experiments, the reproduced sound field at different off-center listening positions is compared with the sound field a listener perceives at the center. We chose two sets of previously produced 5.0 multichannel content (EXC). Each 5.0 multichannel content was simultaneously recorded with three different multichannel microphone techniques (RT). All content was recorded, mixed, and produced by experts who used them in their own experiments on recording technique evaluation (see [4, 3]). To study off-center sound degradation as an effect of listening position we reproduced their content in two different rooms through 5.0 multichannel loudspeaker systems, and captured binaural stimuli at multiple listening positions (POS). Each binaural stimulus was captured at 48 kHz and had a duration of about 7 s. In total, for each tested listening position, six binaural stimuli were captured (2 excerpts $\times$ 3 recording techniques). In a soundproof booth, these binaural stimuli were compared by trained listeners wearing diffuse-field equalized headphones.

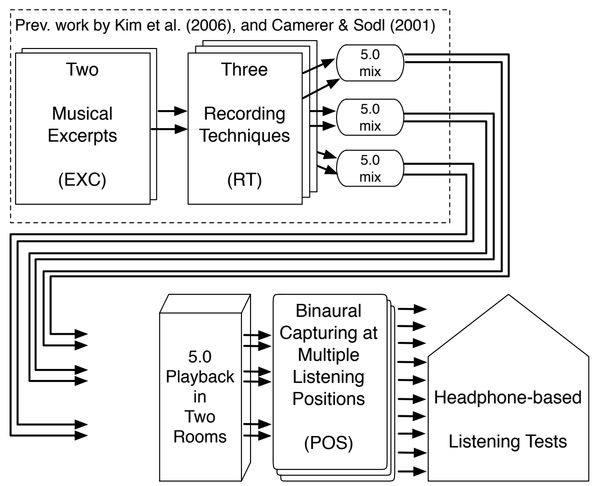


FIGURE 2 – General experimental method.

To study off-center sound degradation as an effect of the reproduction environment, our sets of binaural stimuli were captured in two very different reproduction environments. Both environments are actively used for multichannel sound reproduction for larger audiences. The first reproduction environment (Telus Studio) is a medium size room with a standard 5.0 full-range loudspeaker setup to meet the ITU requirements for multichannel loudspeaker setups for listening rooms. The second reproduction environment (Tanna Schulich Hall) is a small multi-purpose concert venue, a non-ideal, ecologically valid sound reproduction environment. The reproduction environments differ in terms of the room acoustic condition, loudspeaker type, and loudspeaker arrangement (see Fig. 3 for comparison of the reverberation time). Practical reasons led us to create two *most-different* scenarios for our study of perceived off-center sound degradation in 5.0

surround sound environments as a function of the recording technique. A detailed explanation of each reproduction environment is provided in Sections 3 and 4. This general method is depicted in Fig. 2. We discuss the challenges faced when using real-world sound reproduction environments for this type of auditory research in Section 5.

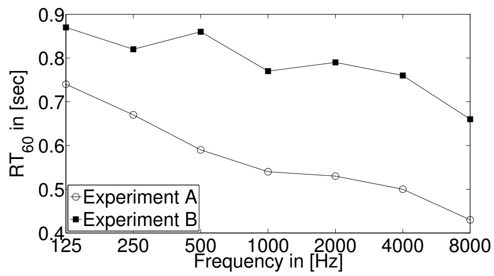


FIGURE 3 – Reverberation time RT_{60} in Telus Studio (Exp. A) and Tanna Schulich Hall (Exp. B).

2.1 Musical Excerpts — EXC

Each musical excerpt was a 5.0 multichannel recording created from the perspective of a concert audience facing a stage with the instrument sounds arriving from the front and ambient sounds and room response from the sides and behind. The excerpts were:

EXC 1: J.S. Bach "Variation 13", Goldberg Variationen for solo piano (BWV 988).

EXC 2: W.A. Mozart "Maurische Trauermusik" in c-minor for symphony orchestra (KV 477).

Detailed information regarding the recording and mixing procedures for these two excerpts are given by Kim [4] for excerpt 1 and by Camerer [3] for excerpt 2. An overview of these recording techniques follows.

2.2 Recording Techniques — RT

Each musical excerpt was recorded with three prominent multichannel recording techniques. These techniques differ in their strategy for reducing correlation across the channels. We provide a short overview of these techniques including drawings of the recording setups in Fig 4. Detailed descriptions on all three recording techniques can be found in [27].

Coincident Microphone Technique — Ambisonics. Ambisonics extends Blumlein's coincident recording technique. An omnidirectional microphone is added to the pair of perpendicularly oriented figure-eight units. The vertical component of the sound field is captured by adding a third figure-eight unit perpendicular to the others. All microphone capsules are meant to be at exactly the same spatial location. Thus, amplitude differences between the microphones are created. For both excerpts a Soundfield MKV microphone was used. The microphone signals are encoded into the so-called B-format. To reproduce the sound field, the B-format signals are decoded with respect to a specific loudspeaker setup. Although Ambisonics is theoretically best reproduced on regular loudspeaker layouts, algorithms exist to create an optimized decoder for an irregular loudspeaker setup. For instance, the (irregular) 5.0 loudspeaker setup is supported since Gerzon's *Vienna decoder* [28]. In both excerpts the Soundfield SP451 processor [29] was used for 5.0 decoding.

Spaced Omnis Microphone Technique. The omnidirectional microphones are widely spaced, primarily creating inter-channel time differences. To account for the different source widths in EXC 1 and EXC 2, slightly different variations of this technique were used.

Polyhymnia Pentagon (used for EXC 1): This technique uses five widely spaced omnidirectional microphones and is often described as a multichannel version of the Decca Tree. The microphones are arranged in a large circle and their positions correspond to the azimuthal angles of the 5.0 loudspeakers.

Decca Tree + Hamasaki-Square (used for EXC 2): The Decca Tree consists of three omnidirectional microphones arranged in a triangle. The center microphone is placed 0.7 to 1 m forward, whereas the right and left capsules are spaced at a distance ranging from 1.4 to 2 m. In the recording of EXC 2, two additional lateral microphones were used to capture the entire width of the orchestra. Furthermore, the sound field for the two 5.0 surround channels was recorded with a Hamasaki Square.

Spaced Cardioid Microphone Technique. The Optimized Cardioid Triangle (OCT) reduces channel crosstalk by creating both inter-channel amplitude and inter-channel time differences. Two outer hyper-cardioid microphones face $\pm 90°$ sideways from the center cardioid microphone, which is usually placed 8 cm forward. For both excerpts, the OCT array was extended with a Hamasaki Square to feed the two 5.0 surround channels.

2.3 Procedure and Apparatus

The listeners were asked to *Rate the degradation in sound quality of sound B relative to sound A.* Sound A represented one of the six central listening position (reference) stimuli, whereas sound B could be: a) one of the off-center stimuli of the same musical excerpt and recording technique as sound A ; b) the hidden reference (the same central listening position stimulus as sound A) ; or c) the hidden anchor, which is a monaural stimulus captured at a very off-center position, where the left audio channel was presented to both ears. The purpose of the hidden reference and anchor was to set best- and worse-case references for the rating scale and to validate listeners' reliability.

Listeners are typically asked to rate the absolute difference (or similarity) between stimuli. Absolute diffe-

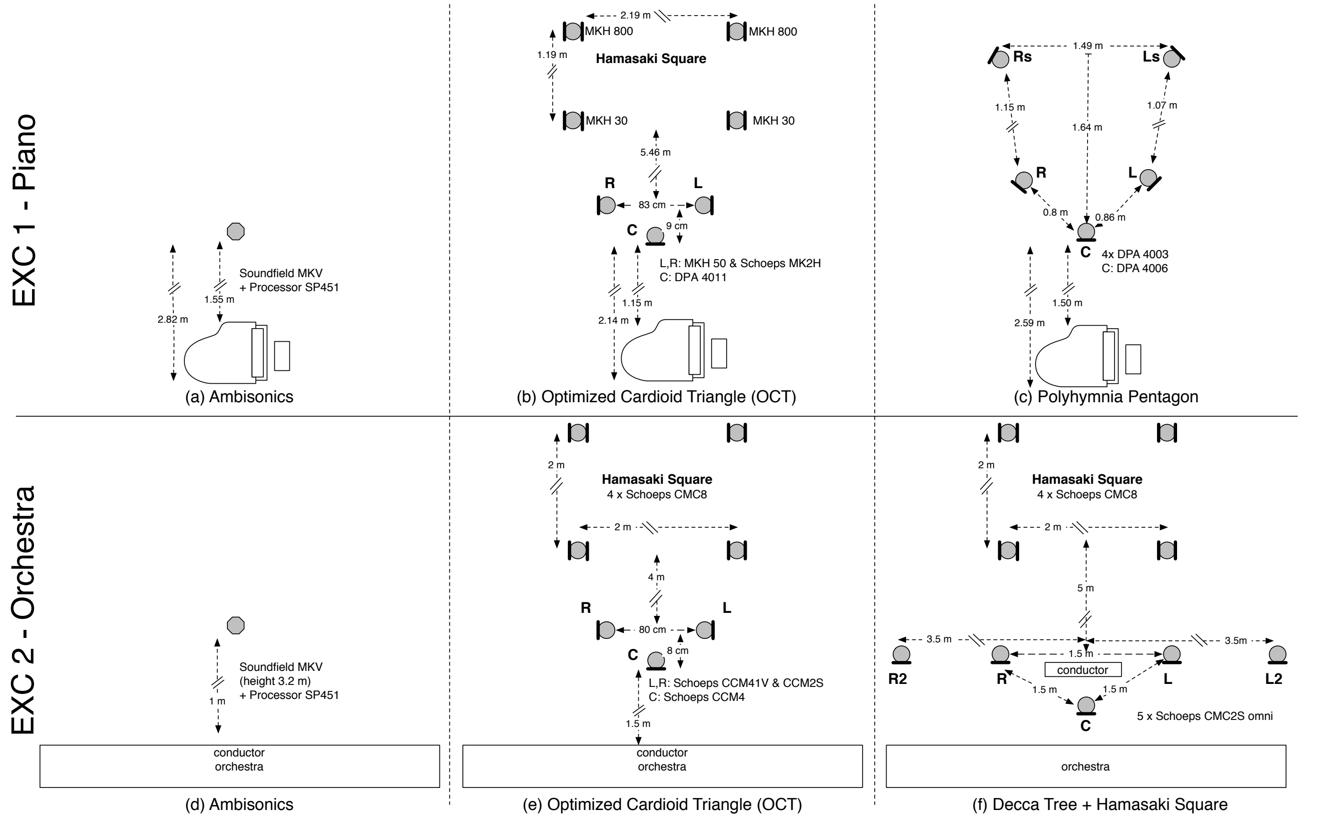


FIGURE 4 – Multichannel microphone array setups used in the recordings of the musical excerpts. (a)-(c) for EXC 1 adapted from [4] and (d)-(f) for EXC 2 adapted from [3].

rence/similarity does not necessarily indicate preference or quality. We chose to ask listeners to rate *sound quality degradation*. Rating perceived sound degradation explicitly asks the listener about quality (better, worse), and is therefore more meaningful for describing preference in one listening position over another.

The pairwise comparison trials were presented in random order. A graphical user interface was employed and the ratings were made with a computer mouse on a slider with a continuous scale from 0 (total degradation) to 100 (no degradation). The scale was also marked by the following descriptors: *very strong degradation - strong degradation - moderate degradation - slight degradation - very slight degradation*. This scale corresponds roughly to an analogical-categorical scale, found in psychophysical research to increase response reliability [30]. Within the presented pair, listeners could switch between sounds A and B at will and could listen as many times as necessary.

The experiments consisted of a training phase (phase 1), a familiarization phase (phase 2), and the experimental phase (phase 3). In phase 1, five trials with musical excerpts that were different from those presented in phase 3 were presented for interface training. Listeners were informed that these ratings would not be recorded. In phase 2, a representative collection of 30 binaural stimuli were used to familiarize them with the musical material. They were told that phase 2 would give them the range of variation in sound degradation so they could subsequently use the full scale for their judgments in the experimental phase, which lasted about 60 min. To increase the reliability of the data, each stimulus pair appeared twice. We used Sennheiser HD 600 headphones at a normal listening level (70 dB(A) for the recording at the central listening position). Besides diffuse-field headphone equalization, no additional filtering was applied. The listeners were told to face the frontal direction and to keep their heads steady. Breaks were allowed.

2.4 Discussion of Experimental Method

The ideal test design for this experiment would make participants listen and relocate from seat to seat in the actual listening room. Unfortunately, such an *in situ* design has various drawbacks: it would be almost impossible to allow for double-blind, comparative, and repeatable evaluations in a reasonable time-frame ; for the participants it would also be extremely challenging to memorize the perceived sound quality while physically changing listening positions. Our method allowed listeners to switch between two binaural stimuli in real time, and thus had the advantage that listening positions could be compared quickly and repeatedly in a double-blind test while minimizing cognitive challenges. Furthermore, by isolating and presenting the binaural stimuli via headphones, the potential for sound quality biases based on visual cues on the part of the listeners was also circumvented.

Our method relies on the assumption that the presentation of the binaural stimuli can evoke all perceptually important elements of the captured sound field as they would have been perceived by a subject directly. Toole [31] discussed the potential and drawbacks of using a binaural reproduction system in listening experiments. In particular, the absence of head movements in static binaural recordings and non-individual HRTF cues may cause localization errors mainly in the median plane and in the region of the cone-of-confusion. Therefore we acknowledge that not all perceptual dimensions may be perfectly reproduced by the binaural system. However, because the binaural reproduction conditions were equal for all stimuli in the listening experiment, we think that the effect generates a constant bias for all stimuli, and thus, the relative differences are preserved. Despite these constraints, several related studies have successfully used similar methods. In [32], for one test listeners rated loudspeakers *in situ* in different rooms. In a second test, listeners were asked to rate via headphones binaural recordings of these loudspeakers captured in each room. Although some differences in the ratings between the two experiments occurred, the pattern of results was essentially the same.

As an alternative to static binaural recordings, a binaural room-scanning system (BRS) could have been used [33]. BRS allows head movements through head tracking in the binaural reproduction system, reduces localization errors and increases out-of-head localization. However, those two advantages diminish when room reflections are included in the capturing process [34], as is the case in this presented study.

3 EXPERIMENT A — TELUS STUDIO

The Telus Studio at the Banff Centre for the Arts has a floor-space of ca. 140 m^2 and a volume of ca. 800 m^3 and is used for lectures, film presentations, and as a recording room for medium-large ensembles. For the reverberation times (Fig. 3) and SNR, the Telus Studio marginally meets the recommendation by the ITU [10] as well by the IEC [16] for multichannel loudspeaker setups for listening rooms. The Schroeder frequency, below which the modal density distribution dominates, is about 53 Hz. For the 5.0 loudspeaker setup, five Dynaudio BM15A loudspeakers were placed at a height of 1.2 m on an arc with a radius of 4.2 m. To capture the binaural stimuli, omnidirectional probe microphones (DPA 4060) were placed at the entrance of the first author's ear canals. To avoid uncontrolled head movements during recordings, a neck-brace was used. The ten tested positions were chosen as depicted in Fig. 5 and included the best- and the two left-sided worst-case listening positions as shown previously in Fig. 1. The listening positions cover only the left side of the listening area because one expects that a quasi-symmetrical sound field occurs due to the symmetrical shape of the room and the loudspeaker setup. In total, 72 pairwise comparisons were prepared for the listening experiment (2 excerpts $\times$ 3 recording techniques $\times$ 12 positions). A monaural recording at position 10 was used as the hidden anchor. The SPL varied between 73.5 and 79 dB(A) depending on position and was 75 dB(A) at the central listening position.

Ten trained listeners (8 male, 2 female) with normal hearing were tested. They were sound recording students with technical ear training and work experience between 1 and 23 years (Median=9). Their age varied between 24 and 44 (Median=30).

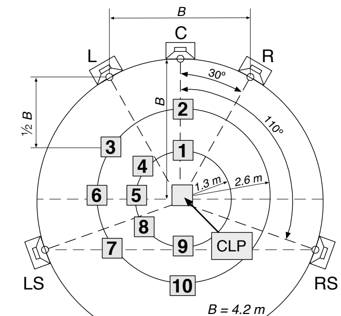


FIGURE 5 – Listening positions in Experiment A.

3.1 Results

The hidden reference and the hidden anchor were used to post-screen the behavioral data for potential outliers. There was a strong agreement across listeners for the rating of the hidden reference (M=95.6, SD=5.1) and the hidden anchor (M=11.9, SD=11.7). After excluding the ratings for the hidden reference and the hidden anchor, an EXC(2)$\times$RT(3)$\times$POS(10) repeated-measures analysis of variance (ANOVA) was performed. Besides the EXC main effect and the EXC$\times$RT interaction (Table 1), all effects are significant ($p < .001$), The effect size measure η_p^2 indicates that the recording technique (RT) and the listening positions (POS) have by far the largest effects.

TABLE 1 – ANOVA results for Experiment A.

Effect	df	F	p	η_p^2	η_p^2-Rank
EXC	1, 9	0.7	.794	.01	7
RT	2, 18	34.6	$< \mathbf{.001}$	.80	1
POS	9, 81	26.9	$< \mathbf{.001}$	.75	2
EXC×RT	2, 18	3.5	.054	.28	6
EXC×POS	9, 81	7.1	$< \mathbf{.001}$	.44	3
RT×POS*	18, 162	5.4	$< \mathbf{.001}$	.37	5
EXC×RT×POS*	18, 162	5.2	$< \mathbf{.001}$	.37	4

* Greenhouse-Geisser correction for violation of sphericity

To determine statistical differences across recording techniques pairwise comparisons (Bonferroni-Holm adjus-

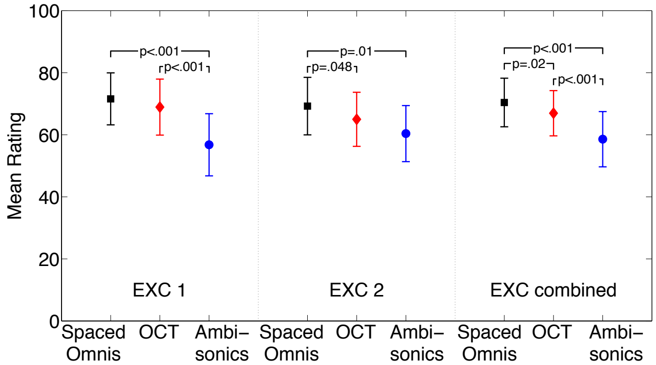


FIGURE 6 – Experiment A: Mean ratings and 95% confidence interval as a function of recording technique and excerpt: Brackets show significant differences between two recording techniques evaluated with Bonferroni-Holm-adjusted pairwise comparisons.

ted) were performed. The results are depicted in Fig. 6. As indicated by the ANOVA results (EXC main effect not significant), the group means and the 95% confidence intervals of all recording techniques have a similar trend across musical excerpts with Spaced Omnis rated best and Ambisonics rated worst. When combining the behavioral data for both excerpts, the pairwise comparisons indicate significant differences ($p < .05$) between all three recording techniques (right section in Fig. 6).

Figure 7 visualizes the sound-quality mean ratings across the listening area. A spatial cubic interpolation was used to estimate the sound degradation between the tested listening positions. Starting at the central listening position, a radially diminishing sound quality can be observed for all three recording techniques. The slope of this radial degradation however varies across recording techniques and is steepest for Ambisonics. An opposite trend can be observed for the standard deviation of the rating, which tends to increase the more off-center a listening position is. Therefore, one can say that the agreement among listeners is higher the better the sound quality is and the closer the listening position is to the center.

The so-called sweet area, the listening area around the central listening position that was rated equally well, was estimated by a Tukey-Kramer HSD post-hoc test (see white lines in Fig. 7). The largest sweet area for EXC 1 was created by the Spaced Omnis recording technique and for EXC 2 by the Optimized Cardioid Triangle. For both excerpts, Ambisonics produced the smallest sweet area. For the Optimized Cardioid Triangle and Ambisonics, the listening area of EXC 2 (orchestra) seems to be slightly wider than for EXC 1 (solo piano). Interestingly, the sweet area shows different shapes across recording techniques and musical excerpts and is never front/back symmetric.

The largest difference between the different recording techniques can be found at listening positions 5 and 10 for EXC 1 and at positions 1 and 2 for EXC 2.

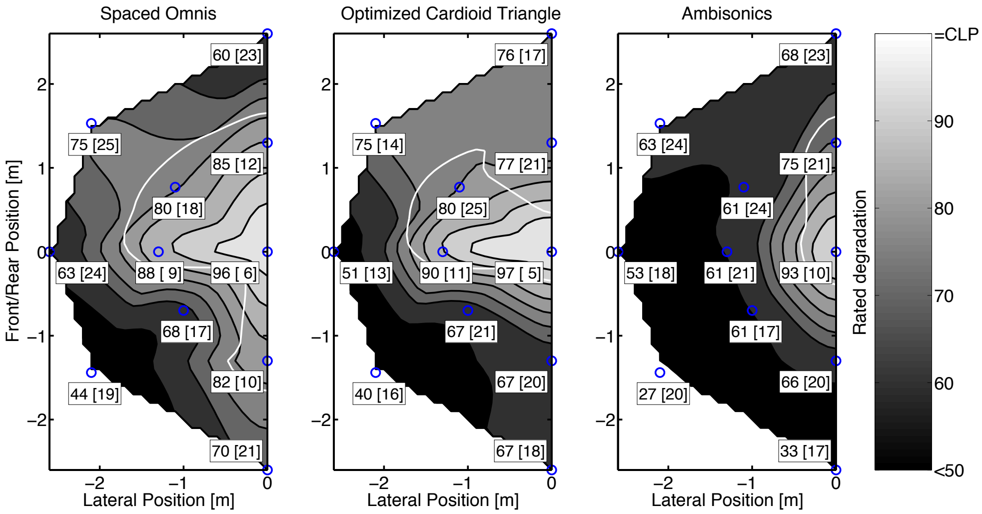
3.2 Discussion

The results of the ANOVA suggest that recording technique (RT) followed by the listening position (POS) are the two largest effects in the behavioral data. The effect of POS is expected and confirms the consensus among listeners and audio engineers concerning the limited ideal listening area of surround-sound reproduction systems. It is surprising that the largest ANOVA effect size was found for the RT main effect. This finding suggests that choosing the right multichannel recording technique during the sound recording process is an essential parameter to reduce off-center sound quality degradation. The pairwise comparisons across recording techniques (Fig. 6) show that in both excerpts the Spaced Omnis microphone technique significantly outperformed its contenders OCT and Ambisonics most of the time considering the ratings of all 10 listening positions. Nevertheless, with respect to the sweet area, the OCT recording technique created a larger sweet area than the Spaced Omnis technique for EXC 2.

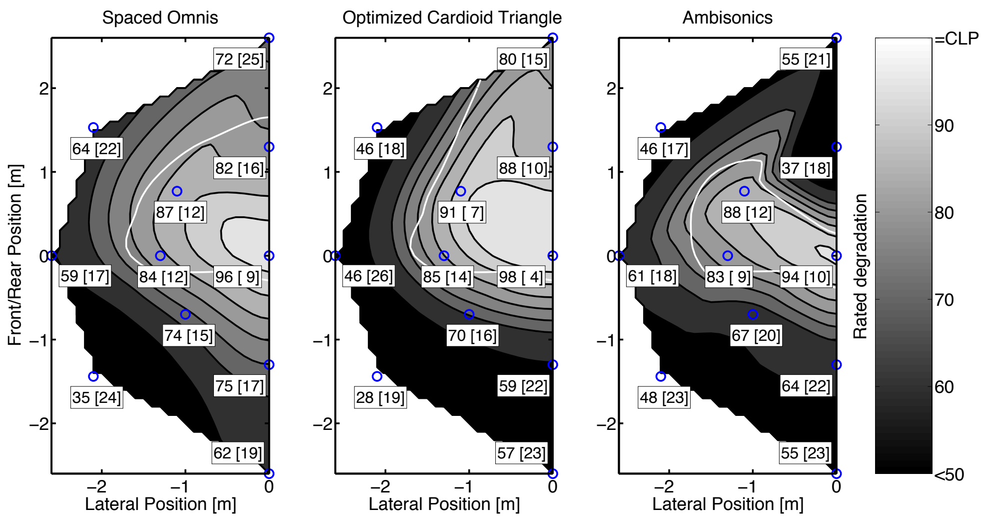
The third-largest ANOVA effect was found for the EXC×POS interaction effect, which can be observed by studying the sound degradation maps in Fig. 7, e.g., comparing the ratings at listening position 1 between both excerpts. The ratings for listening positions 3 and 7 are particularly interesting, because both positions are classified in ITU-R BS.1116 [10] as worst-case positions. In all six EXC×RT conditions, position 7 always received the lowest ratings of all tested positions (M=37), making position 7 the least desired seat. In comparison, in all but the Ambisonics recording of the orchestra, position 3 was rated 65% better than position 7 (M=61).

4 EXPERIMENT B — TANNA SCHULICH HALL

Tanna Schulich Hall (McGill University) has a floor space of ca. 240 m^2 with 188 seats and a volume of ca. 1400 m^3. It is used for jazz and chamber music performances, as a lecture hall, and for electroacoustic and mixed music concerts with multi-loudspeaker arrays. It is known for its intimacy and short reverberation time (Fig. 3). The Schroeder frequency is about 47 Hz. The hall's 5-channel surround loudspeaker system was used and calibrated for optimal sound quality at the central listening position (Kling & Freitag CA 1515 for the front and CA 1001 for the surround). Due to the rectangular shape of the room, the positions of the loudspeakers differ from ITU-R BS.1116-1: instead of $\pm 110°$, the rear speakers are placed at $\pm 150°$ with an arc of ca. 8.2 m, measured from the central listening position. Because of this displacement, the expected effect of the surround loudspeaker (to enhance listener envelopment) may be reduced. Further, the center speaker is noticeably elevated to



(a) EXC 1 - piano



(b) EXC 2 - orchestra

FIGURE 7 – Sound degradation maps for Experiment A. Referring to Fig. 5, the listening positions are marked with circles. At position (0,0) the rating of the hidden reference. Each position shows the mean rating and [standard deviation]. The size of the sweet area (estimated with Tukey-Kramer HSD) is shown by white contours.

account for an optional projection screen. Due to the raked seats in the hall, the listening perspective relative to the elevated speakers varies. This entire layout we consider as a non-ideal, yet ecologically valid real-world setup. A B&K dummy head was placed at 13 positions (see Fig. 8). In concordance with experiment A, the sound pressure at the central listening position was calibrated to 75 dB(A) and varied between 74-77 dB(A) depending on the listening position. The independent variables for the experiment yield 78 conditions (2 excerpts $\times$ 3 recording techniques $\times$ 13 positions). The hidden anchor was a monaural recording of the position marked as “anchor” in Fig. 8.

Nineteen trained listeners (16 male, 3 female) with normal hearing participated in the experiment, including all of the listeners from experiment A. Ages ranged from 23 to 44 (Median=27) and work experience within the sound recording field varied from 1 to 23 years (Median=7).

4.1 Results

Similar to Experiment A, there was a strong agreement across listeners how to rate the hidden reference (M=95.5, SD=3.9) but a less strong agreement for the hidden anchor (M=19.6, SD=16.1). After removing the ratings for the hidden reference and anchor, a EXC(2)$\times$RT(3)$\times$POS(11) repeated-measures ANOVA was performed on the sound degradation ratings. Results are shown in Table 2. All main effects (EXC, RT, POS) and all interactions were found to be significant ($p < .05$). The POS main effect has the largest η_p^2 effect size followed by the EXC×RT interaction and the RT main effect.

TABLE 2 – ANOVA results for Experiment B.

Effect	df	F	p	η_p^2	η_p^2-Rank
EXC	1, 18	10.5	**.004**	.37	4
RT	2, 36	15.2	< **.001**	.46	3
POS*	10, 180	69.0	< **.001**	.79	1
EXC × RT	2, 36	28.2	< **.001**	.61	2
EXC × POS*	10, 180	5.6	< **.001**	.23	5
RT × POS*	20, 360	4.2	< **.001**	.19	7
EXC×RT×POS*	20, 360	5.1	< **.001**	.22	6

* Greenhouse-Geisser correction for violation of sphericity

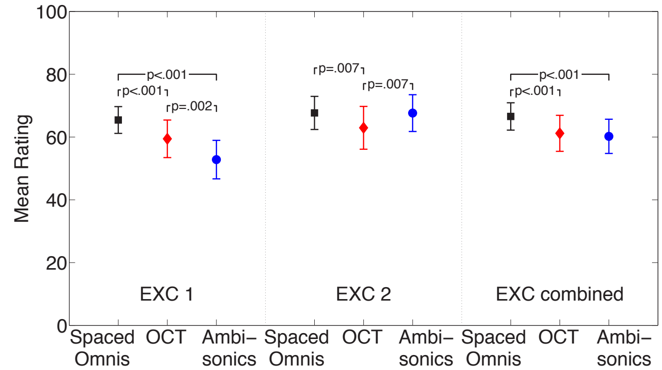


FIGURE 9 – Experiment B: Mean ratings and 95% confidence interval as a function of the recording technique and excerpt. Brackets show significant differences between two recording techniques indicated by pairwise comparisons (Bonferroni-Holm adjusted).

The mean ratings and 95% confidence interval as a function of the recording technique and the musical excerpt are shown in Fig. 9. This figure displays also the results of a Bonferroni-Holm-adjusted pairwise comparison to evaluate the recording techniques against one another. For both excerpts, the Spaced Omnis technique was rated significantly higher than the OCT technique. The EXC×RT interaction revealed in the ANOVA can be attributed to the Ambisonics technique: While in both excerpts there is a similar relation of Spaced Omnis to OCT, for excerpt 1 (solo piano), Spaced Omnis and OCT were both rated better than Ambisonics, but in excerpt 2 (orchestra), the Ambisonics technique received the higher scores. When combining the ratings from both excerpts, the Spaced Omnis technique is significantly better rated than OCT and Ambisonics ($p < .001$) while OCT and Ambisonics are statistically similar. The recording technique with the lowest mean rating (Ambisonics for EXC 1 and OCT for EXC 2) also has the largest confidence intervals. In contrast, the data for the Spaced Omnis recording technique have the smallest confidence interval of all three recording techniques for both excerpts, which means that listeners were more in agreement than for the other two techniques.

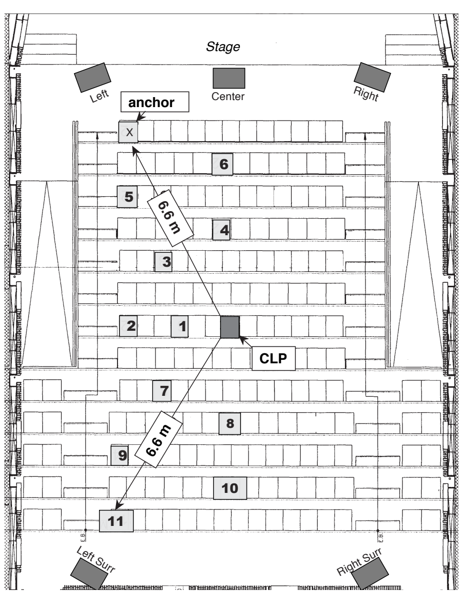
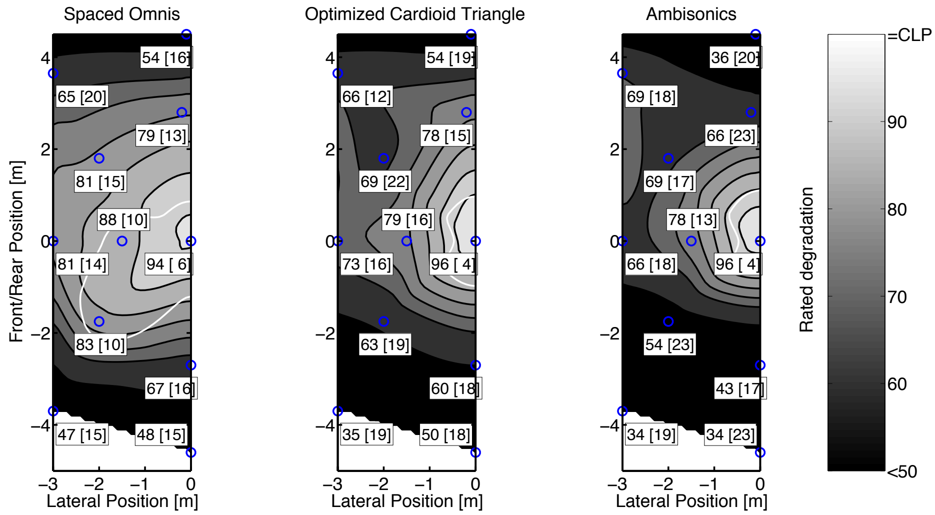


FIGURE 8 – Listening positions in Tanna Schulich Hall.

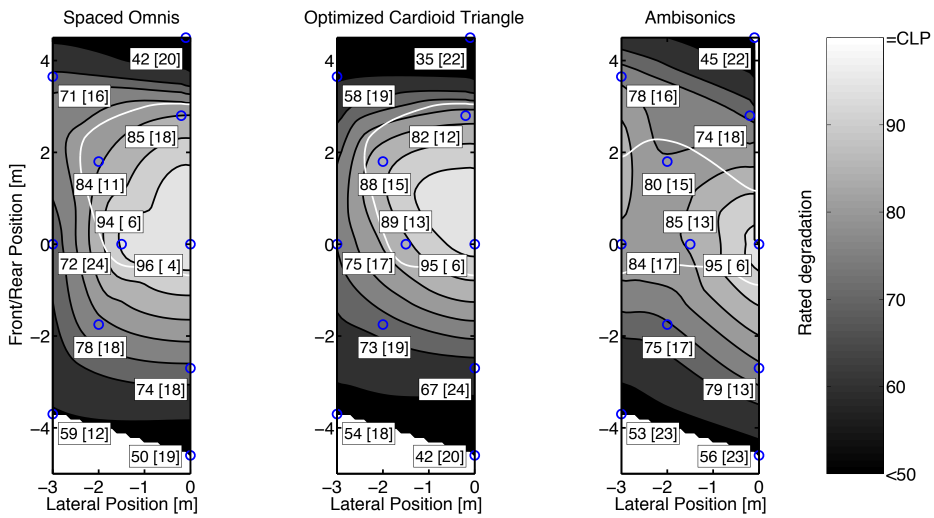
The sound quality maps based on the average ratings of the listening area are visualized in Fig. 10. The white line indicates the sweet area, the listening area around the central listening position that was rated equally well, identified with a Tukey-Kramer HSD post-hoc test. For EXC 1 (piano, Figure 10(a)), the biggest reference listening area was created by the Spaced Omnis technique. Our post-hoc analysis suggested a similarly sized reference listening area for the other two recording techniques. The largest differences for EXC 1 between recording techniques can be found at listening positions 7 and 8. For EXC 2 (orchestra, Figure 10(b)) the contours are less uniform and show less pronounced differences across recording techniques. Generally for all three recording techniques, the reference listening area around the central listening position is bigger in EXC 2 than in EXC 1. Further, the plots show equivalent sound quality degradation for Spaced Omnis and the OCT. Ambisonics was rated in EXC 2 much better than in EXC 1, in particular for position 8. Interestingly, at positions 2 and 5, the Ambisonics recording produced the best off-center sound quality across all three techniques.

4.2 Comparison with Experiment A

Because the experimental design did not involve a direct comparison of listening positions between Experiment A and Experiment B, we cannot compare the behavioral data of these two experiments directly, but we can compare the relative performance of each recording technique with each musical excerpt. This relative comparison is visualized in Fig. 11. The mean ratings already shown in Fig. 6 and 9 were ranked and show that the Spaced Omnis microphone technique performed best overall in three out of the four visualized condi-



(a) EXC 1 - piano



(b) EXC 2 - orchestra

FIGURE 10 – Sound degradation maps for Experiment B.: Referring to Figure 8 the listening positions are marked with circles. Each position shows the the mean rating and standard deviation. The size of the sweet area (estimated via Tukey-Kramer HSD) is shown by white contours.

tions. In two of these three conditions, the difference between the first and the second best recording technique (OCT) is also significant. However, in Experiment B for EXC 2, the Ambisonics recording received the highest mean rating, but when compared to Spaced Omnis (second highest rated technique), Ambisonics is not significantly better. In all other three conditions the Ambisonics technique was always ranked third. The OCT recording technique was rated second best in three conditions and ranked third in one condition.

By comparing the sound quality maps from Experiments A and B (Figs. 7 and 10), one sees that in both reproduction environments EXC 2 is perceived to have a wider area with good sound quality than EXC 1 regardless of recording technique. Further, one sees a similar radial shape of the sound degradation in the two reproduction environments for all the recording techniques, except for the Ambisonics recording for EXC 2. Here, in both reproduction environments the shape of the sweet area is more lateral than radial. Further, the large ANOVA effect size of listening position (POS) in both reproduction environments shows that the listening position has the most influence on the perceived sound degradation. Contrary to Experiment A, the EXC×RT interaction in Experiment B, clearly visible in Fig. 9, is significant and has the second largest effect size, which suggests that in this non-ideal listening environment, the off-center sound quality depends on the combination of recording technique and actual content.

Also in contrast to Experiment A, the mean ratings of sound quality are higher for EXC 2 than for EXC 1 (compare Fig. 6 with Fig. 9), meaning that listeners were less critical in their judgements for EXC 2. This might indicate that in

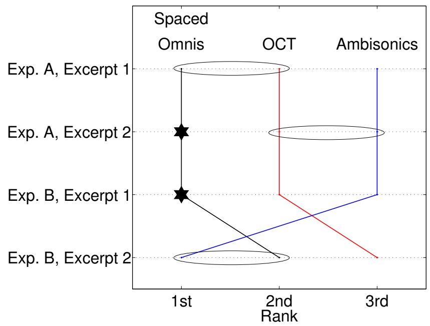


FIGURE 11 – Ranked overview of the recording technique mean ratings. A star indicates significant differences between first ranked and second ranked recording technique, an ellipse indicates similarly rated recording technique (Bonferroni-Holm pairwise comparison).

non-ideal (more reverberant) reproduction environments for complex musical material, such as in the case of an orchestra reproduced in Tanna Schulich Hall (Experiment B, EXC 2), a variety of perceptual artifacts are at play in the listeners' evaluations. Another explanation could be that the task (analyze a complex acoustic scene such as a symphonic excerpt in a reverberant room) is more demanding than it is for a less complex acoustic scene, e.g., a solo piano excerpt. Listeners may be attending more to listening envelopment than localization. A diffused sound image is by definition less localizable and unstable, perhaps democratizing sweet spot as a function of listening position. In view of Rumsey's scene-based approach to spatial quality evaluation [15], listeners may pay more attention to ensemble-related sound quality aspects, e.g., the apparent source width or brilliance of the orchestra, rather than to aspects related to the individual sound sources, such as the location of an instrument within the orchestra. Other studies have also found that sound quality preference judgments depend on the audio material, (e.g., [1, 33]) or on the acoustical conditions (e.g., room reverberation [35]).

To make a direct comparison about the sound quality between recording techniques at off-center listening positions, another experiment is necessary in which all three recording techniques at every off-center position are compared with each other. Such experimental design would result in three times as many pairwise comparisons as in our experiments, might be exhausting for the listeners, and may not even be necessary. Consider that our study measured the sound degradation at all tested listening positions relative to the central listening position for all three recording techniques, and previous studies [3] and [4] (from which we borrowed our musical excerpts) evaluated the sound quality of the recording techniques at the central listening position. Putting the results of these previous studies and our study into dialogue, we can make an informed prediction about the absolute sound quality for each recording technique at off-center positions. From Kim et al. [4] we know that for the piano excerpt (EXC 1) the preferred recording technique (at the central listening position) was Spaced Omnis, followed by OCT and Ambisonics. For the orchestra excerpt (EXC 2) Camerer [3] tested nine perceptual aspects of the recordings at the central listening position. The rating of the Spaced Omnis and OCT were comparable and both techniques were rated better than Ambisonics regarding "image stability", "sound colour", or "room impression". The Ambisonics recording of the orchestra was rated as having too little "presence of room information".

5 SUMMARY AND DISCUSSION

The off-center sound degradation in two different listening room environments was investigated with respect to three recording techniques (RT), two classical musical excerpts (EXC), and multiple off-center listening positions (POS). We found that the tested recording techniques significantly affect the sound degradation strength at off-center listening positions and the size of the sweet area. In most conditions, a somewhat radial sound degradation from the central listening position occurs, but with varying slope across the recording techniques. With increasing distance to the central listening position, the agreement across listeners (indicated by the standard deviation per listening position) also tends to decrease. In all but one condition, spaced microphone techniques create less sound degradation at off-center positions than the coincident Ambisonics techniques (see Fig. 11), supporting Griesinger's hypothesis that time-delay-based decorrelation among the loudspeaker feeds (Interchannel Time Differences) increases the listening area [9].

In a listening environment featuring a standard loudspeaker configuration (experiment A), the worst listening position was typically near the rear surround speaker (Pos. 7 in Fig. 5). For this position, the rear surround speaker dominates the sound image (unbalanced SPL) to the extend that the Listening Envelopment (LEV) is compromised. Future work needs to identify recording and reproduction methods that create a more balanced SPL across the listening area.

In a non-ideal listening environment (Experiment B), the interaction between recording technique and musical excerpt played a significant role in listener preference. Our data suggest that in a more reverberant listening room, a more diffuse sound material (e.g., an orchestra recording) is likely to be better reproduced at off-center listening positions than a recording with more precise source images (e.g., a piano recording). Regarding the reproduction environment, our study shows that when reverberant, classical, multichannel recordings are reproduced in a medium-sized, moderately reverberant space, the usable listening area is larger than it is in a smaller, less reverberant space. Better understanding of listener preference for the Ambisonics recording technique in the EXC 2 (orchestra) condition of Experiment B is required, especially since this recording technique was least preferred for all other conditions. It seems possible that the space itself is adding credible reflected sounds to the mix of sounds arriving at the listeners' ears and that the space favors sound sources that are reproduced by relatively uncorrelated loudspeaker feeds. It may also be possible that the non-ideal loudspeaker configuration in Experiment B constrained reproduction quality of both excerpts.

Uncoupling all of the variables that differentiated experiment A and experiment B (room acoustics, loudspeaker type, and loudspeaker arrangement) would yield better understanding of the interactions. One approach could be to use auditory virtual environments that can simulate a multichannel recording scenario (e.g., [36]). The trade-off involves more controlled variables but less ecological validity [37]. In future work, we hope to examine the instrument–microphone–room interaction at the recording site embedded in musical excerpts. Generating impulse responses from the instrument's position (similar to the loudspeaker orchestra approach in [38]) and capturing them with the tested microphone arrays would provide insights into sound propagation characteristics and performance of microphone arrays. Such impulse responses do not exist for the musical excerpts used in our study.

The selection of the musical excerpts was constrained by the limited availability of content that was simultaneously captured with different recording techniques. A significant amount of equipment, time, and effort is necessary to create such material. While we limit our findings and discussion to two of the most popular genres of surround recordings (solo piano and orchestra), the question remains whether our findings can be generalized to other content types, e.g., ambience recordings for broadcast and film. Although ambience is captured with a variety of microphone arrays, including those used in our study (see e.g., [39]), further work is needed to generalize our findings.

Between the two musical excerpts, the recording techniques slightly differ in positioning, type, and brand of microphone (see Fig. 4, especially the different arrangements of the Spaced Omnis in (c) and (f)). These differences exist to optimize the recording technique for a specific recording environment and musical material, but they also make it difficult to compare directly the perceptual experience of the recorded material. Using exactly the same arrangement to capture both musical excerpts would have made the experimental conditions more controlled but less meaningful, because the recordings would not represent what Tonmeisters actually record and mix in these situations. Our aim was to extend previous work and explore how perceptual data from off-center listening positions. Comparing these musical excerpts and recording techniques within this paradigm is reasonable, considering the small amount of prior work in this area. Our study is exploratory, and we consider our work as a starting point for further discussion and future research.

6 ACKNOWLEDGMENTS

This work was funded by a grant from the Canadian Natural Sciences and Engineering Research Council and the Canada Council for the Arts (NSERC, CCA, STPGP 322947) to Stephen McAdams and Jonas Braasch, an NSERC grant (RGPIN 312774) to Stephen McAdams, and a student award from the Centre for Interdisciplinary Research in Music Media and Technology (CIRMMT) to Nils Peters. Many thanks to Bruno L. Giordano, Georgios Marentakis, Sungyoung Kim and William L. Martens for fruitful advice. The authors would like to to thank the reviewers for their helpful comments.

REFERENCES

[1] Y. Ando. *Architectural Acoustics: Blending Sound Sources, Sound Fields, and Listeners* (Springer Verlag, New York, 1998).

[2] S. Bech, N. Zacharov. *Perceptual Audio Evaluation—Theory, Method and Application* (Wiley & Sons, New York, 2006).

[3] F. Camerer, C. Sodl. "Classical Music in Radio and TV - a multichannel challenge ; The IRT/ORF Surround Listening Test." http://www.hauptmikrofon.de (2001).

[4] S. Kim, M. de Francisco, K. Walker, A. Marui, W. L. Martens. "An examination of the influence of musical selection on listener preferences for multichannel microphone technique." In "Proc. of the AES 28th International Conference," (Piteå, Sweden, 2006).

[5] H. Irimajiri, T. Kamekawa, A. Marui. "Correspondence relationship between physical factors and psychological impressions of microphone arrays for orchestra recording." In "123rd AES Convention, Preprint 7233," (New York, US, 2007).

[6] Y. Yun, T. Cho. "The study on surround sound production beyond the stereo techniques." In "Computer Applications for Web, Human Computer Interaction, Signal and Image Processing, and Pattern Recognition," pp. 133–140 (Springer, 2012).

[7] G. Marentakis, N. Peters, S. McAdams. "Auditory resolution in virtual environments: Effects of spatialization algorithm, off-center listener positioning and speaker configuration (A)." J. Acoust. Soc. Am., **123**, 3798 (2008).

[8] V. Pulkki. "Microphone techniques and directional quality of sound reproduction." In "112th AES Convention, Preprint 5500," (Munich, Germany, 2002).

[9] D. Griesinger. "The Psychoacoustics of Listening Area, Depth, and Envelopment in Surround Recordings, and their relationship to Microphone Technique." In "AES 19th Intern. Conference," pp. 182–200 (Schloss Elmau, Germany, 2001).

[10] ITU. *Recommendation BS.1116-1, Methods for the Subjective Assessment of Small Impairments in Audio Systems Including Multichannel Sound Systems* (International Telecommunication Union, Geneva, Switzerland, 1997).

[11] F. E. Toole. *Sound reproduction: loudspeakers and rooms* (Focal Press, Oxford, UK, 2008).

[12] R. Y. Litovsky, H. S. Colburn, W. A. Yost, S. J. Guzman. "The precedence effect." J. Acoust. Soc. Am., **106**, 1633–1654 (1999).

[13] S. E. Olive, F. E. Toole. "The detection of reflections in typical rooms." J. Audio Eng. Soc., **37**, 539–553 (1989).

[14] S. Bech. “Spatial aspects of reproduced sound in small rooms.” J. Acoust. Soc. Am., **103**, 434–445 (1998).

[15] F. Rumsey. “Spatial quality evaluation for reproduced sound: Terminology, meaning, and a scene-based paradigm.” J. Audio Eng. Soc., **50**, 651 – 666 (2002).

[16] IEC. *Draft 60268: Sound System Equipment - Part 13: Listening Tests on Loudspeakers* (International Electrotechnical Commission, Geneva, Switzerland, 1997).

[17] T. Lund. “Enhanced localization in 5.1 production.” In “Proc. of the 109th AES Convention, Preprint 5243,” (Los Angeles, US, 2000).

[18] T. Okano, L. Beranek, T. Hidaka. “Relations among interaural cross-correlation coefficient $(IACC_E)$, lateral fraction (LF_E), and apparent source width (ASW) in concert halls.” J. Acoust. Soc. Am., **104**, 255–265 (1998).

[19] H.-K. Lee, F. Rumsey. “Investigation into the effect of interchannel crosstalk in multichannel microphone technique.” In “Proc. of the 118th AES Convention, Preprint 6374,” (Barcelona, Spain, 2005).

[20] J. Bradley, G. Soulodre. “Objective measures of listener envelopment.” The Journal of the Acoustical Society of America, **98**, 2590–2597 (1995).

[21] F. Rumsey, S. Zieliński, R. Kassier, S. Bech. “On the relative importance of spatial and timbral fidelities in judgments of degraded multichannel audio quality.” J. Audio Eng. Soc., **118**, 968–976 (2005).

[22] F. Rumsey, S. Zieliński, R. Kassier, S. Bech. “Relationships between experienced listener ratings of multichannel audio quality and naïve listener preferences.” J. Acoust. Soc. Am., **117**, 3832–3840 (2005).

[23] A. Devantier, S. Hess, S. Olive. “Comparison of loudspeaker-room equalization preferences for multichannel, stereo, and mono reproductions: Are listeners more discriminating in mono ?” In “124th AES Convention,” (Amsterdam, The Netherlands, 2008).

[24] D. Clark. “Measuring audible effects of time delays in listening rooms.” In “Proc 74th AES Convention, Preprint 2012,” (Audio Eng. Soc., New York, US, 1983).

[25] M. Brüggen. “Coloration and binaural decoloration in natural environments.” Acta Acustica united with Acustica, **87**, 400–406 (2001).

[26] B. Rakerd, W. Hartmann, J. Hsu. “Echo suppression in the horizontal and median sagittal planes.” J. Acoust. Soc. Am., **107**, 1061–1064 (2000).

[27] F. Rumsey. *Spatial Audio* (Focal Press, Oxford, UK, 2001).

[28] M. A. Gerzon, G. J. Barton. “Ambisonic Decoders for HDTV.” In “92nd AES Convention, Preprint 3345,” (Vienna, Austria, 1992).

[29] Soundfield SP451. www.soundfield.com/products/sp451.php (accessed Sept. 2013).

[30] R. Weber. “The continuous loudness judgement of temporally variable sounds with an “analog" category procedure.” In “Results of the third Oldenburg Symposium on Psychological Acoustics. A. Schick.”, pp. 267–294 (Oldenburg, Germany, 1990).

[31] F. E. Toole. “Binaural record/reproduction systems and their use in psychoacoustic investigations.” In “Proc. of the 91st AES Convention, Preprint 3179,” (New York, US, 1991).

[32] S. E. Olive, P. L. Schuck, S. L. Sally, M. Bonneville. “The variability of loudspeaker sound quality among four domestic-sized rooms.” In “Proc. of the 99th AES Convention, Preprint 4092,” (New York, US, 1995).

[33] S. E. Olive. *Interaction Between Loudspeakers and Room Acoustics Influences Loudspeaker Preferences in Multichannel Audio Reproduction*. Ph.D. thesis, McGill University, Montreal, Canada (2008).

[34] D. Begault, E. Wenzel, M. R. Anderson. “Direct comparison of the impact of head tracking, reverberation, and individualized hrtfs on the spatial perception of a virtual speech source.” J. Audio Eng. Soc., **49**, 904 – 916 (2001).

[35] C. Gilford. “The acoustic design of talks studios and listening rooms.” Proc. Inst. of Electrical Eng., **106**, 245–258 (1959).

[36] J. Braasch, N. Peters, D. L. Valente. “A loudspeaker-based projection technique for spatial music applications using virtual microphone control.” Computer Music Journal, **32**, 55–71 (2008).

[37] C. Guastavino, B. Katz, J. Polack, D. Levitin, D. Dubois. “Ecological validity of soundscape reproduction.” Acta Acustica united with Acustica, **91**, 333–341 (2005).

[38] J. Pätynen, S. Tervo, T. Lokki. “A loudspeaker orchestra for concert hall studies.” In “Proc. of the Institute of Acoustics,” volume 30, pp. 45–52 (2008).

[39] H. Wittek. “Microphone techniques for 2.0 and 5.1 ambience recording.” In “Proc. of the VDT International Convention,” (2012).

The Universal Sense: How Hearing Shapes the Mind
Seth S. Horowitz
Bloomsbury Publishing, USA, 2012
List price: Cd$26.50 (Hardcover)
320 pp., ISBN: 978-1-608190-90-4

Sound is our perception of airborne vibration within a certain frequency range. Almost without exception, where there is vibration, there is sound. We live in a world filled with various sources of vibration and are therefore immersed in sound. Given sound's all-pervasive nature, we are constantly forced to engage with it through our sense of hearing. Yet, despite its universal engagement with the world, we take our sense of hearing for granted and do not understand how integral it is for our day-to-day lives. In this book, Horowitz attempts to make us realize its importance by focusing on the theme of "how sound and hearing have shaped the evolution, development, and day-to-day function of the mind."

The Universal Sense, while being a rich information source filled with scientific facts and phenomena pertaining to sound and hearing, also provides us with a sense of Horowitz's own personal journey as a neuroscientist in sound and hearing. Horowitz presents a wealth of scientific phenomena using many of his own research experiences as context, interspersing them with generous doses of humour. It is this latter aspect that makes *The Universal Sense* appealing, reflecting Horowitz's passion and fascination for this area. He presents various findings from past and current research while debunking scientific myths and speculating on futuristic themes, some of which have been explored in science fiction.

The book is organized into 11 chapters. Chapters 1 through 8 cover various topics that fit within the theme of "evolution, development, and day-to-day function of the mind" while Chapters 9 through 11 appear slightly disconnected from this theme. An implicit but somewhat recurring plea throughout this book, particularly in Chapters 1 through 4, is for us to realize how complex our sense of hearing is, and how important its role is in enabling us to make sense of the rich, signal-filled, but noisy acoustic environment we live in.

Chapter 1 explains how our sense of hearing and perception may have developed on an evolutionary time scale. With constant activity going on since the early, violent beginnings of the earth, vibration sensitivity has played a critical role in shaping evolution. Typically, evolution is explained from the standpoint of survival of species. However, the focus here is more on how vibrations may have shaped evolution and led to the development of organs for hearing in living organisms, specifically vertebrates. Another aspect this chapter highlights is the difference between sound and other modalities such as vision. Unlike our sense of vision, which is passive, and involves detection of objects using light, sound is used more actively by animals not only as an "early warning system" but also as an active form of communication.

Chapter 2 goes in-depth into the kinds of acoustic environments we live in, what sound consists of, how sound propagates in these environments across different materials, and how our acoustic environment influences perception of our surroundings. The chapter is important within the context of the book, as it introduces technical terms and concepts for the general reader, that are foundational for understanding how we create acoustic models of the environments we interact with. The role of constructive and destructive interference, relationship between frequency and wavelength and their implications, and the role of background noise in urban environments, are some of the topics covered here. The chapter concludes with an excellent dissection of an auditory soundscape, aptly titled "A Walk in the Park," with the help of an oscillogram and a spectrogram.

Chapters 3 and 4 are connected chapters explaining hearing in vertebrates that hear below and above the human range of 20 – 20000 Hz. Although there seems to be a general hearing plan in place for vertebrates where hair cells detect pressure changes and convert them into perception, following which the hindbrain, midbrain, thalamus, and forebrain play different roles from hearing to intentional behaviour, there are differences between terrestrial and aquatic vertebrates. The low frequency vertebrates covered in Chapter 3 are fish and frogs. This chapter explains how based on the medium of propagation, hearing related adaptations have occurred in fish and frogs. Two interesting topics that are covered in this chapter are (a) temporary deafness in tadpoles during an auditory rewiring period when they develop hearing for terrestrial in addition to aquatic environments, and (b) brain healing in bullfrogs after auditory nerve damage, and how bullfrog healing studies might provide pharmacological therapies to restore hearing ability in humans after hair cell damage. Chapter 4 talks about the evolution of a complex physical structure for hearing in terrestrial mammals involving hair cells, and outer and inner ears, giving them greater acoustic range. The high frequency vertebrates covered here are mice and bats. While both mice and bats have the same hearing range, mice use hearing only to detect danger, whereas bats also use it for echolocation. More details are presented pertaining to echolocation and differences in bats with respect to how they use echolocation (e.g. constant-frequency and frequency-modulation). Interesting comparisons are made between humans and bats; while mammals lose hearing with aging, bats do not.

Chapter 5 discusses processing speed of hearing in recognition and localization contexts, the role of hearing in focusing attention, and how different sounds cause specific emotional responses. This chapter clearly explains the superior processing speeds of hearing when compared with vision. Despite light traveling incredibly fast at the speed of 300 million metres per second, vision takes hundreds to thousands of milliseconds from input to recognition, and allows us to detect a maximum of 15 to 25 events per second. In contrast, despite the slower speed of sound, it takes less than 50 milliseconds for us to identify and localize a sound; hair cells can lock to vibrations up to 5000 times per seconds, and auditory event changes can be detected up to 200 times per second. While informing the reader about hearing's superior processing speed when compared to vision, surprisingly Horowitz does not speculate on why this might have developed from an evolutionary standpoint. Could this considerable difference in processing speeds between hearing and vision have evolved as a need to compensate for the difference in speeds between sound and light? Other important topics covered in this chapter include (a) Hebbian plasticity to focus attention and detect familiar signals in noisy environments, and (b) how sound compared to other modalities is salient for signalling danger, triggering emotional responses that promote survival.

Chapter 6 deals with various aspects of music. Horowitz talks about the challenge in defining "music" based on inconsistent definitions across different disciplines. He suggests approaching music as pieces of a jigsaw puzzle fitting together, consisting of different elements that may be examined locally or in broader contexts. Relevant topics such as consonance and dissonance and their probable causes are covered. The chapter also touches upon topics such as hemispheric specialization for tempo, emotion, and pitch processing. The Mozart effect and the scientific legend around it are covered in some level of detail. However, several important topics pertaining to music and sound that should have been addressed are left out. Some of these topics include a comparison between music and speech, important similarities and differences between the two, and problems faced by hearing aid users in switching between music and speech modalities.

Chapter 7 is dedicated almost entirely to sound and emotion. Horowitz explains how sound is used to enhance the emotional experience of a listener in various media related environments that are either audio-only (e.g. radio) or audiovisual (e.g. soundtracks). Some interesting questions that are tackled include (a) what makes a jingle effective? and (b) what effects do loudness and silence have on arousal? The area of music and emotion is currently an extremely hot area with researchers in music cognition and music information retrieval interested in identifying and predicting listeners' emotional responses to music. This is especially relevant today with the explosion of music streaming and music recommendation services. A related area involves studying relationships between audio and music features, physiological responses in listeners, and their emotional responses. This chapter does not cover any of this exciting research pertaining to music and emotion.

Chapter 8 describes ways in which our states of consciousness may be altered using sound, referred to as "brain hacking." Two major types of brain hacking are listed: (a) those that induce global changes in the brain and increase arousal, and (b) those that make specific changes to our mental states without inducing global changes. The chapter describes ways in which these changes might be induced using sensory input manipulations such as noise reduction, and increase in loudness. Information regarding the five major brain rhythms underlying global functions is presented along with rhythm entrainment. Other related topics covered include Sopite syndrome, and neural marketing involving voice frequency manipulations.

Chapter 9 describes how sound has been historically used as a weapon, and its potential effectiveness as a present and future weapon. It addresses what the requirements are for achieving physical and physiological damage with different types of sounds based on frequency range and amplitude, and what kinds of physiological and psychological effects might result from these sound manipulations.

Chapter 10 describes future directions we might undertake in hearing and sound research. Some of the topics covered include: (1) Restorative hearing, including hair cell regeneration research and the challenges involved, (2) acoustic ecology, including the role of sound as a measure of the environment as well as an instigator of environmental change, and (3) the need for our sense of hearing to adapt on other planets, specifically Mars.

One unfortunate omission in *The Universal Sense* is the lack of any links to audio files. A dedicated web page with audio examples of some of the scientific phenomena listed in the book would considerably improve the reading experience. Given the plethora of scientific information on various phenomena pertaining to sound and hearing provided in this book, it comes across at times as disconnected. Despite these limitations, Horowitz's passion and enthusiasm come through as both transparent and contagious, keeping the reader's interest level high throughout the book. A general reader should find this book informative and entertaining. Academics in research disciplines related to sound and hearing inclusive of audiologists, acousticians, speech and hearing scientists, and music cognition researchers should find the book satisfying and perhaps helpful in broadening their research perspective.

Dr. Naresh N. Vempala
SMART Lab, Department of Psychology
Ryerson University, Toronto
nvempala@psych.ryerson.ca

PRIZE ANNOUNCEMENT • ANNONCE DE PRIX

CANADIAN ACOUSTICAL ASSOCIATION
ASSOCIATION CANADIENNE D'ACOUSTIQUE

Prize

Edgar and Millicent Shaw Postdoctoral Prize in Acoustics
Alexander G. Bell Graduate Student Prize in Speech Communication and Hearing
Eckel Graduate Student Prize in Noise Control
Fessenden Graduate Student Prize in Underwater Acoustics
Raymond Hetu Undergraduate Student Prize in Acoustics
Thomas D. Northwood Graduate Student Prize in Architectural and Room Acoustics
Albert S. Bregman Graduate Student Prize in Psychological Acoustics

Prix

Prix Post-doctoral Edgar et Millicent Shaw en Acoustique
Prix etudiant Alexander G. Bell en Communication orale et audition (2^{e} ou 3^{e} cycle)
Prix etudiant Eckel en Controle du bruit (2^{e} ou 3^{e} cycle)
Prix etudiant Fessenden en Acoustique sous-marine (2^{e} ou 3^{e} cycle)
Prix etudiant Raymond Hetu en Acoustique (1er cycle)
Prix etudiant Thomas D. Northwood en Acoustique Architecturale et Acoustique des Salles (2^{e} ou 3^{e} cycle)
Prix etudiant Albert S. Bregman en Psychoacoustique (2^{e} ou 3^{e} cycle)

Deadline for Applications:
April 30th 2014

Date limite de soumission des demandes:
30 Avril 2014

Consult CAA website for more information
Consultez le site Internet de l'ACA pour de plus amples renseignements
(http://www.caa-aca.ca)


NEW TYPE 4448 PERSONAL NOISE DOSE METER
Damaged hearing costs you dearly
Preventing it doesn't
Brüel & Kjær
DURATION
Type 4448
TYPE 4448 FROM BRÜEL & KJÆR
Home of the world's best sound and vibration instrumentation
Type 4448 – Helping to improve workplace noise assessment
Simple reliability
No cables, no connectors
Forget it is there
Secure shoulder mount with pin or clip attachment
Ready when you are
Long 28 hour battery-life
Verify your Standards compliance
HML option – verify hearing protection requirements
Works with Protector PC software – for intuitive analysis and reporting
www.bksv.com/Type4448
BN 1054–11

Canadian Acoustical Association

Minutes of Annual General Meeting

Montreal, Quebec
June 5, 2013

Call to Order

President Christian Giguère called the meeting to order at 6:50 p.m. with 18 members in attendance, and presented the Agenda for acceptance *(Moved by A. Behar, seconded by S. Dosso, carried.)*

Minutes of the previous Annual General Meeting held on October 11, 2012 in Banff were approved as printed in the December 2012 issue of *Canadian Acoustics*. *(Moved by J., Voix, seconded by S. Abel, carried)*

President's Report

Christian Giguère briefly summarized his report to the Board meeting on June 4th. Christian Giguère mentioned several initiatives that have been launched in the past year, such as the online membership database and dues payment system, the online publishing of Canadian Acoustics, the establishment of two new CAA Awards, and the revamped website. After serving for several years as President, Christian indicated that it is time for a change-over.

Secretary's Report

Chantal Laroche provided an overview of membership and operational activities.

- The total of 445 paid renewals and new memberships is up from last year, presumably due to reminders sent by email to members.
- Jeremie Voix has put in place a new system that allows CAA members to pay online.

(Acceptance of Secretary's report moved by N. Ellaham, seconded by S. Abel, carried.)

Treasurer's Report

On behalf of Dalila Giusti, Christian Giguère presented an overview of her written report to the Board on CAA finances. CAA is in good financial standing, with $231,527 in TD Canada Trust fund and $122 123 in operating fund. The Banff Conference has generated $21,299 in net revenue. The fiscal year now ends on December 30th.

The Treasurer's report was accepted. *(Moved by A. Behar, seconded by S. Dosso, carried)*

Editor's Report

Frank Russo mentioned that the Editorial Board counts 15 members. An international Editorial team will be considered in the near future. An Advisory Board is now in place with Jérémie Voix, Brian Gick and Frank Russo.

The reviewing time is approximately 8 weeks. There are 17 papers in queue for publication The Journal is now available online, and the new website and logo are also ready.

A 6 month free promotional offer was announced during ICA 2013. New subscribers will freely receive an online copy of Canadian Acoustics for 6 months.

It is hoped that there will be an author agreement signed with EBSCO by the end of June. The September issue of Canadian Acoustics will feature contributions from new scholars. July 1 is the submission deadline.

It is foreseen that an application will be submitted within the next 2 years to become a journal with a listed impact factor (IF).

All journal back-issues were digitized and put online (161 issues, 2149 articles, and more than 15,000 pages). This huge effort was made possible thanks to the relentless work of Dr. Eugen Popovici and the personal hardcopy archives kindly lent by Dr. John Bradley, Dr David Quirt, Dr. Ramani Ramakrishnan, Dr. Christian Giguere and Dr. Chantal Laroche. Ms Rebecca Reich was also thanked for her contribution to the online system and her presence at the CAA table during ICA 2013.

Award Coordinator's Report

Hugues Nélisse presented a report summarizing decisions from all individual prize coordinators. Eligible applications were available for all awards and winners have been selected, except for the Student Prize in Architectural Acoustics (no candidacy) and the Bell Student Prize in Speech Communication and Speech (1 candidacy but not eligible). Winners have been announced at the ICA Awards Ceremony on June 5th and will appear in the September issue of *Canadian Acoustics*. Two new awards have been created (Bregman Prize in Psychological Acoustics and Northwood Prize in Architectural and Room Acoustics).

Past and Future Meetings

2012 (Banff): Stan Dosso reported that they were approximately 100 papers with 136 attendees and a profit of $21,299.54.

2013 (Montreal, ICA 2013): Mike Stinson reported *that they are* approximately 2500 participants (600 students) at the meeting. This is one of the largest meeting in Acoustics ever held.

2014 (Winnipeg):
Christian Giguère mentioned that Karen Turner is in charge of the local organization. She is collected information about hotel venues. She will also need to finalize her committee. A few names were suggested, Christian Giguère will do the follow up. He also mentioned that the online system includes a separate conference system that could be used for registration and handling of abstracts.

2015: Halifax has been suggested. To be discussed with local people.

Acoustical Standards Committee

Christian Giguère gave some background. The CAA Standards Committee is proposing adoption of the CAA Guide 101 to Acoustic Standards. The BoD wish to formalize the terms of reference for the Committee and clear liability issues before going ahead with the guide's approval.

Website

Sean Pecknold presented the new website. Christian Giguère thanked Sean and his team for the good work accomplished.

Nominations and Election

CAA corporate bylaws require that each year we elect the Executive and Directors. The Past President, Stan Dosso, presented nominations and managed the election process.

For the election process, Stan read the name of the nominee(s) and asked if there were other nominees from the floor.

- Jeremie Voix served as a Director for the maximum term of 6 years. Alberto Behar is nominated to replace him as new Director. The other Directors (namely Roberto Racca, Kathy Pichora-Fuller, Sean Pecknold, Clair Wakefield, Karen Turner, Bryan Gick and Hugues Nelisse) indicated their willingness to stand.
- Chantal Laroche and Dalila Giusti indicated their willingness to stay as Executive Secretary and Treasurer, respectively.
- Christian Giguère is stepping out as President and becomes Past President. Stan Dosso is stepping out after 10 years of service on the Executive. Frank Russo was nominated as the new President. Jérémie Voix was nominated as the new Editor-in-Chief.

There were no other nominations from the floor, so these nominees were declared elected by acclamation. Stan Dosso and Christian Giguère were thanked for their service. The new Board of Directors will be in effect on October 15th 2013.

Adjournment

Meeting adjourned at 8 p.m. *(Moved by J. Voix, seconded by P. Van Delden, carried)*

Canadian Acoustical Association

Minutes of the Board of Directors Meeting
Montreal, Quebec
June 4, 2013

Present: Christian Giguère (chair), Jérémie Voix, Hugues Nélisse, Stan Dosso, Dalila Giusti, Chantal Laroche, Roberto Racca, Kathy Pichora-Fuller, Frank Russo, Sean Pecknold, Bryan Gick

The meeting was called to order at 7:15 p.m. Minutes of the previous Board of Directors' meeting on October 9th 2012 were approved as published in the December 2012 issue of *Canadian Acoustics*. *(Moved by R. Racca, seconded by J. Voix, carried).*

President's Report

Christian Giguère thanked everyone involved in the several initiatives that have been launched in the past year, such as the online membership database and dues payment system, the online publishing of Canadian Acoustics, the establishment of two new CAA Awards, and the revamped website. In addition to providing better services to our members, these initiatives will facilitate the management of the Association and increase its visibility. After serving for several years as President, Christian indicated that it is time for a change-over and he indicated he will not seek re-election at the AGM.

(Approval of report moved by S. Pecknold, Seconded by F. Russo, carried)

Secretary's Report

Chantal Laroche reported that the new system put in place by Jeremie Voix is officially in place since December 2012. CAA now accepts online payments. Very few members are still paying by cheque or by fax. There were a few bugs to deal with, but as of June 4th, membership and renewals are up by 25 from last year (see Table). There are 445 active members. With respect to routine CAA communications:

- Annual filing with Corporations Canada was submitted
- Renewal to I-INCE has been paid by Dalila Giusti for 2013
- Access Copyright: $94.10 received in October 2012

Category	**Paid 2011**	**Change from 2012**
Member	290	16
Emeritus	1	0
Student	78	4
Sustaining subscriber	51	4
Indirect subscribers		
- Canada	9	0
- USA	6	0
- International	5	0
Direct subscribers	5	1
Total	445	+25

Secretarial operating costs from September 1st 2012 to May, 31st 2013 totaled $458.89. The secretary is requesting a budget of $500 to reimburse postal box fees and to cover expenses for the rest of the fiscal year. (Moved by S. Pecknold, Seconded by D. Gick, carried)

The Treasurer, Dalila Giusti, has arranged for the Association to subscribe to Directors' liability insurance, and the Board members are now covered against eventual fraud.

For indirect USA and international subscribers, it was proposed to charge an extra amount to cover the mailing cost of the journal. The amount will be determined at a later date. These members will be informed of this change during the membership renewal period.

A 6-month free promotional offer was announced during ICA 2013. It was proposed that new enrolled members received a free paper copy of the September issue via mail. (not seconded). It was then proposed that people who signed for a free offer would receive an online copy of Canadian Acoustics for 6 months (Moved C. Laroche, Seconded K.P.-Fuller, carried).

(Approval of report moved by D. Giusti, seconded by R. Racca, carried)

Treasurer's Report

The Treasurer, Dalila Giusti, submitted a report including a preliminary financial statement for the fiscal year. CAA finances are in reasonable standing. The 2012 Conference (Banff) made a substantial profit. Overall, Association revenues well exceeded expenses and the costs for student awards.

Dalila will transfer $40,000 from the Operating Account to the Capital Account to cover Student Awards. $9,450 has been distributed in awards at the 2012 Conference.

Travel funds for students where discussed. It was proposed to cover 50% of traveling cost to a maximum of $250 per student (pending submission of an estimate budget at the date of abstract submission) and a maximum cap amount of $7,500 for the next two years, funds permitted. (Moved by R. Racca, Seconded S. Dosso, carried). Kathy has offered to review the generic form used for travel funds request.

The CAA fiscal year end has been moved to December 30.

(Approval of report moved by B. Gick, seconded by S. Pecknold, carried)

Editor's Report

Frank Russo mentioned that the Editorial Board counts 15 members who have been renewed/replaced (no vacancies) and committed for 2 years from January, 2013. An international Editorial team is considered in the near future. An Advisory Board has been suggested by Kathy to increase the visibility of the Journal.

The reviewing time is approximately 8 weeks. There are 6 papers in press for the June issue (coordinated by Josée Lagacé) and 5 papers are currently under review. 6 more papers are in the online system. The Journal was available online just in time for the 40th anniversary (Phase 1). The new website and logo are also ready (Phase 2) and the cost was $1600 as budgeted. The initiation of new website and logo were approved through emails. Sean has created a mailbox (clerk@caa-aca.ca) in order to track down the decisions made between face-to-face meetings.

It is hoped that there will be an agreement with EBSCO by the end of June. It was proposed that once we have an agreement in place, two Executive Board members will sign the agreement *(Moved by F. Russo, Seconded by B. Gick, carried)*.

The September issue of Canadian Acoustics will feature contributions from new scholars. For the purposes of this issue, a new scholar is defined as someone who is within 10 years of the terminal degree at the time of submission (this pertains to the corresponding author only). Authors who have not previously published articles in the journal are especially welcome to submit..July 1 is the submission deadline.

According to Frank, we should consider submitting an application within the next 2 years to become a journal with a listed impact factor (IF). Many authors refer to IF before considering submission.

CAA Conferences – Past, Present & Future

2012 (Banff): Stan Dosso reported that there were approximately 100 papers with 136 attendees and a profit of $21,299.54.

2013 (Montreal, ICA 2013): Mike Stinson reported *that they are* approximately 2500 participants (600 students) at the meeting. This is one of the largest meetings in Acoustics ever held.

2014 (Winnipeg): Karen Turner is in charge of the local organization. She is collecting information about hotel venues. She will also need to finalize her committee. A few names were suggested, Christian Giguère will do the follow up. Jeremie Voix mentioned that a separate conference system, similar to the system now hosting the journal, could be used for registration and handling of abstracts.

2015: Halifax has been suggested. To be discussed with local people.

Awards

Hugues Nélisse presented a report summarizing decisions from all individual prize coordinators. Eligible applications were available for all awards and winners have been selected, except for the Student Prize in Architectural Acoustics (no candidacy) and the Bell Student Prize in Speech Communication and Speech (1 candidacy but not eligible). Winners will be announced at the joint ICA/ASA/CAA Awards Ceremony on June 5th and in the September issue of *Canadian Acoustics*. The Directors' award will be selected later as the process has not been launched yet. Two new awards have been created (Bregman Prize in Psychological Acoustics and Northwood Prize in Architectural and Room Acoustics). A motion was put forward that Aeracoustics would sponsor a new award after John Bradley's name and that an ad-hoc committee would work on the exact name and description of the award as well as the financial terms.

(*Moved by KP Fuller. Seconded by B. Gick, carried*)

Acoustical Standards Committee

Christian Giguère presented a report on behalf of Tim Kelsall, the Chair of the Acoustical Standards Committee. The Committee produced the "CAA Guide 101 to Acoustical Standards" and asked that the BoD endorses it and approves its posting on the CAA website. A long conversation followed. The Board members asked that the Committee clarifies its expectations and explain the kind of endorsement that is sought from the CAA BoD, especially as it may expose the Board to potential liability issues. (*Moved by D. Giusti, Seconded by S. Pecknold, Carried*). Christian said he will talk to Tim Kelsall about this as well as the need to formalize the terms of reference for the Committee now that documents are being produced.

CAA Website

Jérémie Voix reported on the Journal Website and Membership Database migration effort that is still within budget ($6,500 budgeted, $5000 expended) and ahead or within schedule. The journal online migration was completed by December 24th 2012 ahead of schedule (French was to be unrolled in June 2013). The Automated membership management was debugged in time for automated renewal emails to be sent on February 1st, 2013. The Online editorial system is live since January and used since February. All journal back-issues were digitized and put online, this is 161 issues, 2149 articles, and more than 15,000 pages that have been put online just before Christmas 2012! This huge effort was made possible thanks to the relentless scanning, coding and scripting work of Dr. Eugen Popovici (more than 100 hours of PC crunching time and 350 hours of hard work); the personal hard-copies archives kindly lent (in chronological issue order) by Dr. John Bradley, Dr David Quirt, Dr. Ramani Ramakrishnan, Dr. Christian Giguère and Dr. Chantal Laroche; the mental support and encouraging words of Dr. Bryan Gick and Dr. Frank Russo; the financial support of the Canadian Acoustical Association enabled by its Board of Directors; the frantic & friendly supervision of Dr. Jérémie Voix. Finally the journal is now indexed by Google Scholar and Open Access Initiative and now gets excellent coverage from search engines and publishing databases.

The remaining item is to finalize the journal online publishing Latex-XML transformation scripts with Mr popovici. Jeremie Voix requested a little extra budget of $600 for this. (*Approved*.)

Jeremie Voix also mentioned the need to move the

JCAA website to the CAA legacy servers with Sean Peckold's help.

Sean Peckold reported that some Sustaining Subscribers complained that their logos were sometime missing or out of date. It is suggested that the secretary could ask the sustaining members each time he/she receive an automated subscription notification and post that into the "note" field of the subscription info.

Other business

CAA Logo**:** Dalila Giusti explains the history of the blue logo. Frank Russo proposed to adopt the new logo. It is decided to go for another round of edits.

ICA Special: Jérémie reported on the ICA initiative (upload of all individual complete PDF of past issues, printing of the posters for the CAA table, printing of the pamphlet in every congress bag, work at the booth) and informed the Board that he called for some help and hired Ms Rebecca Reich on his remaining $1500 budget. More than 50 ICA congress members subscribed to the 6-month free online subscription.

Adjournment

Meeting adjourned at 00:15a.m. *(Moved by J. Voix, seconded by R. Racca, carried)*

Announcement: International Commission on the Biological Effects of Noise (ICBEN)

From the desk of Lawrence S. Finegold, Congress Co-chair

Dear Colleague,

For over 40 years, the International Commission on the Biological Effects of Noise (ICBEN) has been the premier global forum for the exchange of scientific, technical, and practical knowledge about noise as a public health problem. Every three years, ICBEN holds an eagerly-awaited, week-long International Congress in a different region of the world. 2011 was the last meeting which was held in London. We want to extend an invitation to the Canadian Acoustical Association.

Next June 1-5, 2014, ICBEN will assemble 400-500 of the world's top experts on noise and health in Japan's ancient capital city, Nara. The Nara Congress is a particularly important meeting about a topic of growing concern worldwide.

Please inform your members and colleagues about this landmark meeting by: (1) posting this letter on your website and (2) emailing this information to your members and colleagues.

ICBEN provides the only truly global forum for influential, concerned noise researchers, government agencies, and concerned businesses and industries to discuss noise issues. Participants engage with and learn from each other. ICBEN Congresses are well-known for providing fresh, new and authoritative information on the effects of noise, proposing useful concepts for governmental noise regulators, guiding future research and legislation on a variety of noise issues, and supplying research information that is ready for government and industrial use.

Detailed information about ICBEN's Nara Congress is available here: http://www.icben2014.com/. For additional information, contact the organizing committee at secretariat@icben2014.com. You can also click on this link to view the announcement flyer: link for announcement flyer.

I look forward to seeing you in Nara. In the meantime, if you have questions, please contact Darlene Kilpatrick MS, my Executive Assistant at dekilpatrick@icben2014.org.

Sincerely,

Lawrence S. Finegold,
Congress Co-Chair, ICBEN 2014,
Chair, ICBEN Team 9- Noise Policy and Economics

International Commission on Biological Effects of Noise

ICBEN

ICBEN 2014

1-5 June 2014 Nara


Concerto
4-Channel Multi-Function Acoustic Measuring System
All you need in one system:
- 4-channel SLM Class 1
- RT60, EDT, C80, D50 & Ts
- 4-channel Data Logger
- 4-channel Spectrum Analyzer
- Building and Human Vibration
- Monitoring Station with Remote Access
Custom Modules Available
See demo : www.softdb.com/concerto.php
Remote access via
iPhone or PC


I-Track
Automatic Real-Time Sound Mapping
See demo : www.softdb.com/itrack.php
Automotive
Industrial
Laboratory
Architectural
5-Minute Mapping
Freehand Scanning Without Grid

The Canadian Acoustical Association
L'Association canadienne d'acoustique

Application for Membership

CAA membership is open to all individuals who have an interest in acoustics. Annual dues total $90.00 for individual members and $40.00 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 $90.00 per year. Many organizations choose to become benefactors of the CAA by contributing as Sustaining Subscribers, paying $400.00 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 $ 90.00
[ ] CAA Student Membership $ 40.00

Corporate Subscriptions (4 issues/yr)
[ ] $90 including mailing in Canada
[ ] $98 including mailing to USA,
[ ] $105 including International mailing

[ ] Sustaining Subscription $400.00 (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 organisations wishing to pay by cheque, please download the application form at http://www.caa-aca.ca and mail to:

Executive Secretary, The Canadian Acoustical Association, PO Box 74068, Ottawa, Ontario, K1M 2H9, Canada

L’Association canadienne d’acoustique
The Canadian Acoustical Association

Formulaire d’adhésion

L'adhésion à l'ACA est ouverte à tous ceux qui s'intéressent à l'acoustique. La cotisation annuelle est de 90.00$ pour les membres individuels, et de 40.00$ pour les membres étudiants. Tous les membres reçoivent ***l'Acoustique Canadienne***, la revue de l'association publiée quatre fois par année, et ont droit de vote à l’assemblée générale annuelle.

Abonnement à la revue *Acoustique Canadienne* et abonnement de soutien

Les abonnements à la revue ***Acoustique Canadienne*** sont disponibles pour les corporations et institutions au coût annuel de 90.00$. Plusieurs organisations choisissent de devenir bienfaiteurs de l’ACA en souscrivant à un abonnement de soutien de 400.00$ par année (sans droit de vote à l’AGA). La liste des abonnés de soutien est publiée dans chaque numéro de la revue ***Acoustique Canadienne*** et sur le site internet de l’ACA.

Noter que les paiements en ligne sont effectués à http://jcaa.caa-aca.ca

Pour correspondance administrative et financière:

Nom / Organisation ______________________________

Adresse ______________________________

Ville/Province ____________ Code postal ________ Pays ____________

Téléphone ____________ Téléc. ____________ Courriel ____________

Adresse postale pour la revue Acoustique canadienne

Nom / Organisation ______________________________

Adresse ______________________________

Ville/Province ____________ Code postal ________ Pays ____________

Cocher vos champs d'intérêt: (maximum 3)

1. Acoustique architecturale
2. Génie acoustique / Contrôle du bruit
3. Acoustique physique / Ultrasons
4. Acoustique musicale / Électro-acoustique
5. Physio / Psycho-acoustique
6. Chocs et vibrations
7. Audition
8. Parole
9. Acoustique sous-marine
10. Traitement des signaux /Méthodes numériques
11. Autre

Prière de remplir pour les étudiants et étudiantes:

____________ ____________ ____________ ____________

(Université) (Nom d'un membre du corps professoral) (Signature du membre du corps professoral) (Date)

Cocher la case appropriée:
[ ] Membre individuel 90.00 $
[ ] Membre étudiant(e) 40.00 $

Abonnement corporatif (4 numéros/année)
[ ] 90 $ à l'intérieur du Canada
[ ] 98 $ vers les États-Unis
[ ] 105 $ tout autre envoi international

[ ] Abonnement de soutien 400.00 $
(4 numéros/année)

Noter que la méthode de paiement privilégiée est par carte de crédit, en ligne à *http://jcaa.caa-aca.ca*

Les individus et organisations préférant payer par chèque doivent télécharger le formulaire d’adhésion disponible à http://www.caa-aca.ca et le poster à l’adresse suivante:

Secrétaire exécutif, Association canadienne d’acoustique, CP 74068, Ottawa, Ontario, K1M 2H9, Canada

INSTRUCTIONS TO AUTHORS FOR THE PREPARATION OF MANUSCRIPTS

Submissions: The original manuscript and two copies should be sent to the Editor-in-Chief. The manuscript can also be submitted electronically.

General Presentation: Papers should be submitted in camera-ready format. Paper size 8.5” x 11”. If you have access to a word processor, copy as closely as possible the format of the articles in Canadian Acoustics 39(1) 2011. All text in Times-Roman 10 pt font, with single (12 pt) spacing. Main body of text in two columns separated by 0.25”. One line space between paragraphs.

Margins: Top - 0.75”; bottom - 0.75” minimum; sides - 0.75”.

Title: Bold, Times New Roman 14 pt with 14 pt spacing, upper case, centered.

Authors/addresses: Names and full mailing addresses, 10 pt with single (12 pt) spacing, upper and lower case, centered. Names in bold text.

Abstracts: English and French versions. Headings, 12 pt bold, upper case, centered. Indent text 0.5” on both sides.

Headings: Headings to be in 12 pt bold, Times-Roman font. Number at the left margin and indent text 0.5”. Main headings, numbered as 1, 2, 3, ... to be in upper case. Sub-headings numbered as 1.1, 1.2, 1.3, ... in upper and lower case. Sub-sub-headings not numbered, in upper and lower case, underlined.

Equations: Minimize. Place in text if short. Numbered.

Figures/Tables: Keep small. Insert in text at top or bottom of page. Name as “Figure 1, 2, ...” Caption in 9 pt with single (12 pt) spacing. Leave 0.5” between text.

Line Widths: Line widths in technical drawings, figures and tables should be a minimum of 0.5 pt.

Photographs: Submit original glossy, black and white photograph.

Scans: Should be between 225 dpi and 300 dpi. Scan: Line art as bitmap tiffs; Black and white as grayscale tiffs and colour as CMYK tiffs;

References: Cite in text and list at end in any consistent format, 9 pt with single (12 pt) spacing.

Page numbers: In light pencil at the bottom of each page. For electronic submissions, do not number pages.

Reprints: Can be ordered at time of acceptance of paper.

DIRECTIVES A L’INTENTION DES AUTEURS PREPARATION DES MANUSCRITS

Soumissions: Le manuscrit original ainsi que deux copies doivent être soumis au rédacteur-en-chef. Le manuscrit peut être aussi acheminé par voie électronique.

Présentation générale: Le manuscrit doit être soumis avec mise en page en format de publication. Dimension des pages, 8.5” x 11”. Si vous avez accès à un système de traitement de texte, dans la mesure du possible, suivre le format des articles dans l’Acoustique canadienne 39(1) 2011. Tout le texte doit être en caractères Times-Roman, 10 pt et à simple (12 pt) interligne. Le texte principal doit être en deux colonnes séparées d’un espace de 0.25”. Les paragraphes sont séparés d’un espace d’une ligne.

Marges: Haut - 0.75”; bas - minimum 0.75” ; côtés,- 0.75”.

Titre du manuscrit: Caractères gras, Times New Roman 14 pt,avec espace interligne de 14 pt, lettres majuscules, texte centré.

Auteurs/adresses: Noms et adresses postales. Lettres majuscules et minuscules, 10 pt à simple (12 pt) interligne, texte centré. Les noms doivent être en caractères gras.

Sommaire: En versions anglaise et française. Titre en 12 pt, lettres majuscules, caractères gras, texte centré. Paragraphe 0.5” en alinéa de la marge, des 2 cotés.

Titres des sections: Tous en caractères gras, 12 pt, Times-Roman. Premiers titres: numéroter 1, 2, 3, ..., en lettres majuscules; sous-titres: numéroter 1.1, 1.2, 1.3, ..., en lettres majuscules et minuscules; sous-sous-titres: ne pas numéroter, en lettres majuscules et minuscules et soulignés.

Équations: Minimiser le nombre et les numéroter. Insérer directement dans le texte les équations très courtes.

Figures/Tableaux: De petites tailles. Les insérer dans le texte au haut ou au bas de la page. Les nommer “Figure 1, 2, 3,...” Légende en 9 pt à simple (12 pt) interligne. Laisser un espace de 0.5” entre le texte.

Largeur des traits: La largeur des traits sur les schémas techniques doivent être au minimum de 0.5 pt pour permettre une bonne reproduction.

Photographies: Soumettre la photographie originale sur papier glacé, noir et blanc.

Figures numérisées: Doivent être au minimum de 225 dpi et au maximum de 300 dpi. Les schémas doivent être en format bitmap tif. Les photos noir et blanc doivent en format tif sur une échelle de tons de gris et toutes les photos couleurs doivent être en format CMYK tif.

Références: Les citer dans le texte et en faire la liste à la fin du document, en format uniforme, 9 pt à simple (12 pt) interligne.

Pagination: Au crayon pâle, au bas de chaque page. Ne pas paginer si le manuscrit est envoyé par voie électronique.

Tirés-à-part: Ils peuvent être commandés au moment de l’acceptation du manuscrit.

SUSTAINING SUBSCRIBERS / ABONNES DE SOUTIEN

The Canadian Acoustical Association gratefully acknowledges the financial assistance of the Sustaining Subscribers listed below. Their annual donations (of $350.00 or more) enable the journal to be distributed to all at a reasonable cost.

L'Association Canadienne d'Acoustique tient à témoigner sa reconnaissance à l'égard de ses Abonnés de Soutien en publiant ci-dessous leur nom et leur adresse. En amortissant les coûts de publication et de distribution, les dons annuels (de $350.00 et plus) rendent le journal accessible à tous nos membres.

ACI Acoustical Consultants Inc.
Mr. Steven Bilawchuk - (780) 414-6373
stevenb@aciacoustical.com - Edmonton, AB

ACO Pacific Inc.
Mr. Noland Lewis - (650) 595-8588
acopac@acopacific.com - Belmont, CA

Acoustic Solutions LTD
Isidor Gliener
acusticsolutions.com

Acoustec Inc.
Dr. J.G. Migneron - (418) 834-1414
courrier@acoustec.qc.ca - St-Nicolas, QC

Aercoustics Engineering Ltd
Mr. John O'Keefe - (416) 249-3361
aercoustics@aercoustics.com - Rexdale, ON

AMEC
Mr. Frank Babic - 905.568.2929
amec.com

ARMTEC
Ron Galloway - 905-521-0999
armtec.com

Bruel & Kjaer North America Inc.
Mr. Andrew Khoury - (514) 695-8225
andrew.khoury@bksv.com - Pointe-Claire, QC

Conestoga-Rovers & Associates
Tim C. Wiens - 519-884-0510 xx2352
craworld.com

Dalimar Instruments Inc.
Mr. Daniel Larose - (514) 424-0033
daniel@dalimar.ca - Vaudreuil-Dorion, QC

DuraSystems Barriers Inc.
Fred Woo - 905-660-4455
durasystems.com

Eckel Industries of Canada Ltd.
Mr. Bruce Allan - (613) 543-2967
eckel@eckel.ca - Morrisburg, ON

Engineers for Change, Inc.
Richard Joseph Peppin - 301-984-3375

FFA Consultants in Acoustics and Noise Control
Robyn Sharek

H.L. Blachford Ltd.
Mr. Dalton Prince - (905) 823-3200
amsales@blachford.ca - Mississauga, ON

Hatch Associates Ltd.
Mr. Tim Kelsall - (905) 403-3932
tkelsall@hatch.ca - Mississauga, ON

HGC Engineering Ltd.
Mr. Bill Gastmeier - (905) 826-4044
info@hgcengineering.com - Mississauga, ON

Integral DX Engineering Ltd.
Mr. Greg Clunis - (613) 761-1565
greg@integraldxengineering.ca - Ottawa, ON

Jade Acoustics Inc.
Ms. Dalila Giusti - (905) 660-2444
dalila@jadeacoustics.com - Concord, ON

Kinetics Noise Control Inc.
Mehrzad Salkhordeh - 905-670-4922
kineticsnoise.com

Mc SQUARED System Design Group
Mr. Wade McGregor - (604) 986-8181
info@mcsquared.com - North Vancouver, BC

MJM Conseillers en Acoustique Inc.
M. Michel Morin- (514) 737-9811
mmorin@mjm.qc.ca - Montréal, QC

Novel Dynamics Test Inc.
Mr. Andy Metelka - (519) 853-4495
metelka@aztec-net.com - Acton, ON

Peutz & Associés
M. Marc Asselineau +33 1 45230500
m..asselineau@peutz.fr - Paris, FRANCE

Pinchin Environmental Ltd.
(905) 363-0678; FAX: (905) 363-0681
info@pinchin.com - Mississauga, ON

Pyrok Inc.
(914) 777-7770; FAX: (914) 777-7103
info@pyrokinc.com - Mamaroneck, NY

Scantek Inc.
Mr. Richard J. Peppin, (410)-290-7726
peppinr@scantekinc.com - Columbia, MD

SNC/Lavalin Environment Inc.
M. Jean-Luc Allard - (514) 651-6710
jeanluc.allard@snclavalin.com - Longueuil, QC

Soft dB Inc.
M. André L'Espérance - (418) 686-0993
contact@softdb.com - Sillery, QC

Sound & Vibration Solutions Canada, Inc.
Mr. Andy Metelka - 519-853-4495

Soundtrap Inc.
Roger Foulds - 705-357-1067
soundtrap.ca

Stantec Consulting Ltd
Zohreh Razavi - 604-606-8472
stantec.com

State of the Art Acoustik Inc.
Dr. C. Fortier - (613) 745-2003,
sota@sota.ca - Ottawa, ON

True Grit Consulting Ltd.
Ms Ina Chomyshyn - 807-626-5640
tgcl.ca

Valcoustics Canada Ltd.
Dr. Al Lightstone - (905) 764-5223
solutions@valcoustics.com - Richmond Hill, ON

Vendatech Inc.
Behrou Ghazizadeh - 416-787-8797
vendatech.com

Vibro-Acoustics
Mr. Tim Charlton - (800) 565-8401
tcharlton@vibro-acoustics.com

Wakefield Acoustics Ltd.
Mr. Clair Wakefield - (250) 370-9302
nonoise@shaw.ca - Victoria, BC

West Caldwell Calibration Labs
Mr. Stanley Christopher - (905) 595-1107
info@wccl.com - Brampton, ON

Xscala Sound & Vibration
Jim Ulicki - 403-274-7577
xscala.com