ISSN 0711-6659

canadian acoustics
acoustique canadienne

Journal of the Canadian Acoustical Association - Revue de l'Association canadienne d'acoustique

MARCH 2017 | MARS 2017
Volume 45 - - Number 1 | Volume 45 - - Numéro 1

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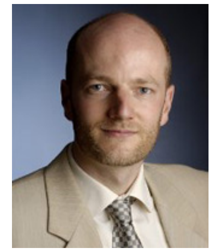

Nos valeurs acoustiques canadiennes

Our Acoustically Canadian Values

En ces temps troubles, je pense qu'il est important de réaffirmer ce que sont nos valeurs acoustiques canadiennes. Par temps troubles, je fais évidemment allusion à cette course effrénée à la publication (avec ce crédo “publier ou mourir”), à la montée des éditeurs “prédateurs” et au risque croissant de plagiat et de contenu douteux (voir le remarquable travail de dénonciation présenté par Cyril Labbé de l'université Joseph Fourier de Grenoble en France). La publication scientifique de qualité est à risque et nous sommes convaincus, à l'Acoustique canadienne, que nous avons un rôle à jouer pour des publications saines, libres de droits et de qualité.

Même si nous n'avons pas le même facteur d'impact que des revues payantes en acoustique, (et profitons de cette opportunité pour reconnaître le travail remarquable du Journal of the Acoustical Society of America dans la publication en acoustique et pour saluer l'important travail de rajeunissement effectué par l'ASA ces dernières années), notre journal, Acoustique canadienne,

In these current times of trouble, I believe it is important to reaffirm the values of Canadian Acoustics. By troubled times, I'm obviously referring to the frantic race to publish (with this infamous credo of “publish or perish”), the rise of rogue publishers (you have probably heard of “predatory open access publishing”), and the increasing risk of plagiarism and even fake content (check out the brilliant debunking work of Cyril Labbé of Joseph Fourier University, Grenoble, France). Sound science is indeed at risk, and we at Canadian Acoustics believe we have a role to play in ensuring reliable, open-access and quality publishing.

While we may not have the same impact factor as other paid journals in acoustics (and let's take this opportunity to acknowledge the tremendous work done at the Journal of the Acoustical Society of America as they lead the way in publishing on acoustics -if JASA is first, can we be second?- and to salute the major work done to refresh and modernise the ASA over the recent year), our journal - Canadian Acoustics - contains truly contient des articles rares et abondamment cités dans des domaines aussi pointus que l'acoustique du bâtiment, l'acoustique sous-marine ou encore la linguistique, pour ne citer que nos plus récents articles plébiscités. À l'Acoustique canadienne, nous sommes également fiers d'être largement référencés et indexés par la majorité des bases de données scientifiques et techniques, incluant Inspec et Compendex. Acoustique canadienne est également indexée par des bases de données récentes, telles Google Scholar ou DOAJ et est compatible avec OAI-PMH, une plateforme d'interopérabilité pour les publications électroniques.

Même si nous avons bien une barrière, il s'agit d'une “barrière mobile” dans le vocabulaire des maisons d'édition, qui fait en sorte que tous les articles publiés dans Acoustique canadienne passent en libre-accès, gratuit, 12 mois après leur publication initiale. Cela permet un usage libre et à grande échelle des connaissances et de la recherche de pointe, permettant ainsi aux chercheurs, aux universitaires, aux cliniciens, aux législateurs, au secteur privé, aux organismes sans but lucratif et au public en général d'utiliser et de construire à partir de cette connaissance. Depuis 2015, les trois organismes subventionnaires fédéraux, l'Institut de recherche en santé du Canada (IRSC), le Conseil en recherches en sciences naturelles et en génie du Canada (CRSNG), et le Conseil de recherches en sciences humaines (CRSH), ont d'ailleurs explicitement demandé à tous les chercheurs subventionnés de s'assurer que leurs publications passent le plus rapidement possible en libre-accès. Acoustique canadienne est fière d'appuyer un tel modèle de publication scientifique et de participer ainsi à l'avancement sociétal.

Même si la publication trimestrielle d'une revue évaluée par les pairs selon des normes scientifiques élevées reste certainement un défi important pour l'équipe bénévole du comité éditorial, la qualité scientifique d'Acoustique canadienne est en grande partie due au dévouement des évaluateurs externes qui donnent gracieusement de leur temps et de leur expertise. Nous, à l'Acoustique canadienne, sommes fiers de nos 43 années d'existence et de nos plus de 3000

unique and widely cited content, in very specific areas like building acoustics, underwater acoustics and linguistics, to cite only our latest top hits. We, at Canadian Acoustics, are also proud of being referenced and indexed by major scientific and technical bibliographic databases, including Inspec (published by the Institution of Engineering and Technology) and Compendex (now published by Elsevier). Canadian Acoustics is also comprehensively covered by recent citation indexes such as Google Scholar, the Directory of Open Access Journals (DOAJ) and complies with the Open Archives Initiative Protocol for Metadata Harvesting (OAI-PMH), the standard framework for interoperability among e-publishing providers.

While we do indeed have a wall, ours is a “moving wall” in the publisher's lingo, that ensures that all articles published in Canadian Acoustics become open access, free of charge, 12 months after they have been initially published. This ensures a widespread and barrier-free access to cutting-edge research and knowledge, enabling researchers, scholars, clinicians, policymakers, private sector and not-for-profit organizations and the public to use and build on this knowledge. Since 2015, the three federal granting agencies, Canadian Institutes of Health Research (CIHR), the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Social Sciences and Humanities Research Council of Canada (SSHRC), have therefore explicitly requested all their grant recipients to ensure that their related publications become open access at the earliest possible opportunity. Canadian Acoustics is proud to support this scientific publishing model and thereby make societal advancements possible.

While publishing a peer-reviewed journal quarterly according to high scientific standards is certainly a challenging task for the volunteer editorial team, the high scientific standards maintained by Canadian Acoustics in its papers owe much to the continuing dedication of the journal's reviewers, who give freely of their time and expertise. We at Canadian Acoustics are proud of our 43 years of existence and of our +3000 peer-reviewed quality articles, from Canada and articles de qualité évalués par des pairs, provenant du Canada comme de l'étranger, et qui sont disponibles gratuitement en ligne pour tous les domaines de l'acoustique.

Enfin, tandis que je vais progressivement m'éloigner de mes responsabilités d'éditeur en chef pour laisser notre éditeur associé, le professeur Umberto Berardi, prendre la relève dès juin 2017 avec une nouvelle équipe éditoriale, je voudrais remercier Madame Cécile Le Cocq d'avoir accepté le rôle de Directrice de publication et de prendre en charge la production de la version électronique du journal grâce au système OJS et aux nombreux scripts Latex qu'elle a développés au cours des années. Je ne suis pas sûr d'avoir réussi à améliorer l'Acoustique canadienne, dans la mesure où mes prédécesseurs l'ont toujours bien gérée, mais je suis tout à fait fier de notre migration vers Open Journal System en 2012, qui a non seulement permis de faciliter le processus de révision et la publication en ligne de notre revue, mais a également grandement facilité les choses pour notre association, notamment en automatisant la gestion de la base de données des membres.

Et en parlant de membres, mon dernier mot vous est destiné, pour vous remercier de votre appui à l'Association canadienne d'acoustique et pour lire en ce moment l'Acoustique Canadienne!

Jérémie Voix
Rédacteur en chef

from abroad, that are now freely available online in all areas of acoustics.

On a final note, as I'll be progressively moving away from my Editor-in-Chief duties to let our current Deputy Editor, Prof. Umberto Berardi, come, in June 2017, into full power with a renewed editorial team, I would like to thank Dr. Cecile Le Cocq for accepting the role of Journal Manager and ensuring the production of the journal electronic copy using our OJS system and the many Latex scripts she developed over the years. I'm not sure if I succeeded to "Make Canadian Acoustics Great Again", as the journal has always been nicely handled by my predecessors, but I am definitely proud of our successful online migration in 2012 to the Open Journal System, that both streamlined the editorial process and electronic publication of our journal, but also made things much easier for our association by automating the management of its membership.

And speaking of members, my last word goes out to you, to thank you for supporting the Canadian Acoustical Association and reading our journal today!

Jérémie Voix
Editor-in-Chief


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EXTENDED OPTIMIZATION STUDY AND PANEL PARAMETER STUDY FOR NOISE RADIATION REDUCTION OF AN AIRCRAFT PANEL EXCITED BY TURBULENT FLOW

Steven A.J. Sonnenberg † and Joana Rocha ‡
Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, Ontario.

Résumé

Le bruit et les vibrations dans une cabine d'aéronef en conditions de croisière sont principalement causés par des excitations extérieures d'écoulement d'air de la Couche Limite Turbulente (CLT). La CLT provoque des vibrations sur les panneaux de fuselage de l'aéronef. Ces vibrations rayonnent de l'énergie sonore sous la forme de bruit. Par conséquent, il est intéressant de déterminer quel paramètre du panneau d'aéronef est le plus susceptible de diminuer la quantité d'énergie acoustique rayonnée afin de permettre l'optimisation de ces paramètres pour réduire le bruit dans la cabine. Un modèle analytique a été créé et validé à l'aide de Matlab pour calculer la Densité Spectrale de Puissance (DSP) de l'accélération, qui est proportionnelle à la Puissance Acoustique Rayonnée (PAR). Une étude de sensibilité paramétrique a été réalisée, afin de déterminer la variation de la DSP de l'accélération, en relation aux sept différents paramètres du panneau : épaisseur du panneau, la densité du matériau, la largeur et la longueur du panneau, le module d'élasticité, le coefficient de Poisson, et le coefficient d'amortissement. Une méthode analytique pour optimiser la performance acoustique d'un panneau d'aéronef est présentée, en changeant les propriétés du panneau, afin de réduire la DSP de l'accélération du panneau provoquée par la CLT. Il est montré que l'épaisseur et la densité du panneau sont les paramètres les plus cohérents et les plus susceptibles de réduire la DSP de l'accélération, dans différentes bandes d'octave dans la gamme des fréquences audibles.

Mots-clefs : Optimisation, Réduction du bruit, Puissance Acoustique Rayonnée, Couche Limite Turbulente, Acoustique structurelle

Abstract

The noise and vibration in an aircraft cabin during cruise conditions is mostly caused by external flow excitations from the turbulent boundary layer (TBL). The TBL causes the fuselage panels on the aircraft to vibrate. These vibrations radiate sound energy in the form of noise. Therefore, it is of interest to determine which aircraft panel parameter is most sensitive in decreasing the amount of radiated sound power and how to optimize these parameters to reduce the noise into the aircraft cabin. An analytical model was created and validated using Matlab that calculates the acceleration power spectral density (PSD), which is related to radiated sound power (RSP). A sensitivity study was performed on the panel parameters, to determine the change in acceleration PSD, in relation to change in seven different panel parameters: panel thickness, material density, panel width and length, Elasticity modulus, Poisson's ratio, and damping ratio. An analytical method to optimize an aircraft panel is presented, by changing the panel properties, in order to reduce the acceleration PSD of the panel caused by the TBL. As expected the panel thickness and the panel density are the most consistent, and effective parameters at reducing the acceleration PSD at different octave bands in the human hearing range.

Keywords: Optimization, Noise Reduction, Radiated Sound Power, Turbulent Boundary Layer, Structural Acoustics

1 Introduction

The noise and vibration in an aircraft cabin, during cruise conditions, is primarily caused by the external turbulent boundary layer (TBL) [1]. The TBL causes the fuselage panels on the aircraft to vibrate, which radiate sound energy in the form of noise in the cabin. In this context, the objective of the work is to determine which aircraft panel parameter(s) is/are most effective in decreasing the panel's radiated sound power, and how to optimize these parameters to reduce the noise in the aircraft cabin.

Many researchers have studied the prediction of the response of a simple panel due to the TBL. Strawderman and Brand have some of the earliest simulated results for a turbulent flow excited panel vibration [2]. Others have modelled the response of the plate using wavenumber-frequency formulations, or have used finite element and boundary element methods, where the plate is excited by a number of distributed forces having proper spatial and temporal correlations [3, 4, 5, 6].

One approach to calculate the radiated sound power (RSP) of vibrating structures is to use a modal analysis, as done by Roy and Lapi [7]. This approach is necessary when analyzing obscure shapes, but requires great computational power and time, making it difficult to iterate the calculations for optimization routines. Therefore, when looking at simple shapes, like that of a flat panel, analytical computational methods become a better choice. The analytical expressions for RSP can be derived for a given aircraft panel, in terms of the displacement power spectral density (PSD) [1, 8, 9]. The

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acceleration PSD is calculated from the displacement PSD, which is proportional to the RSP [9]. The analytical models developed were modified to account for other panel and enclosure combinations [10, 11]. Berry also showed that the same type of analytical analysis was possible for panels with arbitrary boundary conditions [12].

In the present work, an analytical model which calculates the acceleration PSD was developed in Matlab, based on previously developed models by the author [1, 8, 9, 10, 11]. The current study adds a step forward on previous analyzes by the author, by focusing on the use of these models to determine the effects of modifying aircraft panels' properties on the panel acceleration. In addition, an analytical optimization has been applied in order to determine the panel properties to which will result in higher panel acceleration PSD reduction caused by the TBL.

Optimization can be defined as a means to find the best solution among many feasible solutions that are available. Feasible solutions are those that satisfy all the constraints in the optimization problem [13]. An optimization problem can be defined mathematically as [13, 14]:

Minimize:

$$f(x) \tag{1}$$

Subject to:

$$g_i(x) \leq 0 \quad i = 1,2,\ldots,m < n \tag{2}$$

$$h_j(x) = 0 \quad j = 1,2,\ldots,r < n \tag{3}$$

$$x_l \leq x \leq x_u \tag{4}$$

Where x is a vector of n design variables given by:

$$x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \tag{5}$$

The function f, g_i and h_j are all differentiable. In the context of this study, $f(x)$ is the equation for acceleration PSD at a single point on the panel for a given frequency. The design variables (the seven panel parameters being investigated) are bounded by the lower and upper limits, x_l and x_u. The constraints in g_i are inequality constraints compared to the equality constraints in h_j. The constraints are functions of the design variables, and there must be less constraints than the number of design variables. For this initial study there are no constraints being used in order to determine general trends when optimizing the seven parameters. However, in future studies these will be the physical constraints of actual materials available for the construction of the panels. These constraints could be considered in future work, for a second phase of the research, since the panel elastic properties are intrinsic to existing materials, and a material with optimum properties obtained independently (i.e. density, elasticity modulus, Poisson's ratio, or damping coefficient) would not result in a realistic solution. If the design variables, between their bounds, can be proven to satisfy all of the constraints, then a feasible region exists. This feasible region is then solved to determine the optimal design variables, which minimize the objective function.

After the optimization problem can be defined, there are many options when it comes to solving the problem. Optimization algorithms are iterative. They begin with an initial guess and then continue to make improved estimates until the program terminates, hopefully when it has converged on a minimum. The process by which the algorithm selects the next estimate is the defining feature of the algorithm. Good algorithms should be robust, efficient and accurate [15] .

There are many free software codes available that can be used for optimization. The optimizing code used throughout this study is an add-on to Matlab. It uses an interior point algorithm for a nonlinear equation. The equations being analyzed are not linear functions, therefore no linear optimization equation could be used. An interior point algorithm is an approach to constrained minimization by solving a sequence of approximate minimization problems [16]. The name interior point methods means the iterations lie in the interior of the feasible region. This is different from the simplex method, which moves its iterations along the boundary of the feasible region from one extreme point to another [17]. Over the past 30 years interior point methods have been advanced, following the work by Karmarkar [18]. Many books have been written explaining the basics of the method, and the applications it has for both linear and nonlinear functions [19, 17, 20]. This type of algorithm has been used to solve for: optimal electrical power systems, shakedown analysis of pavements and power flow unsolvability [21, 22, 23]. The algorithm can be used in many types of applications and therefore it was selected as a way to obtain initial optimized design variables. In this work, this algorithm has been used to find the minimum acceleration PSD given seven panel parameters.

2 Methodology

The panel is assumed to be flat and simply supported on all four sides. A panel, in the context of an aircraft, might not be defined as the boundary of a sheet of material, but instead as the enclosed area on that sheet, between the stringers and the formers. The connections of the material to the stringers and formers cause that section of material to act as a single, simply supported panel. The vibration of a single panel can be defined as [1]:

$$w(x,y,t) = \sum_{m_x=1}^{Mx} \sum_{m_y=1}^{My} \alpha_{m_x}(x)\beta_{m_y}(y)\, q_{m_x m_y}(t) \tag{6}$$

α_{m_x} and $\beta_{m_y}(y)$ are spatial functions that define the variation in vibration and can be defined as follows, for a simply supported plate [1]:

$$\alpha_{m_x}(x) = \sqrt{\frac{2}{a}}\sin\left(\frac{m_x \pi x}{a}\right) \quad (7)$$

$$\beta_{m_y}(y) = \sqrt{\frac{2}{b}}\sin\left(\frac{m_y \pi y}{b}\right) \quad (8)$$

Where:

a = Panel Length [m]
b = Panel Width [m]
(m_x, m_y) = Plate Mode
$M = Mx * My$ = Total Number of Plate Modes Considered

The first step to calculating the acceleration PSD is to determine the panel modes and the natural frequency that corresponds with each mode, as follows [10]:

$$\omega_{m_x m_y}^{P} = \sqrt{\frac{1}{\rho_p h_p}\{D_p\left[\left(\frac{m_x \pi}{a}\right)^2 + \left(\frac{m_y \pi}{b}\right)^2\right]^2 + N_x\left(\frac{m_x \pi}{a}\right)^2 + N_y\left(\frac{m_y \pi}{b}\right)^2\}} \quad (9)$$

Where:

$$D_p = \frac{E_p h_p^3}{12(1-\nu_p^2)} \quad (10)$$

ρ_p = Panel Density [kg/m^3]
h_p = Panel Thickness [m]
ν_p = Poisson Ratio
N_x = Panel Longitudinal Tension [N/m]
N_y = Panel Lateral Tension [N/m]
E_p = Panel Elasticity Modulus [Pa]
D_p = Panel Bending Stiffness [Nm]

The dispersion equation (9) applies to a pressurized fuselage which will be analyzed in the future however, this equation can be simplified to assume that the panel is not under tension in either direction, which is the same assumption used for the validation case, in this study. This simplified equation can be seen below [10]:

$$\omega_{m_x m_y}^{P} = \sqrt{\frac{D_p}{\rho_p h_p}}\left[\left(\frac{m_x \pi}{a}\right)^2 + \left(\frac{m_y \pi}{b}\right)^2\right] \quad (11)$$

In order to determine how many modes are needed at a specific frequency, a convergence test must be completed. Convergence is reached when the distance between two nodes of the structural mode shape is less than, or equal to, half-wavelength, $\lambda/2$, of the bending wave on the plate at the analysis frequency [10]. These values must be rounded to the next highest whole number, to coincide with a plate modal number [10]:

$$N_{Max} = 2a/\lambda \quad (12)$$

$$M_{Max} = 2b/\lambda \quad (13)$$

$$\lambda = 2\pi\omega^{-0.5}\left(\frac{D_p h_p}{\rho_p}\right) \quad (14)$$

The convergence test determines the point at which additional panel modes does not change the overall shape of the final plot, but instead, appears to make the plot slightly noisier. By running a convergence test at every target frequency, it allows the program to limit the number of panel modes used for lower target frequencies, speeding up the computational time to run the program.

Rocha's Research is able to reduce a "coupled system governing equations into the following matrix form" [1]:

$$\begin{bmatrix} M_{pp} & 0 \\ M_{cp} & M_{cc} \end{bmatrix}\begin{Bmatrix} \ddot{q}(t) \\ \ddot{r}(t) \end{Bmatrix} + \begin{bmatrix} D_{pp} & 0 \\ 0 & D_{cc} \end{bmatrix}\begin{Bmatrix} \dot{q}(t) \\ \dot{r}(t) \end{Bmatrix} + \begin{bmatrix} K_{pp} & K_{pc} \\ 0 & K_{cc} \end{bmatrix}\begin{Bmatrix} q(t) \\ r(t) \end{Bmatrix} = \begin{Bmatrix} P_{tbl}(\omega) \\ 0 \end{Bmatrix} \quad (15)$$

This equation can be written as follows [1]:

$$Y(\omega) = H(\omega)X(\omega) \quad (16)$$

$$Y(\omega) = \begin{Bmatrix} W(\omega) \\ P(\omega) \end{Bmatrix} \quad (17)$$

$$X(\omega) = \begin{Bmatrix} P_{tbl}(\omega) \\ 0 \end{Bmatrix} \quad (18)$$

$$H(\omega) = \begin{bmatrix} -\omega^2 M_{pp} + i\omega D_{pp} + K_{pp} & K_{pc} \\ -\omega^2 M_{cp} & -\omega^2 M_{cc} + i\omega D_{cc} + K_{cc} \end{bmatrix}^{-1} \quad (19)$$

This matrix form assumes that the panel is simply supported, and encloses a cavity (like the panels surrounding the enclosed cabin of the aircraft). In this study, the approach taken to analyze the panel does not include the attached chamber since the objective is to compare panel parameters and not cavity parameters. Since the equation must be derived for only the panel, the equation can be reduced to:

$$H_w(\omega) = H(\omega) = \left[-\omega^2 M_{pp} + i\omega D_{pp} + K_{pp}\right]^{-1} \quad (20)$$

Where [1]:

$$M_{pp} = diag[\rho_p h_p] \text{ = Mass Matrix} \quad (21)$$

$$D_{pp} = diag[2\rho_p h_p \omega_m \zeta_p] \text{ = Damping Matrix} \quad (22)$$

$$K_{pp} = diag[\rho_p h_p \omega_m^2] \text{ = Stiffness Matrix} \quad (23)$$

Each of these matrices are of the size MxM. With this information, $S_{ww}(\omega)$ Matrix can be defined as follows [1]:

$$S_{ww}(\omega) = H_w^*(\omega)S_{tbl}(\omega)H_w^T(\omega) \quad (24)$$

In this equation, $S_{tbl}(\omega)$ is a generalized PSD Matrix of the TBL excitation, which has been derived into an analytical equation in Rocha's research, to allow for quick evaluation [1]. With this Displacement PSD Matrix, the Displacement PSD at a single point (taken to be the centre of the panel in all calculations for this study) can be calculated for a given frequency as follows [1]:

$$S_{WW}(x_1, y_1, x_2, y_2, \omega) = \sum_{m_{x_1}, m_{x_2}=1}^{M_x^2} \sum_{m_{y_1}, m_{y_2}=1}^{M_y^2} \alpha_{m_{x_1}}(x_1) * \alpha_{m_{x_2}}(x_2) * \beta_{m_{y_1}}(y_1) * \beta_{m_{y_2}}(y_2) * S_{ww}(\omega)_{m_1, m_2} \quad (25)$$

The equations required to calculate the Velocity (S_{VV}) and the Acceleration PSD (S_{AA}), at a single point on the panel are as follows [9]:

$$S_{VV} = \omega^2 * S_{WW} \quad (26)$$

$$S_{AA} = \omega^4 * S_{WW} \quad (27)$$

To show that calculating either S_{WW}, S_{VV}, or S_{AA} will give direct correlations to how it effects the RSP of a panel, the basic equations required to calculate RSP have been provided [8, 24]:

$$RSP(x_1, y_1, x_2, y_2, \omega) = \sum_{m_{x_1}, m_{x_2}=1}^{M_x^2} \sum_{m_{y_1}, m_{y_2}=1}^{M_y^2} \psi_{m_{x_1}}(x_1) * \psi_{m_{x_2}}(x_2) \; \phi_{m_{y_1}}(y_1) * \phi_{m_{y_2}}(y_2) * \prod(\omega)_{m_1, m_2} \quad (28)$$

$$\prod(\omega) = S_{VV} * M(\omega) \quad (29)$$

$$M(\omega) = 8\frac{\rho_0}{c_0}\left(\frac{\omega ab}{\pi^3 m_x m_y}\right)^2 \int_0^{\pi/2}\int_0^{\pi/2} \left\{\frac{\frac{\cos}{\sin}\left(\frac{\alpha}{2}\right)\frac{\cos}{\sin}\left(\frac{\beta}{2}\right)}{\left[\left(\frac{\alpha}{m_x\pi}\right)^2-1\right]\left[\left(\frac{\beta}{m_y\pi}\right)^2-1\right]}\right\}^2 \sin\theta \, d\theta d\emptyset \quad (30)$$

These equations show that the RSP is related to S_{VV}, so that any conclusions made from the sensitivity study on S_{AA}, will be related to the RSP. This allows for meaningful conclusions to be made about RSP without having to run a more time intensive program.

3 Results

A sensitivity study was performed on seven panel parameters, to determine which parameter is most effective at reducing the acceleration PSD in select octave bands. The parameters were varied individually while maintaining the other variables at their initial values, and the changes in the acceleration PSD in each of the octave bands were analyzed. In the present study, no constraints have been considered (one parameter relative to another), in order to determine the general trends when optimizing each of the seven individual parameters. Future work could consider these constraints. The following octave bands (in the human hearing range) have been analyzed: 89.1-178 Hz, 178-355 Hz, 355-708 Hz and 708-1410 Hz. The sensitivity study was run for seven parameters: thickness, material density, panel width and length, elastic modulus, Poisson's ratio and damping ratio.

Table 1 contains the initial panel parameters used in the sensitivity study and Figure 1 to Figure 4 contain the sensitivity studies, for each of the octave bands.

Table 1: Initial panel parameters for optimization.

Variable	Value
Length	0.46 m
Width	0.33 m
Thickness	0.0048 m
Elasticity Modulus	$6.5 * 10^{10}$ Pa
Density	1.225 kg/m^3
Poisson's Ratio	0.3
Damping Ratio	0.01

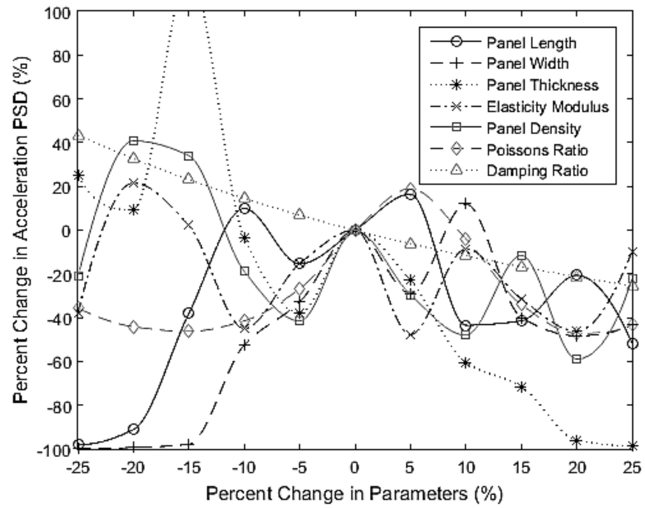

Figure 1: Percent change in acceleration PSD versus percent change in panel parameter for octave 89.1-178 Hz with limited Y-axis extents.

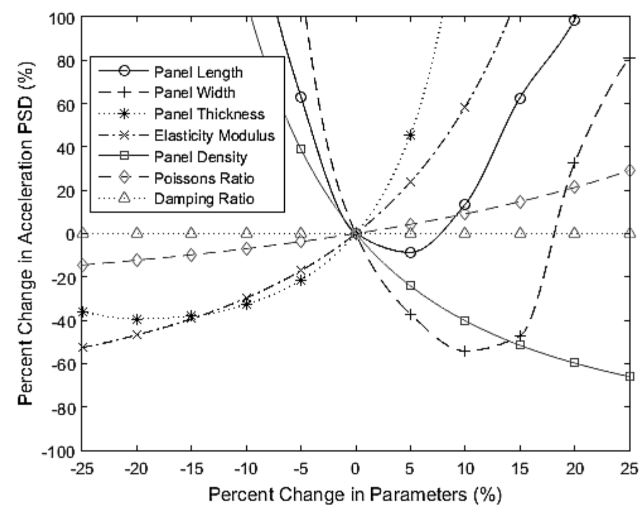

Figure 2: Percent change in acceleration PSD versus percent change in panel parameter for octave 178-355 Hz with limited Y-axis extents.

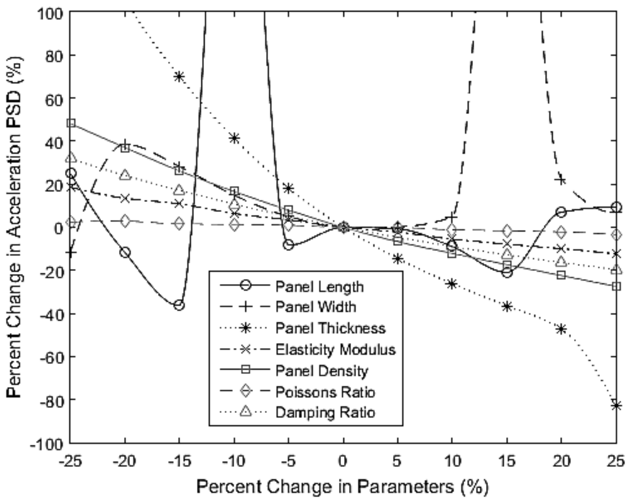

Figure 3: Percent change in acceleration PSD versus percent change in panel parameter for octave 355-708 Hz with limited Y-axis extents.

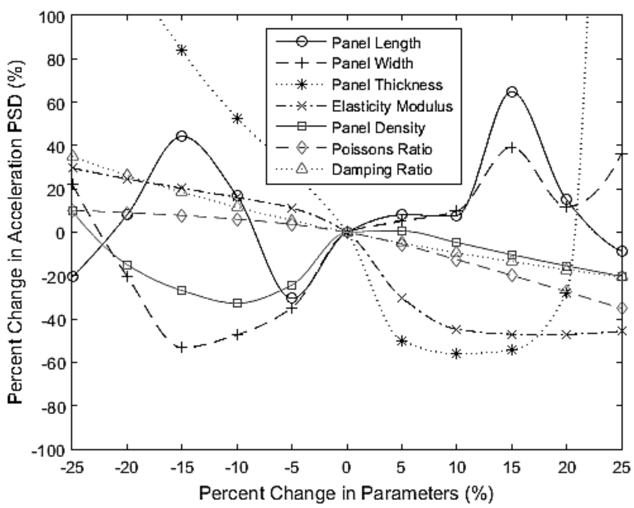

Figure 4: Percent change in acceleration PSD versus percent change in panel parameter for octave 708-1410 Hz with limited Y-axis extents.

It can be seen from Figure 1 that there is a very low correlation between change in panel parameters and change in acceleration PSD at frequencies, between 89.1-178 Hz. This could be due to the low number of panel modes existent at low frequencies. This can be seen as well from the convergence criteria [10], when one observes that decreasing the frequency, less panel modes are required to achieve convergence. When the parameters are modified at these lower frequencies, it allows for the convergence test to result in values less than one. Therefore, the octave band 89.1-178 Hz will be ignored when determining which panel parameter is most sensitive to changing the acceleration PSD.

As shown in Figure 2 to Figure 4, both the panel width and length have fluctuating values. These fluctuations are believed to occur because the panel width and length are main components of calculating $S_{tbl}(\omega)$. The variables are located within sinusoidal functions, with the change in these parameters being non-linear. For this reason, these parameters cannot be defined by a simple trend, and therefore, are not the most sensitive at reducing the overall acceleration PSD.

It was found that the two parameters that are the most effective for reducing the average acceleration PSD, within the different octave bands, are panel thickness and panel density, as these two parameters have the steepest slopes. As the thickness is increased, the higher frequency noise is reduced, as expected. However it has less effect on the lower frequency (longer wavelength) signals. Even though the panel density has more gradual slopes in comparison to the panel thickness, the trend is more consistent across all of the analyzed octave bands. Hence, it is likely that panel density is the most sensitive at reducing the overall noise across the human hearing range, whereas thickness may be the most sensitive at reducing the noise at certain octave bands.

The analysis was then modified to determine the optimal panel parameters that resulted in the smallest average acceleration PSD over the octave band. The analysis is used to optimize each of the seven parameters individually, and concurrently. Since the general trend of the sensitivity studies predicts that the minimum acceleration PSD is reached when both the thickness and the density are maximized to the upper constraint, optimizing these parameters individually simply results in the upper constraint. Therefore, it is of more interest to determine if there is a correlation between the octave band and the panel length. Figure 5 shows the optimal panel length at the center frequency, of different octave bands, and compares these values to the calculated flexural wavelength, convective wavelength and acoustic wavelength, at the same frequencies.

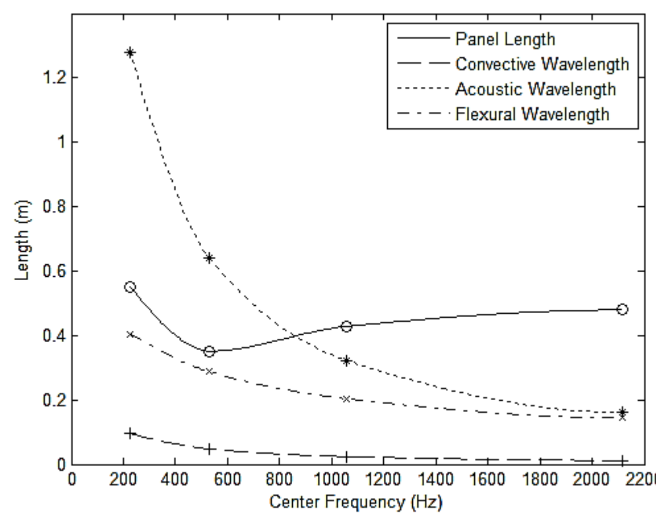

Figure 5: Optimal panel length at the center frequency of different octave bands that result in a local minimum average acceleration PSD compared to the calculated flexural wavelength, convective wavelength and acoustic wavelength.

It was predicted that the optimal panel length would be related the flexural wavelength, convective wavelength and acoustic wavelength; however, Figure 5 does not support this hypothesis. The optimization routine currently finds local minimums in the constrained space, rather than the global minimum. It also shows that by averaging over an entire octave band it becomes difficult to see the exact correlation between the panel length and the frequency.

Two modifications to this approach were then taken to get a better understanding of the relationship between frequency and optimal panel length. The first change was to modify the optimizing routine, to ensure that the overall global minimum was being determined, and to ensure the resulting length was not just the location of a local minimum occurring at some multiple of the wavelength. The second modification was to calculate the optimal panel length, for a single frequency, instead of over an entire octave band. This allows for a more detailed curve to be plotted for length versus frequency. Figure 6 shows the result of this new optimization study, over the first two octave bands previously investigated.

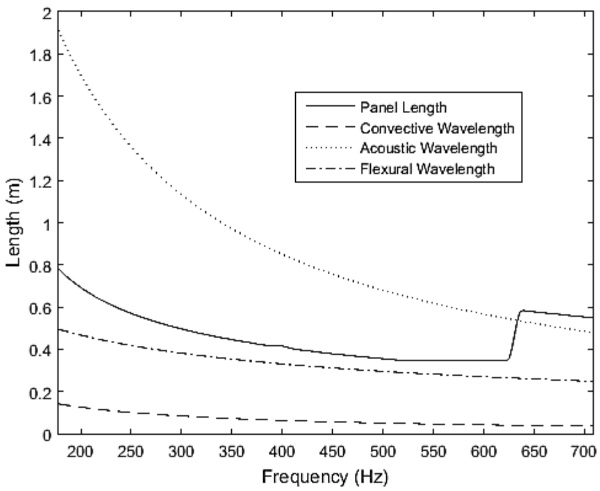

Figure 6: Optimal panel length at individual frequencies that result in a global minimum average acceleration PSD compared to the calculated flexural wavelength, convective wavelength and acoustic wavelength for two octave bands.

Figure 6 shows that there are additional panel lengths that result in local minimum acceleration PSDs and that the optimal panel length that results in the true global minimum, follows the same exponential decay as the flexural wavelength, convective wavelength and acoustic wavelength. From 178 Hz to 500 Hz the global minimum acceleration PSD is found at panel lengths that follow the expected exponential decay. From 500 Hz to 625 Hz the optimization routine levels off at the lower bound of the design space for the optimization routine. The lower bound was decreased as low as it could while running this routine. The lower bound cannot be decreased any farther because of the convergence test. If the panel length is set too small, the convergence test results in a very small number. This means only a few panel modes are used to calculate the acceleration PSD. This causes inaccurate values to be predicted for the acceleration PSD and skews the optimization data. From 625 Hz to 708 Hz there is a shift in the plot. Since the true global minimum would be found below the lower bound of the integration, the optimizing routine finds a local minimum which is now smaller than the acceleration PSD at the lower bound. The local minimum found is approximately equal to two times the expected global minimum. Therefore, there are local minimums at multiples of the optimal panel length.

Figure 7 shows the result of the optimization study, over the four octave bands.

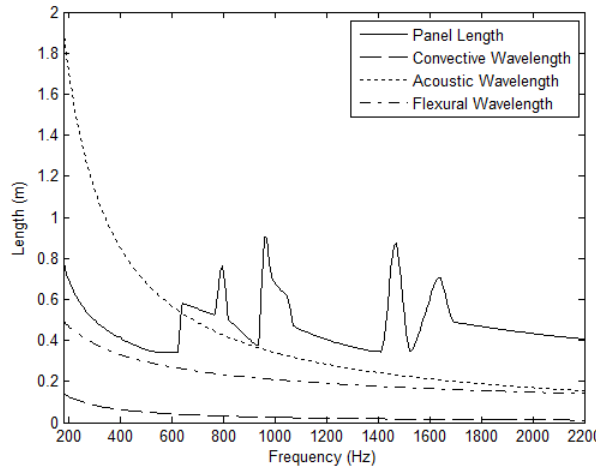

Figure 7: Optimal panel length at individual frequencies that result in a global minimum average acceleration PSD compared to the calculated flexural wavelength, convective wavelength and acoustic wavelength for four octave bands.

From Figure 7 it can be seen that, at certain frequencies, the optimizing model does not find global minimums at lengths which correlate with the convective, acoustic or flexural wavelengths. These regions also coincide with the peaks in the acceleration PSD for the lengths in this study (these same peaks are observed in Rocha's earlier work, associated to the "Validation Case 2" in Figure 5 [1]). At these regions, the peaks shift as the panel length changes making it difficult to determine an optimal panel length. It is found that the length at which the peak shifts farthest away, and not converging to the length that has minimized the amplitude of the peak. However, by moving away from these regions, the lengths still follow the same exponential decay as the convective, acoustic and flexural wavelengths at multiples of the expected optimal panel lengths.

4 Conclusion

An optimization study is presented, with the objective to reduce the acceleration PSD of a panel excited by a TBL by optimizing the panel's length. It has been shown that the optimal panel length that results in the true global minimum, follows the same exponential decay as the flexural wavelength, convective wavelength and acoustic wavelength. It has also been shown that at multiples of the optimal panel length local minimum acceleration PSDs occur. The sensitivity study indicates that panel thickness and panel density are the most consistent, and effective parameters at reducing the acceleration PSD at different octave bands in the human hearing range.

The next step of this research would be to see if the optimal panel width is also a function of the flexural wavelength, convective wavelength and acoustic wavelength. It would also be of interest to continue the sensitivity study into the higher octave bands to determine if panel thickness and density are still the most consistent, and effective parameters at reducing the acceleration PSD.

The optimization model described in the current paper will be useful in the earlier stages of aircraft design, by helping the designer to select panel configurations that reduce the amount of noise due to the TBL inside the cabin of the aircraft.

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USING OPTICAL FLOW ANALYSIS ON ULTRASOUND OF THE TONGUE TO EXAMINE PHONOLOGICAL RELATIONSHIPS

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Résumé

Cet article examine s'il existe des corrélats articulatoires correspondant aux divers degrés d'une opposition phonologique. On y démontre qu'en anglais, l'amplitude des mouvements impliqués dans l'articulation des voyelles tendues en syllabe ouverte (où elles sont généralement en opposition avec les voyelles relâchées) est supérieure à celle observée en syllabe fermée (où cette opposition est moins marquée). Une analyse de flux optique appliquée à des vidéos échographiques de mouvements de la langue a permis de déterminer l'amplitude de ces mouvements. L'avantage de ce type d'analyse est qu'elle permet une comparaison directe entre les locuteurs et l'obtention de mesures pendant toute la durée d'une production donnée.

Mots clefs : échographie, flux optique, opposition, allophony, voyelles

Abstract

This paper examines whether there are articulatory correlates of differing degrees of phonological contrast. English tense vowels are found to be produced with greater average magnitudes of movement when they occur in closed syllables, where they are generally contrastive with their lax vowel counterparts, than when they occur in open syllables, where they are less contrastive. Magnitude of tongue movement was determined by optical flow analysis of ultrasound videos of tongue movements; optical flow analysis allows for direct comparison of results across speakers and for the extraction of data from the entire timecourse of productions.

Keywords: ultrasound, optical flow, contrast, allophony, vowels

1 Introduction

It is well established that sounds that are contrastive in a given language are often perceived as being more distinct from each other than sounds that are not contrastive in that language, based on reaction times in discrimination tasks and overt similarity rating judgments (e.g., [7], [21], [22], [23], [32]). The conventional wisdom is that these are differences only in the way that sounds are perceived by listeners, rather than reflections of any differences in the way contrastive vs. non-contrastive pairs are produced. Indeed, some studies (e.g., [7]) have found different perceptual results while using acoustically identical stimuli. There is also, however, a small body of evidence that such differences may in fact be encoded acoustically in certain contexts (e.g., [1], [9], [11]). These latter studies share a common result: sounds that are more contrastive in some sense are at least somewhat hyperarticulated relative to their less contrastive counterparts (see §2 for more on quantifying contrastiveness). The results are not entirely conclusive, however. Gick et al. [11] used only one speaker and did not test whether the difference was statistically significant. Goldrick et al. [12] found that the statistically significant results of Baese-Berk and Goldrick [1] hold for only some phonetic distinctions in some phonological contexts (e.g., VOT distinctions are enhanced for contrastive voiceless stops in initial position, but not for voiced stops). Cristia and Seidl [9] did find consistent differences between phonemic and allophonic pairs of sounds, but found differing results in infant-directed vs. adult-directed speech.

The present paper probes the possibility that there are production differences in regular adult speech that are dependent on the degree of contrast of various sounds. In particular, we examine the possibility of articulatory differences in production using ultrasound imaging. The main research question to be addressed, then, is whether the contrastive status of sounds affects their articulation, with the prediction that contrastive sounds will be articulatorily more distinct than non-contrastive ones. In doing so, we describe the use of optical flow analysis on ultrasound data of tongue movements as a means of extracting time-varying, normalizable data from a relatively large number of participants.

2 Degrees of Phonological Contrastiveness

We predicate this study on the assumption that phonological contrastiveness is a gradient phenomenon (e.g., [14], [15], [25]). Two of the primary ways in which contrast is defined are lexical distinction and predictability of distribution, each of which is traditionally treated categorically but can be treated gradiently instead. Typically, lexical distinction is categorical in the sense that if there is at least one (near) minimal pair that hinges on some pair of sounds, that pair of sounds is deemed to be contrastive. The measure of the *functional load* of a contrast is a gradient instantiation of the same concept: pairs of sounds that distinguish more lexical items have a higher functional load than pairs that distinguish fewer items (see, e.g., [19], [30], [34]). Although there are several methods of calculating functional load, Wedel et al. [34] provide evidence that a simple count of the number of minimal pairs hinging on a contrast (relative to the number of lexical items in a corpus) is an adequate measure, and illustrate its utility in predicting the likelihood of merger: cross-linguistically, pairs of sounds with higher functional loads are less likely to undergo merger than those with lower functional loads.

Traditionally, predictability of distribution is also treated as a categorical parameter: either two sounds are entirely predictably distributed (i.e., in complementary distribution) and are therefore allophonic, or they are not entirely predictably distributed (i.e., there is at least one phonological context in which the occurrence of one vs. the other is not predictable) and are therefore contrastive. Hall [14], however, proposes a gradient measure of predictability of distribution, using the information-theoretic concept of *entropy*, or uncertainty. This measure has been shown to be helpful in documenting phonological changes in progress ([16]), modeling variability in production ([31]), and understanding synchronic phonological harmony patterns ([13]). When applied to two sounds, *a* and *b*, in a phonological relationship, entropy can range between 0 and 1. An entropy of 0 indicates that there is no uncertainty about which of the two sounds occurs in any given context, and is analogous to perfect allophony. An entropy of 1 indicates that *a* and *b* are in perfectly overlapping distributions, and is analogous to perfect contrast.

The sounds of interest for the current study are the tense vowels [i], [u], [o], and [e] in English, which are generally contrastive with their lax vowel counterparts in closed syllables (e.g., there are minimal pairs such as *beat* [i] vs. *bit* [ɪ]; *bayed* [e] vs. *bed* [ɛ]; *who'd* [u] vs. *hood* [ʊ]; *node* [o] vs. *gnawed* [ɔ]). This contrast is largely neutralized in word-final open syllables, however, with only the tense vowels occurring (e.g., *bee* [i] but *[bɪ]; *bay* [e] but *[bɛ]; *who* [u] but *[hʊ]).[1] Thus, the environments of interest are open vs. closed monosyllabic words; all but one of the stimuli in the experiment were monosyllabic, and using only monosyllables avoids the issue of determining syllable structure in the possible presence of ambisyllabic segments. Both functional load (minimal pair count) and predictability of distribution (entropy) were calculated on a subset of the IPHOD corpus ([30]) containing all and only monosyllabic words of English that have a frequency of occurrence of at least one per million using the SUBTLEX frequencies [8] [N = 238 open + 4102 closed = 4340 total uniquely transcribed monosyllables]. The minimum frequency threshold was used to eliminate extremely rare words, such as *thane* or *yaw*, which may not even be known to all speakers, from influencing the calculations; the overall pattern of results is quite similar if such words are included, however. Following [34], homophones were not distinguished (e.g., 'fit' / 'feat' and 'fit' / 'feet' were counted as a single minimal pair). The actual calculations of both functional load and entropy were carried out using the *Phonological CorpusTools* software ([17]). The results are given in Tables 1 and 2.

Table 1: Functional load of tense vs. lax vowels in closed and open monosyllables in IPHOD.

Vowel Pair	Functional Load	
	Closed Syllables	*Open Syllables*
[i] / [ɪ]	98	0
[e] / [ɛ]	86	0
[o] / [ɔ]	41	7
[o] / [ɑ]	56	17
[u] / [ʊ]	8	0

Table 2: Predictability of distribution of tense vs. lax vowels in closed and open monosyllables in IPHOD.

Vowel Pair	Pred. of Dist.	
	Closed Syllables	*Open Syllables*
[i] / [ɪ]	0.95	0.00
[e] / [ɛ]	0.996	0.00
[o] / [ɔ]	0.99	0.67
[o] / [ɑ]	0.97	0.91
[u] / [ʊ]	0.80	0.00

As can be seen, the pair [u] / [ʊ] is distinct from the other pairs in both measures, looking within the set of closed monosyllables. In terms of functional load, there are only 8 minimal pairs hinging on the [u] / [ʊ] distinction, compared to 41–98 pairs for the other three vowels. In this measure, then, this pair is much less contrastive than the other tense-lax pairs. Similarly, there is a much lower entropy value (by 0.15 bits) in closed syllables for the pair [u] / [ʊ] than there is for any of the other three pairs. Both of these measures clearly indicate that the phonological function of this contrast is much weaker than that of the other contrasts: fewer lexical items hinge on this contrast, and if one were given a random closed monosyllabic word of English from a dictionary, it would be easier to guess which of this pair occurs than it would for any of the other three pairs.

The pair [o] / [ɔ] is also distinct from the other three in that it is not non-contrastive in open monosyllables (it has a non-zero functional load and predictability of distribution); rather, it offers an example of a contrast that is simply *weaker* in open syllables than in closed ones. It should be noted, however, that most of the participants in the current

[1] Interestingly, this neutralization occurs for [i]/[ɪ], [u]/[ʊ], and [e]/[ɛ], but not for [o]/[ɔ]; minimal pairs can occur for the latter even in final position (e.g., *know* [o] vs. *gnaw* [ɔ]). This is true even on the assumption of an [ɔ] / [ɑ] merger, in which case the relevant contrast for the current study is [o] / [ɑ]; this will be addressed below.

study had, at least impressionistically, an [ɔ] / [ɑ] merger, which is certainly not surprising given the fact that the experiment was conducted in western Canada (see, e.g., Labov et al. [24] : 60). This is not directly a problem, in that the vowels of interest in the study are actually the *tense* vowels, but it does mean that measuring the strength of the relevant tense/lax contrast is somewhat more complicated. Specifically, the lax vowel counterpart of [o] for these speakers may be [ɑ], which means that *all* [ɑ]-containing words must be taken into account and not just those that historically contained [ɔ]. The tables above therefore also show the functional load and predictability of distribution calculations for [o] / [ɑ], under the assumption of an [ɔ] / [ɑ] merger. Including these additional [ɑ] words does not in fact change much about the calculations; this pair is still more contrastive than [u] / [ʊ] and less contrastive than [i] / [ɪ] or [e] / [ɛ] in closed syllables, and is still the only pair of the four that is contrastive in open syllables. The primary difference is that the magnitude of the difference in the contrast between closed and open syllables is much smaller if one assumes that there is a merger. That is, while it is still the case that [o] / [ɑ] is less contrastive in open syllables than closed syllables, the two environments are more similar to each other in the merged data than they are in the unmerged data, especially with respect to predictability of distribution.

We now turn to the ultrasound study used to examine whether these differences in contrastiveness have articulatory consequences.

3 Methodology

Stimuli consisted of 78 English target words with tense vowels in stressed word-final syllables. All but one of these words were in fact monosyllabic; the one exception was the word *delay*, which has [e] in a final stressed open syllable. There were 10 closed-syllable words for each of [i], [e], [u], and [o], and 10 open-syllable words for each of [i], [e], and [o], plus 8 open-syllable words for [u]. Additionally, there were 46 filler words with lax vowels in stressed word-final syllables, all monosyllabic. Within these, there were 10 words with each of [ɪ] and [ɔ] in closed syllables; 11 with [ɛ] in closed syllables; 8 with [ʊ] in closed syllables; and 7 with [ɔ] in open syllables. All stimuli are presented in Appendix A.

Twenty-four female speakers participated in the study. It has been suggested (Eric Vatikiotis-Bateson, p.c.) that ultrasound imaging might be clearer for female rather than male speakers because of the generally higher degree of calcification in males as compared to females (e.g. [27]). Ten of the 24 participants were excluded from analysis either because of evidence that they were non-native speakers of standard North American English (e.g., having grown up outside of North America or reporting an alternative first language) and/or because of technical difficulties during recordings. This left a total of 14 participants, who were between the ages of 18 and 26, with an average age of 21.5. Participants were paid $20 each for their participation. No included participants reported any speech or hearing difficulties.

Participants were tested one at a time. They were seated in a fixed chair with a headrest to help minimize movement during the experiment while still allowing for natural productions. An Aloka SSD–5000 ultrasound machine was used to collect ultrasound. A UST–9118 endovaginal 180° electronic curved array probe was placed firmly under the participant's chin. The probe was positioned roughly halfway between the chin and the neck, at approximately the midline (sagittal) position, at an approximately 90° angle to the floor (all aspects judged by two experimenters, viewing from both the front and the side). Slight adjustments to the probe position and pressure under the chin were made to ensure the ultrasound image captured the entire tongue and was as clear as possible. After this point, participants were asked to be as still as possible during the recording. The probe was held with a mechanical arm, which was connected to a pole adjacent to the chair, with a layer of ultrasound gel between the probe and the skin. Two-dimensional mid-sagittal ultrasound video recordings of the tongue were recorded digitally directly to an attached computer at a rate of 30 frames / second.

Productions were simultaneously audio-recorded onto the computer recording the ultrasound data, using a Shure SM63LB Dynamic handheld microphone placed in a floor-stand approximately 18 inches from the participant's mouth. Both the audio and video recordings were made in iMovie.[2]

A laptop computer was placed at a comfortable viewing distance in front of the participant. Stimuli were presented one word at a time on the screen, with one of the experimenters advancing to the next word after it had been produced by the participant. The 124 total stimuli were presented one time through, in random order, though it should be noted that the first four participants (all of whom were included in the final data analysis) happened to see the words in the *same* random order as each other.

4 Analysis techniques

The ultrasound video images were subjected to optical flow analysis (OFA; e.g., [3], [10], [18], [20], [26]), using *FlowAnalyzer* software developed by Barbosa [2], which uses the implementation of OFA described in [3]. OFA provides a way of measuring apparent motion by comparing the difference in brightness of individual pixels from frame to frame.

Consider Figure 1, from Fleet and Weiss ([10]: 10). Figures (1a) and (1b) show two adjacent frames in a video, where the lips have progressed from being more closed to more open. Figure (1c) shows the optical flow field associated with this frame sequence; each pixel is associated with a vector showing apparent motion between frames. This example, of course, illustrates using OFA on direct video of the articulators; in the current study, we applied OFA to ultrasound videos of the tongue rather than video of the tongue itself.

[2] iMovie '11 (vers. 9.0.9), available from Apple Inc., running on Mac OS X 10.10.5.

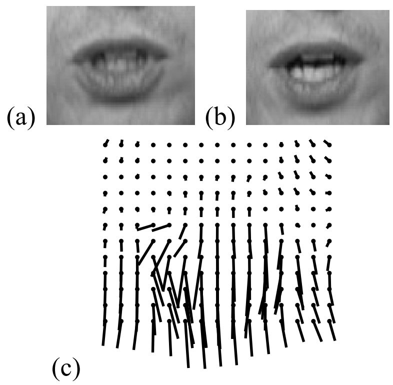

Figure 1: Optical flow field (c) resulting from the apparent motion between adjacent video frames (a)-(b), from Fleet and Weiss ([10]: 10).

OFA has several advantages over standard measures of articulatory posture, especially for the purposes of the present research question. OFA allows for the extraction of information from the entire production of a sound or word, rather than using still images from pre-designated timepoints within the production. Thus, for productions where there is no *a priori* reason to suspect that differences would be localized to particular temporal regions, OFA permits researchers to look for differences throughout. It is also possible to obtain measurements from different physical regions of the video (e.g., isolating the tongue tip, body, or root) separately, to examine effects on these various regions independently, though one can also examine the video as a whole. Furthermore, OFA is relatively fast and automatic (see also [26]). While it may still be necessary to annotate accompanying sound files in order to determine the timepoints of particular intervals of interest, OFA drastically reduces the overall amount of time needed to analyze ultrasound data. Indeed, it makes it possible to analyze ultrasound video data with roughly the same efficiency as acoustic data. Finally, OFA allows for direct comparison of measurements across speakers, which is often not the case for articulatory posture data (though cf. [35] for an example of normalization across tongue curves). OFA data can easily be normalized within a speaker, using, for example, a standard z-score normalization, which then allows data to be pooled across participants.

In order to analyse the data in this study, the audio was first extracted to .wav files from the video recordings of each speaker, using a Python script.[3] The target vowel in each word was identified and delimited using a *Praat* TextGrid ([6]). Vowel boundaries were identified by looking for clearly visible formant structure and increased intensity as compared to the surrounding sounds. Interval boundaries were placed at zero-crossings of the waveform.[4]

FlowAnalyzer was used to extract OFA information from the complete ultrasound video files. No particular regions were specified; movement from all regions of the tongue were included (i.e., movement from the entire video image), as there was no *a priori* expectation that any regions of the tongue would be more likely than others to demonstrate differences based on contrastive status; this is precisely one of the reasons that this type of generalized OFA is advantageous as compared to either edge-tracking analyses or even other types of OFA such as that used in [26]. As described in detail in [3], *FlowAnalyzer* reduces the high-dimensionality of a full optical flow field (with a separate measurement for each pixel in an array) to a single dimension by summing the magnitudes of movements of all of the pixels between a single pair of frames (a ‘frame-step’) to result in one total magnitude measure for that frame-step, given in number of pixels moved, as shown in (1).

(1) Single magnitude measure for the n-th region of interest at time k, where «$\| \ \|$ denotes the vector magnitude, and x_i, x_f, y_i, y_f are the initial and final boundary positions of the region of interest in the horizontal and vertical directions, respectively » (Barbosa et al. [3] : p. 174, eq. 2)

$$v_n(k) = \sum_{x=x_i}^{x_f} \sum_{y=y_i}^{y_f} \left\| \vec{v}(x,y,k) \right\|$$

This number is then divided by the number of pixels in the given region of interest, to result in a mean magnitude of movement, in pixels, for a given frame-step.

Note that the measure « magnitude-per-frame-step » is not directly a measure of magnitude of movement (i.e., a distance measure); it is instead a measure of the *rate* of movement, being a measure of distance (magnitude, i.e., number of pixels) per unit time, where the time is one frame-step.[5]

[3] Specifically, conversion was done using the convert_mov_to_wav.py script in the Ultrasound Analysis package available (March 2017) here : https://github.com/bhallen/ultrasound-analysis/, which in turn makes use of the FFmpeg software, available (March 2017) at http://www.ffmpeg.org/.

[4] Note that unfortunately, the quality of the acoustic recordings accompanying the ultrasound videos in this study is not particularly good. Recordings were made in an open room rather than a sound-attenuated booth, with the microphone relatively far away from the participants, and there was a fair bit of background noise. While the recordings were good enough to allow for rough delimitation of the edges of vowels (and with a frame rate in the video of only 30 frames per second, a high level of resolution isn’t needed), more fine-grained analysis (e.g., of the formant structure of vowels in open vs. closed syllables) is not possible.

[5] We are deeply grateful to an anonymous reviewer for extensive discussion of this point and its implications. This should not be confused with saying that these are the velocities within a given frame; that would be obtained by multiplying the magnitude in the frame-step by the frame rate (30 fps), to result in a measure of how fast the pixels were moving in a particular frame, in pixels per second.

The output of the software is a table of values, one per frame in the video, giving the timestamp of the frame along with the mean magnitude of movement in the x- and y-dimensions for that frame-step, along with the mean total magnitude measure for the frame-step. (Note that these are indeed *magnitude* measures per frame-step and do not include information about the directionality of movement—that is, an upward movement followed by a downward movement of the same distance will have twice the magnitude, rather than having a measure of zero.)

This dimensionality reduction is different from other implementations of optical flow analysis (e.g., [26]), which generally maintain more of the details within the field. As Barbosa et al. [3] : 174 explain, however, « the temporal variation of this seemingly impoverished measure is surprisingly well-coordinated with time-varying measures made in other domains (for example, the RMS amplitude of the speech acoustics) »; see also discussion in [4]. For the present purposes, the reduction is particularly advantageous because the question is really whether there is a correlation between the magnitude of the phonological contrast and the magnitude of tongue movement as a whole, so having a single dimension for each side of the correlation is beneficial. If one wanted to know more specifics about the *mechanics* of the movement and especially about either the directionality or the differences across different regions of the tongue, then a less reductionist approach would be preferable.

Returning to the current analysis, each vowel consists of some (differing) number of frames, but each frame-step encapsulates the same duration from one frame to the following frame. In order to get the total magnitude of tongue movement in a particular vowel gesture, then, the mean magnitudes per frame-step must be summed over all the frame-steps in the vowel. This summation allows one to look for a direct correlation between the magnitude of the phonological contrast and the magnitude of tongue movement.

The drawback of this summative approach from an analysis perspective is that longer vowels have more frames that go into the calculation of total magnitudes, and could possibly show greater magnitudes simply because of a longer duration for reasons other than the degree of their phonological contrastiveness.

To unpack this, consider the experimental hypotheses. Under the null hypothesis that tense vowels are articulatorily the *same* in contrastive and non-contrastive positions, there are two primary possibilities for how this « sameness » could manifest itself in a way measurable by OFA : either the total magnitudes could be the same, or the magnitudes-per-frame-step could be the same. In the former case, longer vowels would show equal total magnitudes as shorter vowels, but would therefore have to have smaller magnitudes per frame-step to compensate. In the latter case, longer vowels would have the same magnitudes-per-frame-step as shorter vowels, but would therefore end up with larger total magnitudes. The logical alternative hypotheses here are that tense vowels in contrastive positions have greater total magnitudes than those in less-contrastive positions, but not simply because they are longer; or that vowels in contrastive positions have greater magnitudes-per-frame-step, but not simply because they are shorter.

Given that in the current dataset, the contrastive vowels are in closed syllables, they are independently shorter on average than their open-syllable, non-contrastive (or less-contrastive) counterparts. Specifically, vowels in closed syllables were an average of 7.72 frames long, while those in open syllables averaged 9.85 frames, which is statistically significantly longer [$t(970.6) = 13.58$, $p < 0.001$]. Similar statistically significant differences are found for each vowel quality individually. This difference in duration makes it impractical to directly compare either total magnitudes or magnitudes per frame-step, as differences could be attributed to durational differences rather than contrastive status.

To test for the effects of contrastive status, then, we run linear mixed-effects regressions in which both duration and contrastive status will be used to predict total magnitude of movement.[6] By first showing that these two predictors are not collinear with each other, and then showing that each has a statistically significant effect on magnitude, we conclude that the total magnitude of tongue movement is dependent on the contrastive status of the vowel's position.

Praat TextGrids were used to determine the time stamps of the beginning and end points of each of the target vowels. These frames were then extracted from the output of the OFA data, giving a list of mean magnitude of movement per frame-step for each frame contained within a target vowel, for each speaker. Only the total mean magnitudes for each frame-step were included, not individual horizontal and vertical magnitudes.

It is quite likely that individual speakers vary widely in their actual movements during production, given different anatomy and speech styles. Thus, the per-frame-step magnitude data for each speaker was subjected to a z-score normalization, such that the mean magnitude of movement per frame-step across all vowels for each speaker was set to 0, with a standard deviation of 1. To then calculate the total magnitude of movement in any particular vowel, the normalized values for all frame-steps in that vowel were summed. This normalization allows for direct comparison of data across speakers.

5 Results

The summed normalized magnitude of movement data for each of the four tense vowels in closed vs. open syllables is shown in Figure 2. There is one (summed) measurement per word per speaker in each box, e.g., 10 words * 14 speakers = 140 tokens for [i] in open syllables. Outliers of more than three standard deviations from the mean total for a given vowel were removed; there was one such outlier for [e] and

[6] We note that we did also do the analyses on the magnitude-per-frame-step measures as well, with similar global results, i.e., in both cases, we find a statistically significant effect of contrastive status separate from that of duration, in the phonologically expected manner.

two each for [o] and [u]. As can be seen, the total normalized magnitude of movement is greater in closed syllables than in open syllables for [i], [e], and [o].

This result must be interpreted carefully, though, as discussed above. The greater values for normalized total magnitude in closed syllables could, for example, be caused by having larger magnitudes per frame-step in an effort to have equal total magnitudes in a vowel that has fewer frames. Thus, a simple comparison of the magnitudes is not sufficient to show that syllable type matters beyond duration.

Linear mixed-effects models in R ([5], [29]) predicting the total magnitude of movement for a given vowel type ([i], [e], [o], or [u]) from the fixed effects of duration and syllable type (open vs. closed), with random intercepts for participant and word, and random by-participant and by-item slopes for the effect of syllable type, however, do indicate that syllable type plays a significant role in its own right. (Note that details of the models are given in Appendix B; relevant aspects are reported in the text.)

First, for each model, we examine the collinearity of the two predictor variables, duration and syllable type, by computing the variance inflation factor (VIF), to ensure that they are not simply duplicating each other. VIFs around a value of 1 indicate that two predictors are not particularly correlated, while those greater than a threshold of 5 or sometimes 10 are considered problematically correlated (see discussion in [28]). In the current situation, the VIFs ranged from 1.21 for [o] to 1.44 for [i], indicating that syllable type and duration are not particularly correlated.

Second, the baseline for each model was taken to be the total magnitude value in closed syllables; thus, if the hypothesis that vowels have smaller magnitudes of movement when they are in less-contrastive positions is correct, then we expect to see statistically significant *negative* estimates for open syllables. Given that open syllables are also longer than closed syllables, we might also see that duration has a negative estimate, so that longer vowels consist, on average, of smaller individual movements.

Finally, for each model, the statistical significance of syllable type was determined by performing a likelihood ratio test of the model in question to a model that was equivalent except that syllable type was not included as an effect. In all cases, visual inspection of residual plots also indicated that the standard assumptions of homoscedasticity and normality for linear models were met.

For all models, the effect of duration was indeed in the expected direction (negative) and was statistically significant or nearly so (in the case of [u]; $p = 0.07$); the details of the results for duration in each model are not further given in the text, as the focus here is the examination of whether syllable type *also* matters.

For [i], syllable type significantly affected total magnitude ($X^2(5) = 22.33$, $p < 0.001$), as predicted, with open syllables reducing the overall magnitude by about 2.41 standardized units, ±0.91 (standard errors). Given that this model had random by-word and by-participant slopes for the effect of syllable type, we can also examine the individual estimates for the effect of open syllables for each word and each participant. In this case, all 21 [i]-containing words and 13 of the 14 participants were assigned negative estimates for open syllables, further confirming the hypothesis.

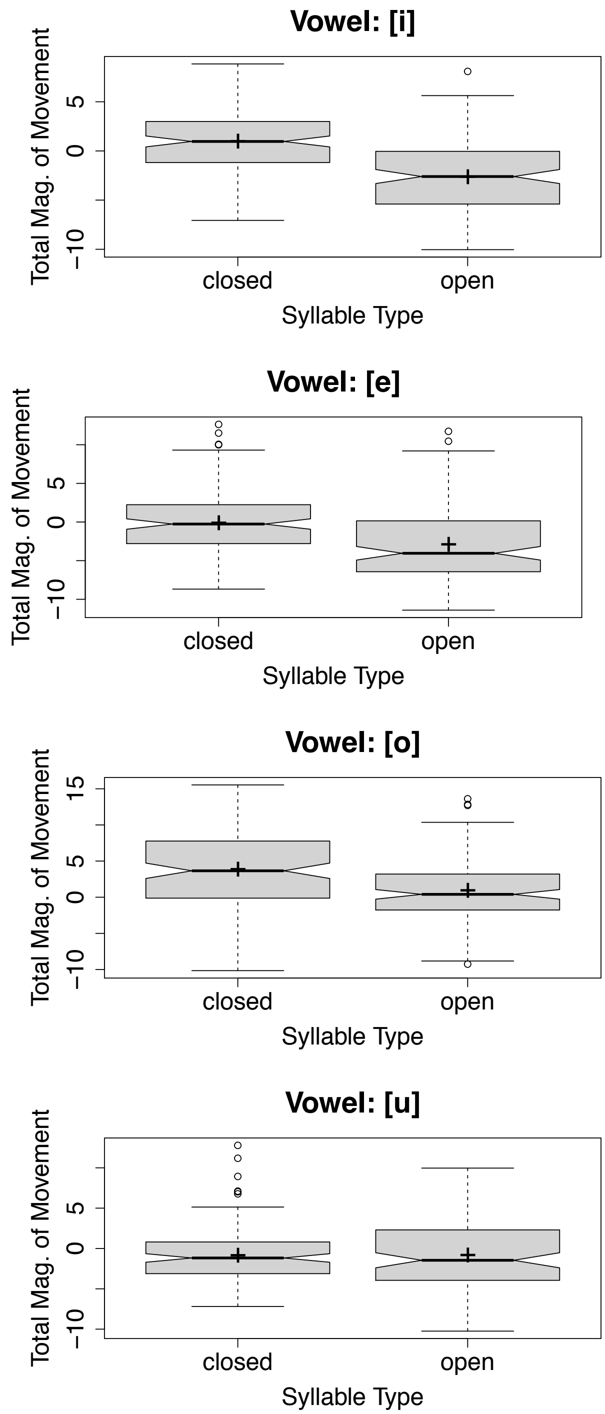

Figure 2: Normalized, summed magnitude of movement data for tense vowels in closed vs. open syllables. Horizontal lines within each plot show the median values; plus signs indicate the mean values.

Similar results hold for [e]: syllable type significantly affected total magnitude ($X^2(5) = 21.43$, $p < 0.001$), as predicted, with open syllables reducing the overall magnitude by about 1.54 standardized units, ±1.25 (standard errors). There is slightly less uniformity across words and participants for this vowel, although the trend is the same: 18 of the 21 [e]-containing words, and 10 of the 14 participants, were assigned negative estimates for open syllables.

For [o], the results are similar, but do not quite reach statistical signficance under the assumption of $\alpha = 0.05$. Syllable type tended to affect total magnitude ($X^2(5) = 9.99$, $p = 0.076$) in the direction predicted, with open syllables reducing the overall magnitude by about 2.16 standardized units, ±1.20 (standard errors). In terms of individual words and participants, 20 of the 22 [o]-containing words and 13 of the 14 participants were assigned negative estimates for open syllables.

The results for [u], however, are decidedly different, as can be seen visually in Figure 2. The effect of syllable type on total magnitude was not close to being significant ($X^2(5) = 1.42$, $p = 0.92$), and the estimate was in the opposite direction (i.e., positive). Indeed, 15 of the 19 [u]-containing words, and all 14 participants, were assigned positive estimates for open syllables.

These results indicate that there tends to be greater total magnitude of movement of tense vowels in closed syllables, where there is a greater potential for lexical contrast, than in open syllables, where the potential is smaller, beyond simply the effect of duration. This is the case for [i] and [e], where the difference between closed and open syllables is categorical, and also for [o], where the difference between contrastiveness in closed and open syllables is simply one of degree. These results will be discussed in more detail in §6, as will the lack of an effect for [u].

First, though, it should be noted that, while the phonetic contexts were not controlled for in this experiment, post-hoc examination of a subset of the stimuli that are matched phonetically suggest that these results are not driven exclusively by context-specific articulations. A post-hoc comparison group was created, containing only closed-syllable, bilabial-final[7] words for which there were open-syllable counterparts with closely matched onsets. The following words were included in this « matched » subset : *beam*, *bee*, *team*, *tea*, *hoop*, *who*, *tube*, *two*, *slope*, *low*, *babe*, and *bay*.

The statistical results for this matched subset were mixed. Because there were so few items, random slopes by syllable type were not possible, and only random intercepts were included. The estimates for open syllables for both [i] and [e] in this subset were negative, but not quite statistically significant ($X^2(1) = 1.92$, $p = 0.16$ for [i] and $X^2(1) = 3.48$, $p = 0.06$ for [e]). The effect for [o] disappeared entirely, with the estimate being positive and not close to statistically significant ($X^2(1) = 0.90$, $p = 0.34$). The effect for [u] was similarly not significant, though interestingly, the estimate here was in fact negative and the result trended toward significance ($X^2(1) = 2.86$, $p = 0.09$).

Future testing with larger datasets that are phonetically matched will need to be done to truly understand the role of phonetic context. At the same time, the results for [i] and [e] in particular seem to be consistent regardless of context, with vowels in open syllables displaying smaller total normalized magnitudes of movement as compared to their closed-syllable counterparts. Given the weaker nature of the contrasts for both [o] and [u], discussed in §6 below, this suggests that there does need to be a clear-cut contrast phonologically in order for an articulatory effect to be present.

6 Discussion and Conclusions

The above results strongly suggest that there is an articulatory difference between most English tense vowels when produced in closed vs. open syllables. The lack of an effect for [u] suggests two things. First, whatever *is* causing the difference for the other vowels, it is unlikely to be the simple fact of syllable structure itself. That is, it doesn't seem to be the case that closed syllables simply involve larger magnitudes of tongue movement than open syllables, regardless of phonological contrastiveness. Second, there seems to be some critical degree of contrast that is relevant. Given that functional load and type-based entropy largely pattern together when it comes to distinguishing [u] / [ʊ] from the other pairs, it is not possible from this study alone to determine whether one of these is in any sense the "critical" factor, and if so, what the critical aspect of that factor might be.

One can speculate, however, that there is some threshold value above which articulations are hyperarticulated relative to other contexts, presumably because they are deemed "contrastive enough" to be relevant. For entropy, this threshold would need to be somewhere between 0.67 bits (the entropy of [o]/[ɔ] in open syllables, where relative hyperarticulation doesn't occur) and 0.95 bits (the entropy of [i]/[ɪ] in closed syllables, the lowest entropy at which the relative hyperarticulation does occur). Under the assumption of an [ɔ] / [ɑ] merger, however, the window for the threshold is quite narrow, as it would need to be somewhere beteen 0.91 and 0.95. For functional load, there may be some minimum number of minimal pairs, greater than 8 (the number of pairs for [u]/[ʊ], where there is no effect) and smaller than 41 (the number for [o]/[ɔ], where there is one), required for relative hyperarticulation to take place. Under the assumption of an [ɔ] / [ɑ] merger, the interval would be between 17 and 56.

The current study is not fine-grained enough to tease the functional load and entropy measures apart, though it does seem somewhat more plausible that a threshold could be found in the intervals defined by minimal pairs than by predictability of distribution, at least under the assumption of an [ɔ] / [ɑ] merger. Nor can it eliminate other possibilities, such as the generally low frequency (both lexically and in use) of [u]/[ʊ] as compared to the other

[7] Bilabial-final words were chosen to minimize co-articulatory effects on tongue movement between the vowel and the coda consonant.

vowel pairs (which is, of course, correlated with the measures used here). At the same time, it does show clear evidence that some measure of contrastiveness is correlated with articulation, with sounds that are *more* lexically contrastive being hyperarticulated relative to sounds that are *less* lexically contrastive; more specifically, sounds that are more contrastive involve larger average movements within any given frame. This correlation is true, however, only if one accepts claims that phonological contrast is not a binary notion but rather a gradient one. Finally, the current study has illustrated the utility of optical flow analysis in the study of ultrasound data. While OFA does not directly reveal patterns of tongue posture, it can tell us about what the tongue is doing continuously during articulation, and the resulting measures can be normalized and directly compared across participants.

Though the current study raises a number of questions – what kind and degree of contrastiveness matters for affecting articulations? is contrastiveness the causal factor, or is it simply also correlated with the causal factor? is this a case of hyperarticulation of contrasts or hypoarticulation of non-contrasts? are there acoustic consequences of these differences? what exactly is the role of phonetic context in determining magnitude of movement? – it is our hope that the methodology and initial results reported here will indeed spur further research that can answer these questions.

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Appendix A

Tense Vowels
(Target Words)

	[i]	[e]	[o]	[u]
Closed Syllables	bead	babe	boat	booed
	beam	bayed	bode	boot
	cheek	cake	code	doom
	feast	cave	cove	duke
	leaf	face	foam	dune
	meat	fame	ghost	food
	seed	gate	globe	fool
	sheep	mail	goal	hoop
	team	phase	nose	moose
	teen	safe	slope	suit
Open Syllables	bee	bay	blow	blue
	fee	clay	bow / go[8]	chew
	glee	day	doe	clue
	key	delay	flow	coo
	knee	hay	hoe	stew
	me	jay	Joe	two
	plea	may	low	who
	spree	ray	mow	zoo
	tea	stay	toe	
	tree	way	woe	

Lax Vowels
(Filler Words)

	[ɪ]	[ɛ]	[ɔ]	[ʊ]
Closed Syllables	bid	bed	boss	foot
	bin	bell	cob	full
	dish	chef	cough	good
	fib	head	dot	hood
	gill	jet	job	pull
	hip	mesh	moss	put
	kid	mess	pause	soot / could[4]
	kiss	pep	pod	wood
	pig	pet	pot	
	pit	test	top	
		web		
Open Syllables			bawdy	
			body	
			claw	
			flaw	
			jaw	
			law	
			paw	

Appendix B

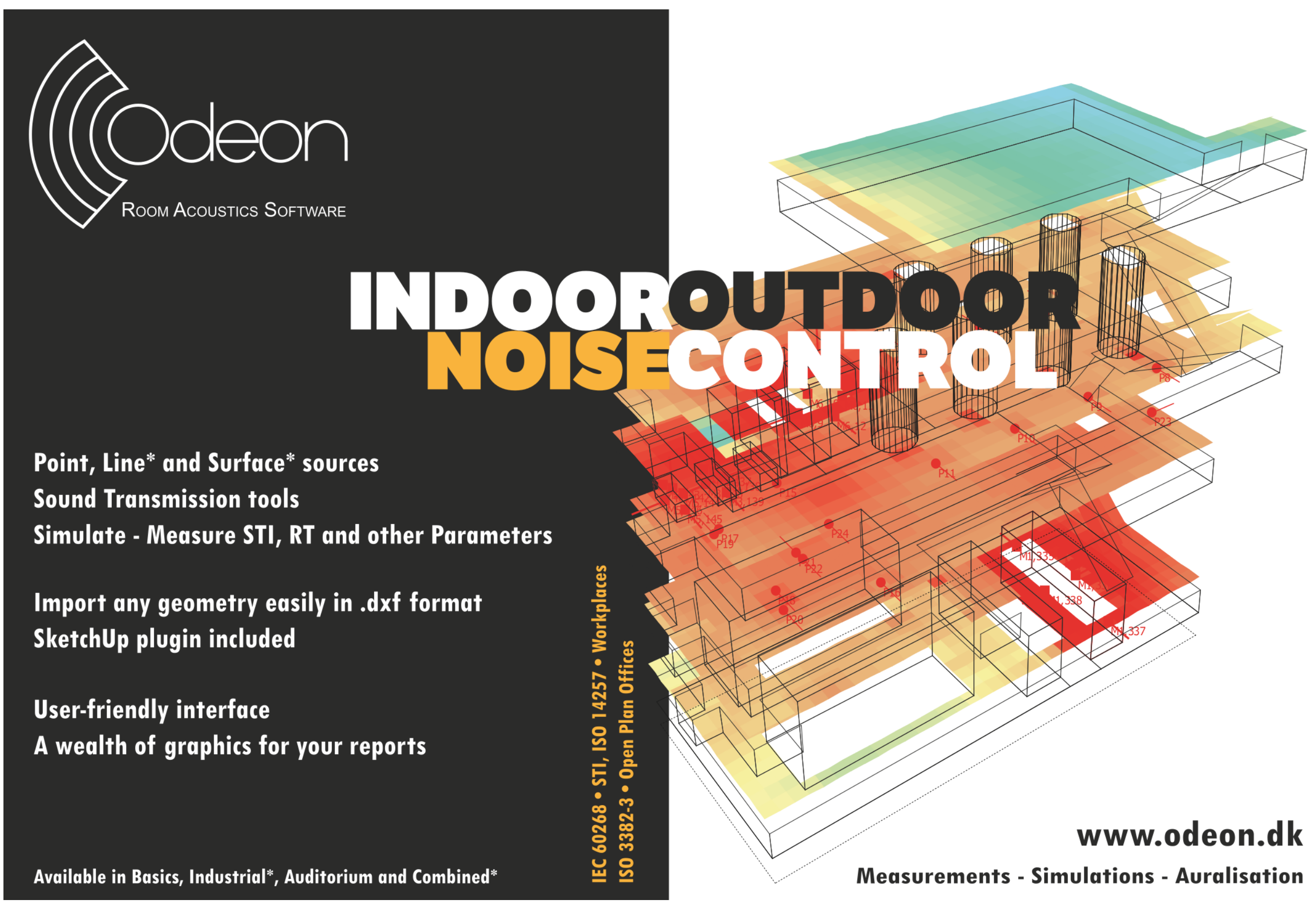
Linear Mixed-Effect Models, Full Dataset

	Fixed effect	Estimate	Standard error	t-value
[i]	(Intercept)	4.79	1.16	4.14
	Open syll.	-2.41	0.91	-2.64
	Duration	-0.54	0.14	-3.83
[e]	(Intercept)	4.12	1.15	3.57
	Open syll.	-1.54	1.25	-1.23
	Duration	-0.53	0.12	-4.51
[o]	(Intercept)	7.43	1.75	4.25
	Open syll.	-2.16	1.20	-1.80
	Duration	-0.42	0.18	-2.37
[u]	(Intercept)	0.99	1.19	0.83
	Open syll.	0.61	1.07	0.57
	Duration	-0.26	0.14	-1.84

[8] The first four participants were run with the words "bow" [bo] and "soot" [sʊt]. There were consistent errors in production of these words, as [baʊ] and [sut], probably due to ambiguity in the former case and unfamiliarity in the latter case. Hence, these words were replaced with "go" and "could," respectively, for the remaining participants.

Linear Mixed-Effect Models, Matched Dataset

	Fixed effect	Estimate	Standard error	t-value
	(Intercept)	9.91	2.94	3.37
[i]	Open syll.	-1.60	1.14	-1.40
	Duration	-1.22	0.35	-3.52
	(Intercept)	1.27	2.54	0.50
[e]	Open syll.	-2.52	1.17	-2.15
	Duration	-0.34	0.26	-1.30
	(Intercept)	7.07	3.29	2.15
[o]	Open syll.	2.16	2.13	1.02
	Duration	-0.48	0.48	-1.00
	(Intercept)	-0.36	1.29	-0.28
[u]	Open syll.	-1.49	0.86	-1.74
	Duration	-0.14	0.18	-0.77



ULTRASOUND STUDY OF EMPHATICS, UVULARS, PHARYNGEALS AND LARYNGEALS IN THREE ARABIC DIALECTS

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Résumé

Différentes études présentent des mécanismes différents et, dans une certaine mesure, inconsistants en ce qui a trait aux sons uvulaires, pharyngés et laryngés, c'est-à-dire les sons dits gutturaux et emphatiques. Les études les plus récentes font usage d'imagerie ultrasonore de la langue afin d'observer les articulations jouant un rôle dans la prononciation des phonèmes gutturaux et emphatiques de trois dialectes arabes, soit l'égyptien, le saoudien et le palestinien. Ces études ont pour but de répondre à la question suivante : quelles formes prend la langue lorsqu'elle produit des sons /ʕ, ħ, ʁ, χ, q/ à rétraction intrinsèque et des sons /ðˤ, sˤ, tˤ, dˤ/ à rétraction secondaire? Les résultats articulatoires indiquent que ces sons sont produits à l'aide des différentes racines de la langue et des mécanismes de rétraction de la partie postérieure de la langue. Les consonnes pharyngales sont articulées en rétractant les racines de la langue et n'impliquent aucune rétraction marquée des racines de la langue. Les sons uvulaires et emphatiques présentent une rétraction de la partie postérieure de la langue et une rétraction inconsistante des racines de la langue. Les sons laryngés ne présentent aucune rétraction marquante de la langue.

Mots clefs : ultrasonore, dialectes arabes, emphatiques, uvulaires, pharyngés, laryngés

Abstract

Different studies show different and to some extent inconsistent mechanisms for the articulation of Arabic uvular, pharyngeal and laryngeal sounds, i.e. gutturals, and emphatic sounds. The current study uses ultrasound imaging of the tongue to examine the articulations involved in guttural and emphatic sounds in three Arabic dialects, Egyptian, Saudi and Palestinian. This investigation attempts to answer the question: what are the tongue shapes during the production of both inherently retracted /ʕ, ħ, ʁ, χ, q/ and secondarily retracted /ðˤ, sˤ, tˤ, dˤ/ sounds. Articulatory results indicate that these sounds are produced with different tongue root and tongue dorsum retraction mechanisms. Pharyngeals are articulated with tongue root retraction and statistically do not involve significant tongue dorsum retraction. Uvulars and emphatics show tongue root and tongue dorsum retraction with inconsistent tongue root retraction. Laryngeals do not show any significant tongue retraction.

Keywords: ultrasound, Arabic dialects, emphatics, uvulars, pharyngeals, laryngeals

1 Introduction

Arabic has a number of sounds that involve post-velar retraction. This retraction is inherent in some sounds, pharyngeals and uvulars and secondary in others, emphatics[1], as shown in Table 1. Analyses of the secondary articulation vary from one study to another. It is accepted, however, that the secondary articulation is a result of the retraction of the tongue body.

Table 1: Arabic gutturals and emphatics phonemes

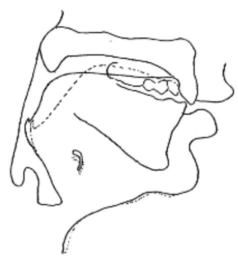
	Dental	Alveolar		Uvular		Pharyngeal		Glottal
Plosives		tˤ	dˤ	q				ʔ
Fricatives	ðˤ	sˤ		χ	ʁ	ħ	ʕ	h

Arabic emphatics are articulatorily similar to their non-emphatic counterparts in their primary coronal constriction. Emphatics differ from plain coronals in their secondary articulation. Despite the advancement in the methods used in investigating these sounds, the secondary articulation in emphatics is difficult to pinpoint. This is due partly to cross-dialectal variation and partly to different methodologies used in the investigation. It is possible, however, that there is no consistent single articulatory exponent of emphasis. Rather, speakers have different articulatory strategies to produce emphatics, which are influenced by dialect, gender, phonological context and social variables (Khattab et al. 2006).

Modern studies show that, beside their primary coronal articulation, all Arabic emphatics have a secondary articulation involving the back of the tongue. Ghazeli (1977) pointed that the tongue body is pulled backwards into the upper oropharynx during the articulation of [tˤ] and the tongue body is depressed during the emphatic consonant but not during the plain coronal as can be seen in Figure 1. In their cinefluorographic study of Iraqi Arabic, Ali & Daniloff (1972) found emphatics to be articulated with simultaneous depression of the tongue and a rearward movement of the tongue dorsum towards the posterior wall of the pharynx. They found that the difference between emphatics and non-

[1] Emphatics are assumed to be pharyngealized at this point

emphatics is that the former class involves a retraction of the tongue dorsum causing a narrowing in the upper pharynx. They also reported that the posterior wall of the pharynx and the velum were not significantly implicated in the articulation of emphatics. The tongue dorsum depression in emphatics was first reported by Ibn Sina (1037 A.D) where he suggested that emphatics are articulated with a depressed tongue surface behind the main articulation point (Semaan 1963). This point is confirmed in other studies (Ali & Daniloff (1972) in Iraqi Arabic; Ghazeli (1977) in Tunisian Arabic; Al-Tamimi & Heselwood (2011) in Jordanian Arabic.



Solid line represents the articulation of /tˤ/
Dotted line represents the articulation of /t/

Figure 1: Articulations of emphatic /tˤ/ and /t/, from Ghazeli (1977) page 69

The precise location of the secondary constriction in Arabic emphatics does not seem to be an area of agreement among articulatory studies in Arabic. Ghazeli (1972) found that the tongue back retraction into the upper pharynx takes place at the level of the second cervical vertebra while Giannini & Pettorino (1982) reported that the constriction takes place at the level of the third vertebra.

Another point of disagreement is the implication of tongue root and epiglottis in the production of Arabic emphatics. Due to this controversial point, researchers have posited that emphatics are uvularized in Jordanian Arabic (Zawaydeh 1999), velarized in Lebanese Arabic (Obrecht 1968) and pharyngealized in Iraqi Arabic (Ali & Daniloff 1972; Gianni & Pettorino 1982). During the articulation of emphatics Ali & Daniloff (1972) and Ghazeli (1977) reported a constriction in the upper pharynx achieved by a retraction of the tongue body while little to no adjustments take place in the lower pharynx. Ghazeli (1977) reported that there is an accompanying backward movement of the epiglottis but no adjustments in the laryngopharynx. Giannini & Pettorino (1982) indicated that the aryepiglottic muscle, which moves the epiglottis backwards, is not implicated in the articulation of Arabic emphatics. Laufer & Baer (1988) suggested that the pharyngeal constriction is less extreme and less consistent in emphatics compared to pharyngeals. Shar (2012) in his MRI study of Saudi Arabic showed that emphatics are produced with dorsal retraction of the tongue, which causes consistent narrowing of the upper part of the pharyngeal cavity; however, the tongue root is not involved in this narrowing gesture. In their video-fluoroscopic study of emphatics in Jordanian Arabic, Al-Tamimi & Heselwood (2011) found that during the articulation of emphatics, the tongue root is seen to press against the anterior surface of the epiglottis, pushing the epiglottis towards the back of the pharynx. However, they suggested that the larynx is raised in emphatics, which means that the pharyngeal volume is reduced. Consequently, it is difficult to judge in the already reduced pharynx whether the tongue root/epiglottis movement is independent or a result of the tongue dorsum retraction. Accordingly, tongue root retraction in emphatics appears to be a mechanical consequence of tongue dorsum retraction.

The coarticulatory effect of emphatics on neighboring vowels was examined in many studies. The most frequently observed effect is a lowered F2 value. Al-Ani (1970) found a considerable F2 onset drop in vowels following emphatic consonants compared to plain coronals. Ghazeli (1977) reported that all vowels have a lower F2 after emphatics as opposed to non-emphatics. Similar results are reported in other studies (Obrecht 1968; Giannini & Pettorino 1982; Khattab et al. 2006; Bin-Muqbil 2006; Shar 2012). A raised F1 is also noticed but not in all studies. Al-Ani (1970) and Hassan (1981) indicated that F1 is raised in vowels after emphatic consonants. However, Bin-Muqbil (2006) found that F1 values after emphatic consonants were not significantly higher than those after non-emphatic coronals in all vowel contexts. He found that while F1 values of vowel [i] after emphatics were significantly higher than non-emphatic coronals, they showed no significance in vowel [a] and showed some variation in vowel [u].

Delattre (1971) described the production of Arabic uvulars [χ, ʁ, q] using X-ray frames of one speaker of Lebanese Arabic. He reported that during the articulation of uvulars, the tongue slides backwards then moves upwards to create a constriction in the upper pharynx, as seen in Figure 2.

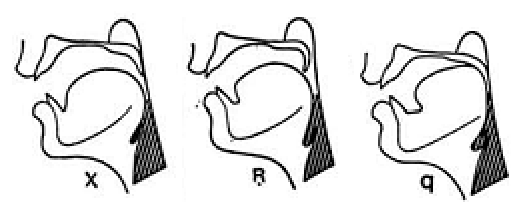


Figure 2: Tracings of the articulation of Arabic uvulars [χ], [ʁ] and [q], from Delattre (1971) page 130

Ghazeli (1977) reported that the anterior wall of the pharynx as well as the epiglottis are pulled backwards towards the posterior wall of the pharynx during [χ] and [q], but not [ʁ]. The tongue is backed the most during [q]. Accordingly, the pharyngeal volume above the epiglottis is smaller during [q] than during [ʁ] or [χ]. This is due to the manner of articulation of [q] which entails a complete closure to fulfill the occlusive nature of the consonant.

Uvulars have similar coarticulatory effects to emphatics in which they lower F2 values in adjacent vowels. However, the size of the effects in uvulars is less than in emphatics. Compared to plain coronals, Al-Ani (1970) found that Arabic uvulars [χ, ʁ, q] have lower F2 values in adjacent vowels with [q] showing the strongest effect. He did not report the effects on F1 values. Ghazeli (1977) suggested that emphatics caused lower F2 values in following vowels [i] and [a] while uvulars caused lower F2 values in following vowel [u]. Similar results were reported in (Ghazeli 1977; Obrecht 1968; Bin-Muqbil 2006; Shar 2012). Bin-Muqbil (2006) reported that uvulars have higher F1 values when compared to plain coronals. However, F1 values were not always significant. F1 values of the vowel [i] were significantly higher after [q] and [ʁ] compared to plain consonants, however, after [χ] F1 value of vowel [i] was not significantly different from plain consonants. Also, F1 values of vowel [a] after [q] and [ʁ] were not significantly different than plain consonants while F1 values of vowel [u] showed no significant difference after all uvulars.

Delattre (1971) indicated that Arabic pharyngeals are articulated by retracting the tongue root towards the posterior wall of the pharynx, as shown in Figure 3. Ghazeli (1977) reported similar results. He added that the constriction during the voiceless pharyngeal [ħ] is narrower than for [ʕ]. This is expected since the voiceless pharyngeal fricative requires a narrow constriction to produce enough friction.

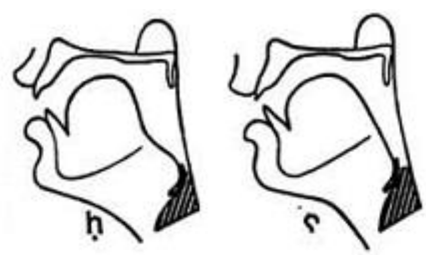


Figure 3: Tracings of the articulation of Arabic pharyngeals, [ħ] & [ʕ] from Delattre (1971) page 130

The nature of the active articulator of pharyngeals is controversial. While Laufer & Condax (1979) suggested that the epiglottis retracts independently from the rest of the tongue, including the tongue root, Boff-Dkhissi (1983) and Laufer & Baer (1988) challenged this claim and showed that the tongue root and the epiglottis covary with each other.

The most frequently observed effect of pharyngeals on neighboring vowels is a rise in F1 (Al-Ani 1970; Ghazeli 1977; Butcher & Ahmad 1987; Zawaydeh 1999; Bin-Muqbil 2006; Shar 2012). Bin-Muqbil (2006) suggested that F2 values in vowels [i], [a] and [u] after pharyngeals are not significantly different than those after plain consonants in almost all cases. Other studies indicated some variation in F2 values after pharyngeals (Al-Ani 1970; Ghazeli 1977; Butcher & Ahmad 1987; Zawaydeh 1999).

The two Arabic laryngeals are articulated at the larynx with a fully open glottis in [h] or fully constricted glottis in [ʔ]. Laufer & Condax (1979) found no evidence of any constriction in the pharynx during the articulation of the two laryngeals in bilingual speakers of Palestinian Arabic and Hebrew. Zawaydeh (1999) concluded in her fiberscopic study of Jordanian Arabic that laryngeals [h, ʔ] show no constriction in the pharynx. She suggested that the pharynx during Arabic laryngeals is as wide as it is during the production of plain coronal sounds. Using laryngoscopy to examine Jaffa dialect spoken in Northern Palestine, Shahin (2011) found that the two laryngeals were produced with no aryepiglottic constriction and no retraction of the tongue root or epiglottis. The [h] of the speaker in her study was like the [ʔ] except with a triangular opening between the vocal folds.

Al-Ani (1970) found that laryngeals have no coarticulatory effect on following vowels. Similarly, Bin-Muqbil (2006) found that next to [a], laryngeals showed high F1; however, no such effect is reported next to vowels [i] or [u]. Zawaydeh (1999) suggested that laryngeals in Jordanian Arabic have higher F1 values compared to plain coronals, however, no such conclusion was reported in any other study.

The additional parameter of larynx height contributes significantly to pharyngeal volume and sound quality in Arabic gutturals and emphatics. Raising the larynx reduces the volume of the pharyngeal cavity. Such action would result in converging F1 and F2 frequencies. Lowering the larynx, on the other hand, would elongate the vocal tract and lowers all formants. Larynx height is reported differently in different studies for different sounds. The larynx is suggested to be raised in emphatics in Jordanian Arabic by about 4-7 mm (Al-Tamimi & Heselwood 2011), similar results were reported by Al-Tamimi et al. (2009). Hassan & Esling (2011) reported that the larynx is lowered in Iraqi Arabic, which is different from the findings of Al-Tamimi & Heselwood (2011). However, the methodology of Hassan & Esling (2011), a laryngoscopic study, is not optimal in assessing vertical changes in the larynx. They relied on auditory examination of the tokens to reach the conclusion that the larynx is lowered during emphatics in Iraqi Arabic. During the production of pharyngeals the larynx was observed to ascend by approximately 9 mm relative to the rest position (Ghazeli, 1977). Similar results were reported in (Bucher & Ahmad 1987; Elgendy 2001; Heselwood 2007).

Thus far, it has been suggested that the articulation of Arabic emphatics and uvulars involve retracting the tongue dorsum. Tongue root retraction in these sounds is questioned. It is has been indicated that the tongue root does not actively retract in these sounds; rather it retracts as a result of the retraction of the tongue dorsum. Emphatics and uvulars differ, however, in the direction of tongue dorsum retraction and in tongue depression behind the point of main articulation in emphatics. Furthermore, it has been suggested that pharyngeals are articulated with a retracted tongue root while laryngeals do not involve tongue retraction in their articulation. A summary of hypotheses regarding Arabic emphatics and gutturals articulation is presented in Table 2.

Table 2: Summary of Arabic emphatics and gutturals articulation hypotheses

1	Arabic emphatics and uvulars share a physical property of tongue dorsum retraction.
2	Emphatics are articulated with a depressed tongue surface behind the main articulation while uvulars lack such a gesture.
3	Emphatics and uvulars retract tongue root as a consequence of tongue dorsum retraction; therefore, tongue root retraction in these sounds is not consistent.
4	Pharyngeals are articulated with a retracted tongue root.
5	Laryngeals do not show any form of tongue retraction.

To test these hypotheses, this study will focus on examining tongue root (TR), tongue dorsum (TD) and tongue body (TB) retraction in laryngeals, pharyngeals, uvulars and emphatics. To achieve this point, this study implements ultrasound technology. All modern descriptions of Arabic emphatic sounds used methodologies that are good for investigating movements in the pharynx. However, it is impossible to see using endoscopy whether the tongue back/dorsum is raised or lowered during the articulation (Hassan & Esling 2011). Ultrasound technology, on the other hand, is optimal for viewing the posterior and anterior parts of the tongue. For the purpose of this paper, it is hypothesized that tongue retraction is the main articulatory component of these sounds and they differ in the degree and direction of retraction. It is expected that these sounds will have different mechanisms of tongue retraction.

The use of ultrasound is limited and still at early stages in Arabic literature. Among the recent studies is an EMA, endoscopic and ultrasound study performed by (Zeroual *et al.* 2011). They provided data from Moroccan Arabic, MA, speakers in order to answer a number of questions. The relevant point is the question related to the nature of secondary articulation in MA emphatics. They compared the properties of MA emphatic coronals /tˤ, dˤ, sˤ/ with their plain counterparts /t, d, s/, uvulars and pharyngeals. For the ultrasound study they recruited two MA speakers. They used words and nonsense words containing emphatic sounds. Their aim was to observe the tongue, and the epiglottis. (Zeroual *et al.* 2011) found that the articulation of emphatics is more similar to uvulars than pharyngeals. Also, emphatic sounds involved a backward movement of the tongue towards the posterior pharyngeal wall while pharyngeals involved backward movement of the tongue and the epiglottis. They suggest that ultrasound technology is not capable of detecting movements of tongue root in pharyngeals. This point is discussed further in the results.

2 Method

2.1 Participants

Three participants were included in this experiment, one Egyptian Arabic speaker, EA, one Saudi Arabic speaker, SA, and one Palestinian Arabic speaker, PA. All participants spoke their respective dialect natively and reported no speech or hearing impairment.

2.2 Stimuli

The stimuli in this experiment consisted of fifteen nonsense words with the form ʔaCCa in which the geminate consonants belonged to the sounds under examination, as shown in Table 3. Geminate consonants were chosen because the rate of ultrasound system used only gives 15 frames per second, thus geminating the segments gives a longer duration of the consonants so the frames can be extracted more easily. The target consonants were preceded and followed by a low vowel [a]. These words were chosen to represent plain coronals, emphatics, uvulars, pharyngeals and laryngeals.

Table 3: Ultrasound experiment stimuli

Emphatics	ʔaðˤðˤa	ʔasˤsˤa	ʔatˤtˤa	ʔadˤdˤa
Plain coronals	ʔaðða	ʔassa	ʔatta	ʔadda
Uvulars	ʔaχχa	ʔaʁʁa		
	ʔaqqa			
Pharyngeals	ʔaʕʕa	ʔaħħa		
Laryngeals	ʔahha	ʔaʔʔa		

2.3 Equipment and procedure

The data were collected using a PI 7.5 MHz *SeeMore* ultrasound probe by *Interson*, connected through a USB port to a computer and recorded on DVD recorder. The depth was set to 10 cm to provide the best visual information and temporal resolution. A non-toxic water based gel was applied to the probe to prevent air from intervening between the surface of the probe and the skin (Stone 1997). The audio signal was recorded using an *AT831b* lavalier microphone via an XLR cable connected to a *SOUND DEVICES USBPre2* pre-amplifier and transferred to the DVD recorder for synchronization with the video. Figure 4 shows the equipment used in the experiment.

Figure 4: Ultrasound equipment (1: Ultrasound probe, 2: PC-TV converter, 3: DVD recorder, 4: SOUND DEVICES USBPre2 pre-amplifier)

Ultrasound probe movements were restricted as much as possible. Tongue measurements can be improved by limiting unwanted movements (Gick et al. 2005). To maintain transducer stability, the ultrasound transducer was attached a long microphone boom arm. To attain transducer stability further, participants were asked to rest their head against a wall behind them and to look at a marked dot in front of them, as shown in Figure 5.

Figure 5: Probe setting with non-participant human model

Recording for the participants took place in a quiet booth at the Department of Linguistics Phonetics Lab at the University of Toronto. Prior to the recording session, the participant read the stimuli to ensure correct reading of the words. Because the focus of this study is to investigate the articulations made in the posterior region of the vocal tract, the probe of the ultrasound was adjusted to capture the best angle of the tongue root, dorsum and body. When the participant was seated in the manner explained previously, a trial of the stimuli was carried out, this helped in getting the needed image of the tongue in the ultrasound screen. Once the needed angle was specified, the participant read the list of the words shown on an iPad screen.

2.4 Data preparation and analysis

For data analysis purposes, using MPEG Streamclip freeware program, with a rate of 30 frames per second, still frames from each repetition of the 15 words for each participant were extracted. Also, a frame was extracted from every pause between repetitions. This pause was used to extract inter-speech rest position of the tongue, ISP. For each token, the frame corresponding to the maximum constriction for the relevant gesture was identified as the highest position or the lowest position of the tongue. The highest position and lowest position is systematically selected as the frame that occurs in mid gemination.

ISP frames are used to assess the degree and direction of tongue retraction of a particular consonant. For this study, ISP frame is the frame that occurs in inter-utterance speech rest position. This frame is identified by Gick et al. (2004) as the speech posture to which articulators return between utterances. This frame occurs 4 to 5 frames before the constriction frame. Figure 6 shows a set of sample frames for the emphatic [sˤ] in token [ʔasˤsˤa].

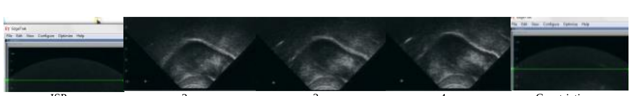


Figure 6: Frames extracted from ultrasound video for a sample emphatic [sˤ] in token [ʔasˤsˤa]. The tongue tip is on the right.

The freeware EdgeTrak (Stone 2005; Li, Kambhamettu & Stone 2005) was used to trace tongue contours for each frame. Then .con files (a text file that contains a set of xy coordinate points for each contour) were saved and converted into Excel files and reformatted for R text. The analysis was done using Smoothing Spline ANOVA (SS-ANOVA) in R (R Development Core Team 2013) (cf. Davidson 2006).

3 Results

In this section the results of the ultrasound experiment are presented. In order to show how these sounds differ in tongue retraction mechanisms, the following subsections discuss the results of comparing emphatics [ðˤ, sˤ, tˤ, dˤ] with plain coronals [ð, s, t, d], uvulars [χ, ʁ, q] with ISP, uvulars with emphatics, pharyngeals [ħ, ʕ] with ISP, laryngeals [h, ʔ] with ISP and finally examining tongue root retraction in emphatics and uvulars compared to pharyngeals. This is motivated partly by hypotheses given in Table 2 and partly by providing explanations for the coarticulatory effects of these sounds on adjacent vowels in terms of tongue shapes. It should be noted that in all the figures the tongue tip is at the right and units are in mm. For simplicity purposes, in each subsection only selected figures from each speaker are discussed and all relevant figures are given in the appendices section[2].

3.1 Emphatics

Comparing emphatic consonants [ðˤ, sˤ, tˤ, dˤ] with their plain coronal counterparts [ð, s, t, d] the tongue dorsum is more raised and retracted as shown in Figure 7. Complete comparisons are given in Appendix A. Also, despite some articulatory variability, the tongue blade behind the point of main constriction is depressed during emphatics. This point is illustrated further in SS-ANOVA graphs in Figure 8, where the significant difference between two tongue contours is plotted as the area where the dotted lines, which indicate the 95% confidence interval, do not overlap (Davidson 2006). Complete SS-ANOVA comparisons between emphatics [ðˤ, sˤ, tˤ, dˤ] and plain coronals [ð, s, t, d] are given in Appendix B.

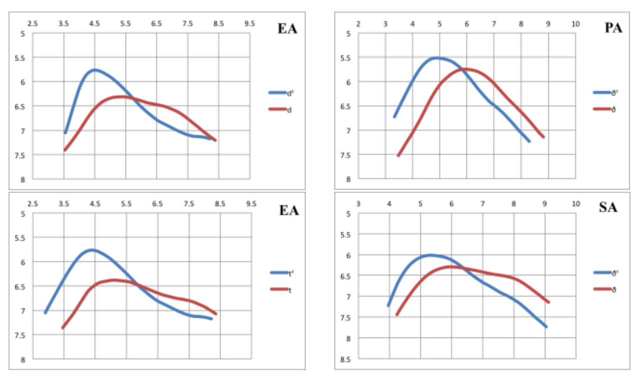


Figure 7: Average tracings of emphatics [ðˤ, sˤ, tˤ, dˤ] and plain coronals [ð, s, t, d]

[2] All appendices can be found on this website http://msolami.kau.edu.sa/ under publications

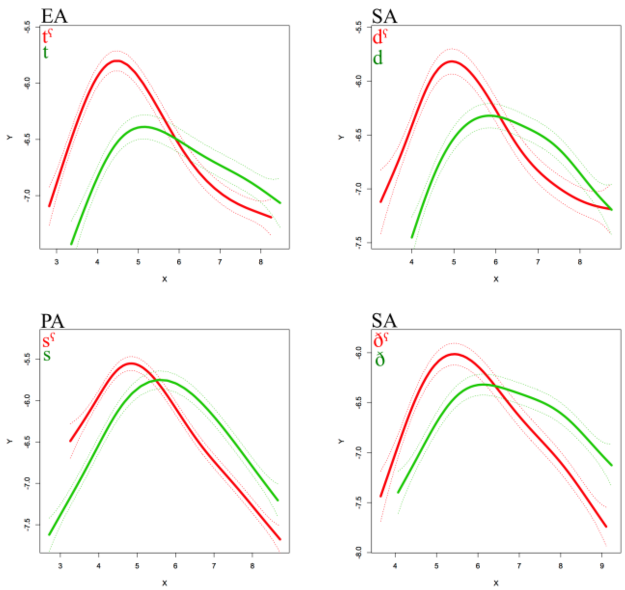


Figure 8: SS-ANOVA tongue-contour graphs of emphatics [ðˤ, sˤ, tˤ, dˤ] and plain coronals [ð, s, t, d]

3.2 Uvulars and ISP

The posterior part of the tongue in uvular consonants [χ, ʁ, q] compared to ISP is more raised and relatively more backed as shown in Figure 9. The constriction location is more posterior for [ʁ] than for [χ] in Egyptian and Palestinian Arabic speakers and the constriction point is more posterior for [χ] than for [ʁ] in Saudi speaker. The uvular stop [q] in Egyptian and Palestinian Arabic speakers has a more raised tongue dorsum compared to the other two uvulars [χ, ʁ].

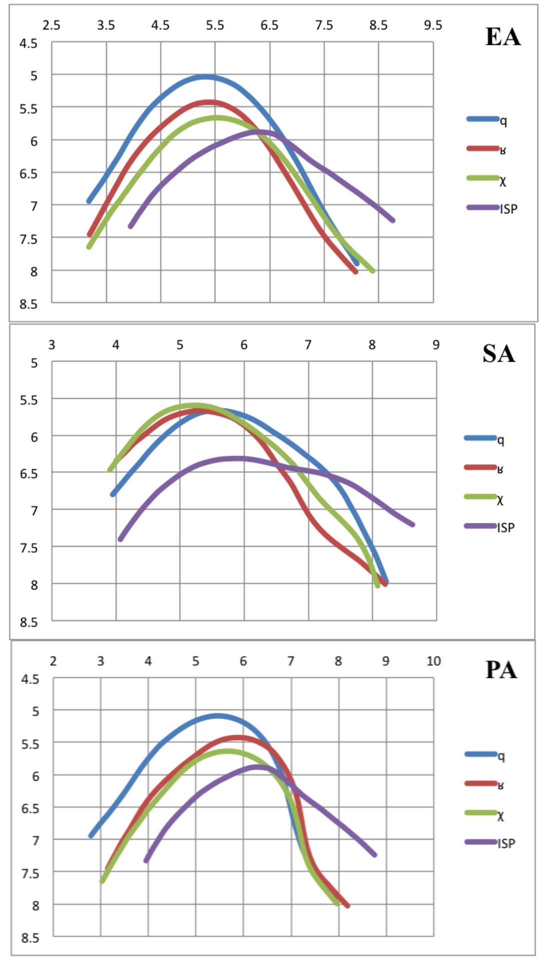


Figure 9: Average tracings of uvulars [χ, ʁ, q] and ISP

3.3 Uvulars and emphatics

Comparing uvulars to emphatics, as illustrated in Figure 10, it can be seen that the anterior part of the tongue in uvular consonants is not depressed compared to emphatics. Also, the back of the tongue is generally moved vertically towards the uvula area during uvulars but horizontally slid backwards during emphatics. This is consistent for all uvular-emphatic comparisons, which are given in Appendix C.

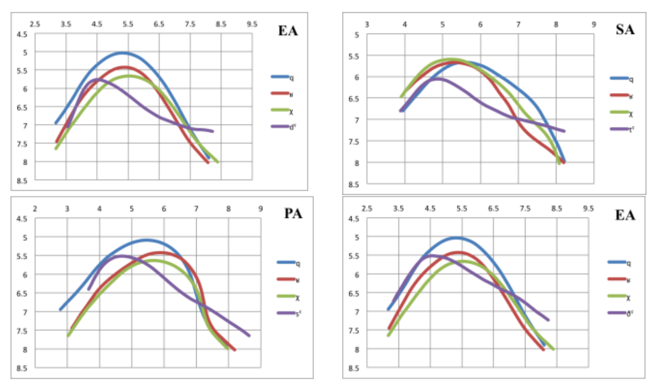


Figure 10: Average tracings of uvulars [χ, ʁ, q] and emphatics [ðˤ, sˤ, tˤ, dˤ]

3.4 Pharyngeals and ISP

In pharyngeals [ħ, ʕ] the tongue root shows more retraction compared to ISP, as given in Figure 11. Tongue dorsum and the anterior part of the tongue are very similar in voiceless pharyngeal [ħ] and ISP. During the articulation of voiced pharyngeal [ʕ], the tongue blade assumes a curved pyramidal shape almost like an inverted "V", especially in the Egyptian Arabic speaker and the Saudi Arabic speaker, as shown in Figure 12 where pharyngeal [ʕ] is compared to ISP.

As shown in Figure 13, tongue contours of laryngeals [h, ʔ] do not show noticeable differences compared to their ISP.

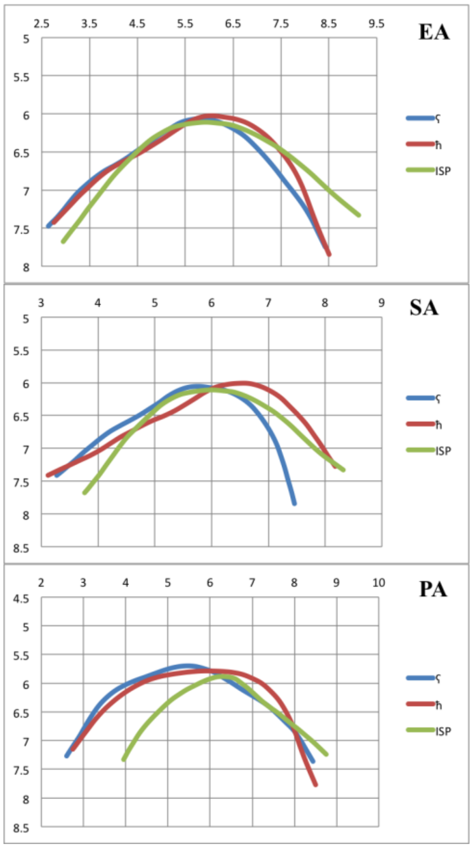


Figure 11: Average tracings of pharyngeals [ħ, ʕ] and ISP

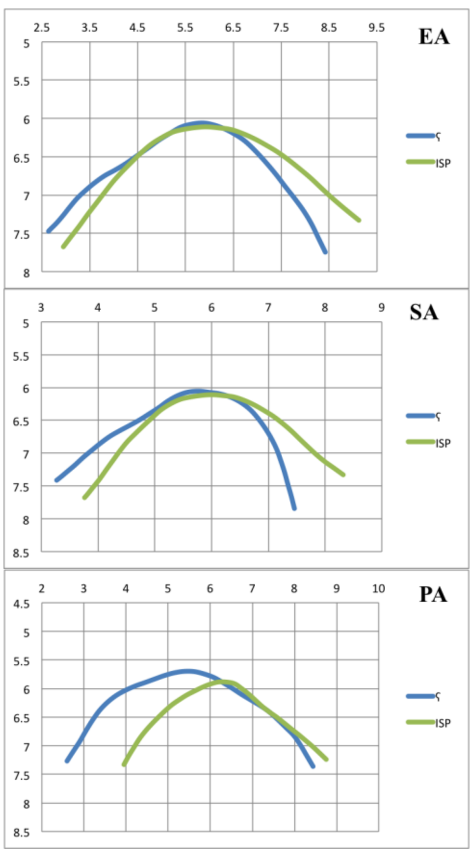


Figure 12: Average tracings of pharyngeal [ʕ] and ISP

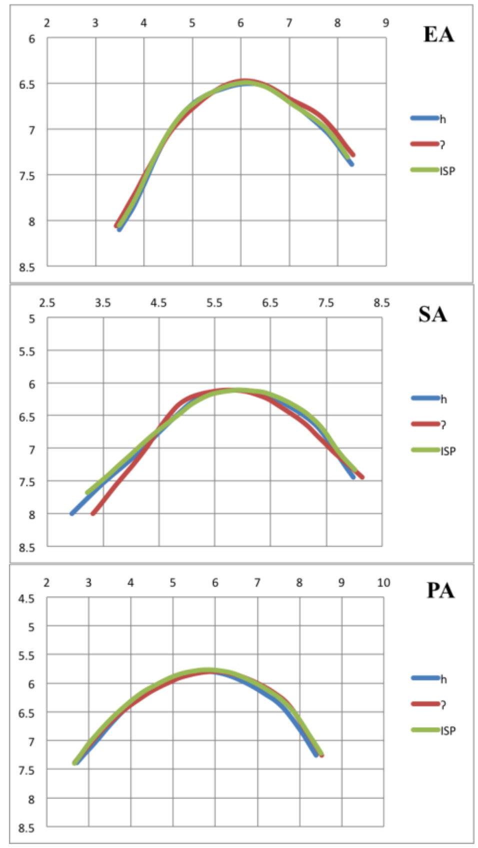


Figure 13: Average tracings of laryngeals [h, ʔ] and ISP

3.5 Tongue root comparisons between emphatics and uvulars and pharyngeals

Despite the fact that ultrasound system does not show the entire tongue root area due to the obstruction of the hyoid bone, when comparing tongue root movement in images obtained from the ultrasound experiment we can get a general idea about the degree of tongue root retraction. Generally speaking, tongue contours show some differences in the degree of tongue root retraction among pharyngeals and emphatics and uvulars. In Figures 14 & 15, SS-ANOVA is used to compare the tongue root retraction in pharyngeals with that in emphatics and uvulars. In Figure 14 the tongue root is similarly retracted for emphatics, uvulars and pharyngeals, while in Figure 15 tongue root retraction degree is different in the three classes of sound. This suggests that tongue root retraction mechanism in these sounds is different. For the complete emphatic-uvular-pharyngeal comparisons see Appendix D.

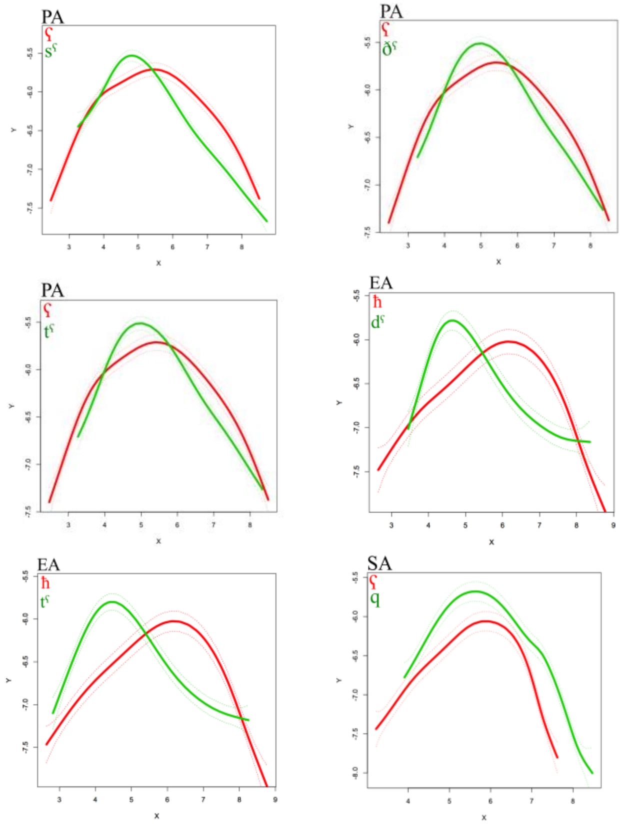


Figure 14: SS-ANOVA tongue-contour graphs of pharyngeals, emphatics and uvulars

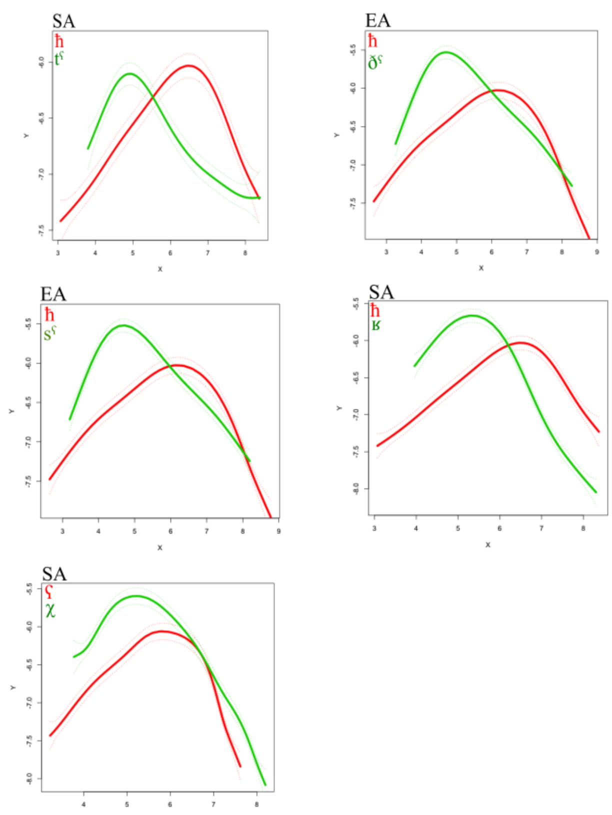


Figure 15: SS-ANOVA tongue-contour graphs of pharyngeals, emphatics and uvulars

4 Discussion

As previously mentioned in Table 2, it is hypothesized that Arabic emphatics and uvulars share a physical property of tongue dorsum retraction. In the results of the ultrasound experiment, as shown in Figures 6 & 7, the tongue dorsum in emphatics is more raised and retracted compared to their coronal counterparts. This is expected since the secondary articulation in emphatics involves pulling the tongue into the upper oropharynx area (Ali & Daniloff 1972; Ghazeli 1977). Comparing uvular consonants [χ, ʁ, q] to their ISP, Figure 8 illustrates that the tongue in uvulars is more raised and relatively more backed. This shape of the tongue in uvulars is a result of moving the rear-most portion of the tongue surface towards the posterior soft palate and the uvula (Catford 1977). Figure 8 also indicates that the constriction location is more posterior for [ʁ] than for [χ] in the Egyptian Arabic speaker and Palestinian Arabic speaker while the constriction point is more posterior for [χ] than for [ʁ] in Saudi Arabic speaker. This difference was also given in Ghazeli (1977) who reported that the constriction point is more posterior for [ʁ] than for [χ], whereas Delattre (1971) found the opposite. However, the tongue position in emphatics and uvulars is different as suggested by Figure 9. While the back of the tongue is generally moved vertically towards the uvula area during uvulars, it moves horizontally during emphatics. This suggests that the articulation mechanisms in these two subsets of sounds are different. The vertical movement in uvulars is due to the constriction between tongue dorsum and the soft palate. Catford (1977) terms the articulation of uvulars as *dorso-uvular*. For emphatics, on the other hand, the tongue moves horizontally to achieve a constriction at the oropharynx area. It is for this tongue movement that Al-Ani (1970) favored pharyngealization over velarization as the proper description for the secondary emphatic articulation. Zeroual et al. (2011) reported based on endoscopic pictures that the back of the tongue moves towards a higher position during [q] and intermediate during [tˤ] which provides a further support for the difference between the two sound categories.

Furthermore, it is hypothesized that emphatics are articulated with a depressed tongue surface behind the main articulation point while uvulars lack such a gesture. The results in Figures 6, 7 & 9 show that behind the point of main constriction the tongue is depressed during the articulation of emphatics, which was reported by Ibn Sina (Avicenna), (d. 1037 A.D) (Semaan 1963); Ali & Daniloff (1972) in Iraqi Arabic; Ghazeli (1977) in Tunisian Arabic; Al-Tamimi and Heselwood (2011) in Jordanian Arabic. Figure 1, repeated in Figure 16 below, from Ghazeli (1977) clearly shows the depression of the tongue during emphatic [tˤ]. Uvulars, on the other hand, do not show similar tongue shape, as illustrated in Figures 9 & 10.

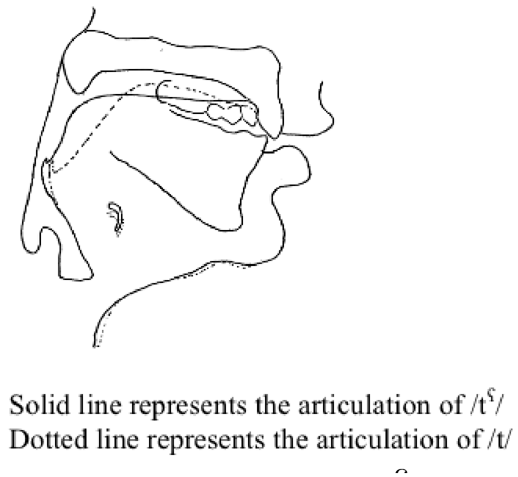


Figure 16: Articulations of emphatic /tˤ/ and /t/ in Tunisian Arabic, from Ghazeli (1977) page 69

As expected, the tongue root region in pharyngeals [ħ, ʕ] shows more retraction degree compared to ISP, as given in Figure 11. Also, the tongue assumes a pyramidal shape during the articulation of pharyngeal [ʕ], as shown in Figure 12. This is reported by Delattre (1971); Ghazeli (1977) and Elgendi (2001). However, these studies did not explain why the tongue assumes such a shape in the voiced pharyngeal [ʕ] only and whether such a gesture would have any coarticulatory effects.

As given in Table 2, it is hypothesized that tongue contours of laryngeals [h, ʔ] do not show noticeable differences compared to their ISP, as illustrated in Figure 12. Zawaydeh (1999) reported that the pharyngeal area during the articulation of the two Arabic laryngeals is as wide as it is during the articulation of plain oral sounds. Zeroual et al. (2011) concluded that compared to laryngeal [h] the back of the tongue is more posterior during [tˤ, χ, q, ħ].

It was suggested in Table 2 that emphatics and uvulars retract tongue root as a consequence of tongue dorsum retraction; therefore, tongue root retraction in these sounds is not consistent. Figures 14 & 15 show that the tongue root retraction degree is similar in pharyngeals, emphatics and uvulars in some instances and significantly different in others. The articulation of pharyngeals [ħ, ʕ] is characterized by a retraction of tongue root and slight forward displacement of the posterior wall of the pharynx, resulting in a place of articulation at the level of the epiglottis (Ghazeli 1977). As far as the pharynx and tongue root are concerned, they do not play an active part in the production of emphatics (Norlin 1987). Instead, it is the tongue dorsum, which by a backing movement causes the constriction. It seems that the tongue root retraction in emphatics is a by-product of the general retraction of the tongue dorsum and not an independent gesture. The variation in tongue root retraction in uvulars is reported by Ghazeli (1977) in which he indicated that the tongue root and the epiglottis are pulled backward towards the posterior wall of the pharynx during [χ] and [q], but not during [ʁ]. Therefore, the variation in tongue root retraction degree given in Figures 14 & 15 might be a result of tongue root inconsistent retraction in emphatics and uvulars. This is also supported by the acoustic properties of these sounds.

According to resonance models, F1 correlates with the amount of constriction in the oropharyngeal area of the vocal tract (Kent & Read 1992; Pickett 1999). Therefore, the greater the constriction in the front oral portion of the vocal tract, achieved by raising the tongue body which reduces the oral space and expands the pharyngeal space, then the lower F1 will become. Accordingly, F1 values will increase when the tongue body is lowered, which lessens the pharyngeal cavity. In other words, the more the pharyngeal area is, the lower F1 will become. Tongue body height also impacts the pharyngeal cavity of the vocal tract. According to Pickett (1999), lowering the tongue body would force the tongue volume towards the pharyngeal wall, which results in tongue root retraction, both of which will raise F1. For that reason, F1 is affected by tongue body height and tongue root retraction.

F2 is correlated with constriction in the oropharyngeal region of the vocal tract. The location of the constriction and the resultant length of the oral cavity in front of the constriction affect F2 (Pickett 1999). A constriction in the front area of the oral cavity shortens the cavity in front of the constriction and lengthens the pharyngeal cavity, which results in a rise in F2. A constriction further back in the oral cavity lengthens the cavity anterior to the constriction and shortens the pharyngeal cavity, which lowers F2. In other words, the shorter oral cavity with the forward tongue position resonates at a higher F2 frequency and the longer the oral cavity becomes as the tongue is retracted, the lower the frequency that will be resonated. Therefore, F2 is correlated with the location of the tongue body in the front-back dimension.

According to the perturbation theory of Chiba and Kajiyama (1958), a constriction at or near the antinode of a certain formant lowers the formant and a constriction near the formant node causes that formant to be raised. Widening nodes and antinodes have the opposite effect. Therefore, widening a point near an antinode of a formant causes the formant to be increased, while widening a point near a node of a formant causes the formant to be lowered. Points of the nodes and antinodes for F1 and F2 are illustrated in Figure 17.

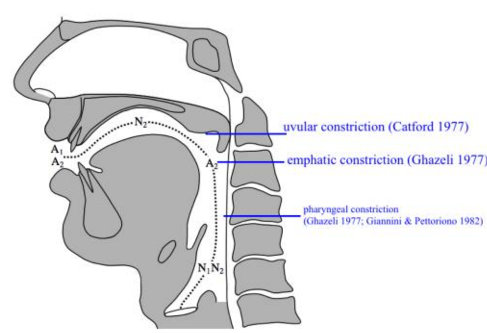


Figure 17: Locations of nodes & antinodes for F1 & F2, adapted from (Bin-Muqbil 2006) page 11

The acoustic studies mentioned in the introduction show that the coarticulatory acoustic effects of emphatics on neighboring vowels distinguish them from their non-emphatic coronals. The main acoustic effect of emphatics on adjacent vowels is a drop in F2 transitions compared to plain coronals. Uvulars, like emphatics, also lower F2 transitions in adjacent vowels. However, the size of F2 drop next to uvulars is not as low as that next to emphatics.

A low F2 value next to emphatics and uvulars is due to constricting an area that coincides with F2 antinode, as shown in Figure 17. Emphatics are associated with lower F2 transition values than uvulars because the point of constriction in emphatics is further back compared to uvulars. As indicated by Figure 7, the point of constriction in emphatics requires further backing of the tongue dorsum towards the upper pharynx, which results in more constriction near F2 antinode. Furthermore, the depression of tongue blade area associated with emphatics, as shown in Figures 7 & 8, coincides with F2 node. The widening of formant node, as suggested by perturbation theory, causes the formant values of the vowel to decrease. Another physiological parameter that lowers F2 in emphatics is lowering the larynx, which is suggested by Hassan & Esling (2011), which elongates the vocal tract. No such adjustment in the larynx was reported for uvulars. These findings support the hypotheses that Arabic emphatics and uvulars both trigger low F2 values in adjacent vowels and that emphatics have lower F2 values in adjacent vowels compared to uvulars.

Pharyngeals are associated with higher F1 values in all adjacent vowels compared to plain coronals. These sounds are articulated with a narrow constriction at the lower part of the pharynx which corresponds to the node of F1 explaining the high values of that formant, as can be seen in Figure 17. Furthermore, raising the larynx during pharyngeals, as reported by (Ghazeli 1977; Bucher & Ahmad 1987; Elgendy 2001; Heselwood 2007), reduces the volume of the pharyngeal cavity, which further increases F1 frequencies.

Laryngeals show no coarticulatory effects on F1 or F2. This outcome in laryngeals is expected since laryngeals do not have any supraglottal adjustments (Zawaydeh 1999; Shar 2012).

The nature of the secondary articulation in Arabic emphatics is a point of disagreement in Arabic literature. This is reflected in different descriptions of Arabic emphatics in different studies. Emphatic consonants have been described differently in different dialects. Emphatics have been termed uvularized in Jordanian Arabic, velarized in Lebanese Arabic and pharyngealized in Iraqi Arabic. Based on the findings of this study, pharyngealization is not an accurate characterization of the secondary articulation in emphatics. Emphatics do not share acoustic correlates or articulatory properties with pharyngeals. Emphatics are associated with low F2 while pharyngeals are associated with high F1 in adjacent vowels. Furthermore, the point of constriction is achieved by tongue root in the lower pharynx in pharyngeals while emphatics are articulated with tongue dorsum retraction to the upper oropharynx. Uvularization, on the other hand, is possible. However, in addition to the fact that no other language is reported to have uvularized consonants besides Arabic, the use of the term uvularization to describe emphatics is problematic since the tongue dorsum retraction in emphatics is different than that in uvulars, as suggested by Figure 10 and reported in many studies such as Al-Ani (1970) and Ghazeli (1977). Velarization is characterized with lowering F2 and F1 is generally not affected (Ladefoged & Maddieson 1996). For the lack of a better term, velarization seems to be relatively the least problematic term compared to pharyngealization and uvularization because velarized consonants in other languages, such as Russian, are phonetically similar to Arabic emphatics. Figure 18 shows X-ray tracings of Russian velarized [$l^{ɣ}$] with its palatalized counterpart [l^{j}] (Bolla 1981). Russian velarized [$l^{ɣ}$], which Bolla (1981) refers to as ‘pharyngealized’, retracts tongue dorsum to the upper pharynx, which is very similar tongue retraction mechanism to Arabic emphatics. This mechanism is accompanied with a decrease in F2 values in adjacent vowels (Ladefoged & Maddieson 1996). As a result, the secondary articulation in Arabic emphatics should be referred to as velarization instead of pharyngealization or uvularization. Perhaps a more suitable term is a one that indicates that Arabic emphatics are retracted to the oropharynx area. Such term would exclude emphatics from being associated with uvulars or pharyngeals, which has bearings on Arabic phonology in which many studies suggest that emphatics are not a subclass of Arabic guttural natural class (e.g. McCarthy 1994).

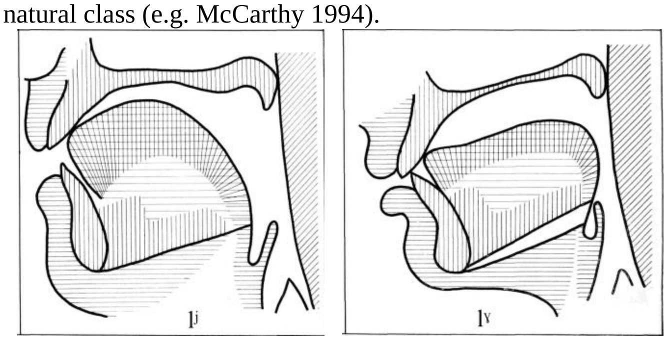


Figure 18: Tongue configurations during [l^{j}] & [$l^{ɣ}$], Bolla (1981), pages 78 & 80

5 Conclusion

The experiment focuses on tongue movements during the articulations of Arabic emphatic and guttural sounds. The use of ultrasound provides good images for the tongue dorsum movement, which is important in distinguishing emphatic from uvular consonants. Results indicate that tongue dorsum retraction is different in these two sound categories. While in uvulars the tongue dorsum moves vertically towards the uvula, it moves horizontally in emphatics towards the oropharynx region. Furthermore, emphatics showed tongue depression behind the main articulation point, which is absent in uvulars. Also, ultrasound technology captures enough of the tongue root to indicate the similarities and differences between pharyngeal consonants and emphatic and uvular consonants in terms of tongue root retraction that can provide further evidence for the variation in tongue root retraction in emphatics and uvulars compared to pharyngeals.

Besides including more participants in future work on Arabic emphatics and gutturals, Arabic sounds can be examined using an ultrasound machine that gives better frame rate. The ultrasound probe used in this study provided reliable images, however, 15 frames per second rate is slower than North American standard, which is 30 fps. To overcome this limitation, geminated consonants are used in the ultrasound stimuli. Another point that warrants more investigation is the effect of gender on emphasis in Arabic as reported in Wahba (1993) for Egyptian Arabic as well as in Khattab et al. (2006) for Jordanian Arabic. A point of uncertainty in this paper is the involvement of the epiglottis in the articulation of Arabic retracted consonants. It is impossible to see the epiglottis, and difficult to see the part of the tongue root that is obscured by the hyoid bone shadow. This could be avoided by including an additional suitable method of examining the lower part of the pharynx such as endoscopy. The study had not included palate images, which will make the exact point of passive articulators more accurate to measure. Finally, a cross-linguistic articulatory comparison of post-velar sounds is needed in order to gain solid understanding of Arabic emphatics and gutturals.

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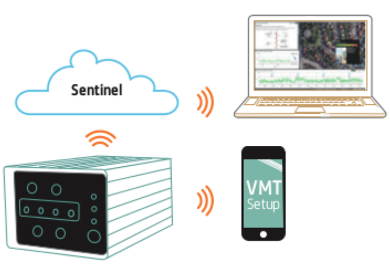

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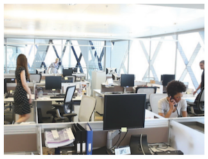


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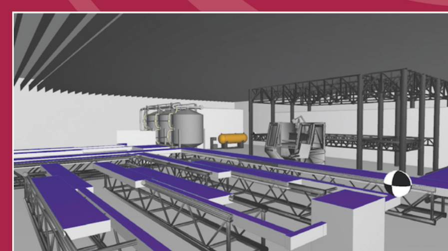
Efficient Workflow

Change your view from 2D to 3D within a second. Multiply the modeling speed by using various shortcuts and automation techniques. Many time-saving acceleration procedures enable a fast calculation process.

Modern Analysis

CadnaR uses scientific and highly efficient calculation methods. Techniques like scenario analysis, grid arithmetic or the display of results within a 3D-grid enhance your analysis and support you during the whole planning and assessment process.

Fields of Application

Office Environments

- Process your acoustic calculations and assessments according to DIN 18041, VDI 2569 and ISO 3382-3
- Receiver chains serve as digital “measurement path” and provide you with relevant insights into the acoustic quality of rooms during the planning phase
- Import of DWG-/DXF-/SKP-files (e.g. pCon.planner, AutoCAD, SketchUp)
- Visualization of noise propagation, noise levels and parameters for quality criteria like the Speech Transmission Index STI

Production Plants

- Calculation of the sound load at workplaces based on the emission parameters specified by the machine manufacturer according to the EC guideline 2006/42/EC while also taking the room geometry and the room design into account
- Tools for enveloping surfaces and free field simulations to verify the sound power of the sources inside of the enveloping surface
- Calculation of the sound power level based on technical parameters such as rotational speed or power

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Carleton University

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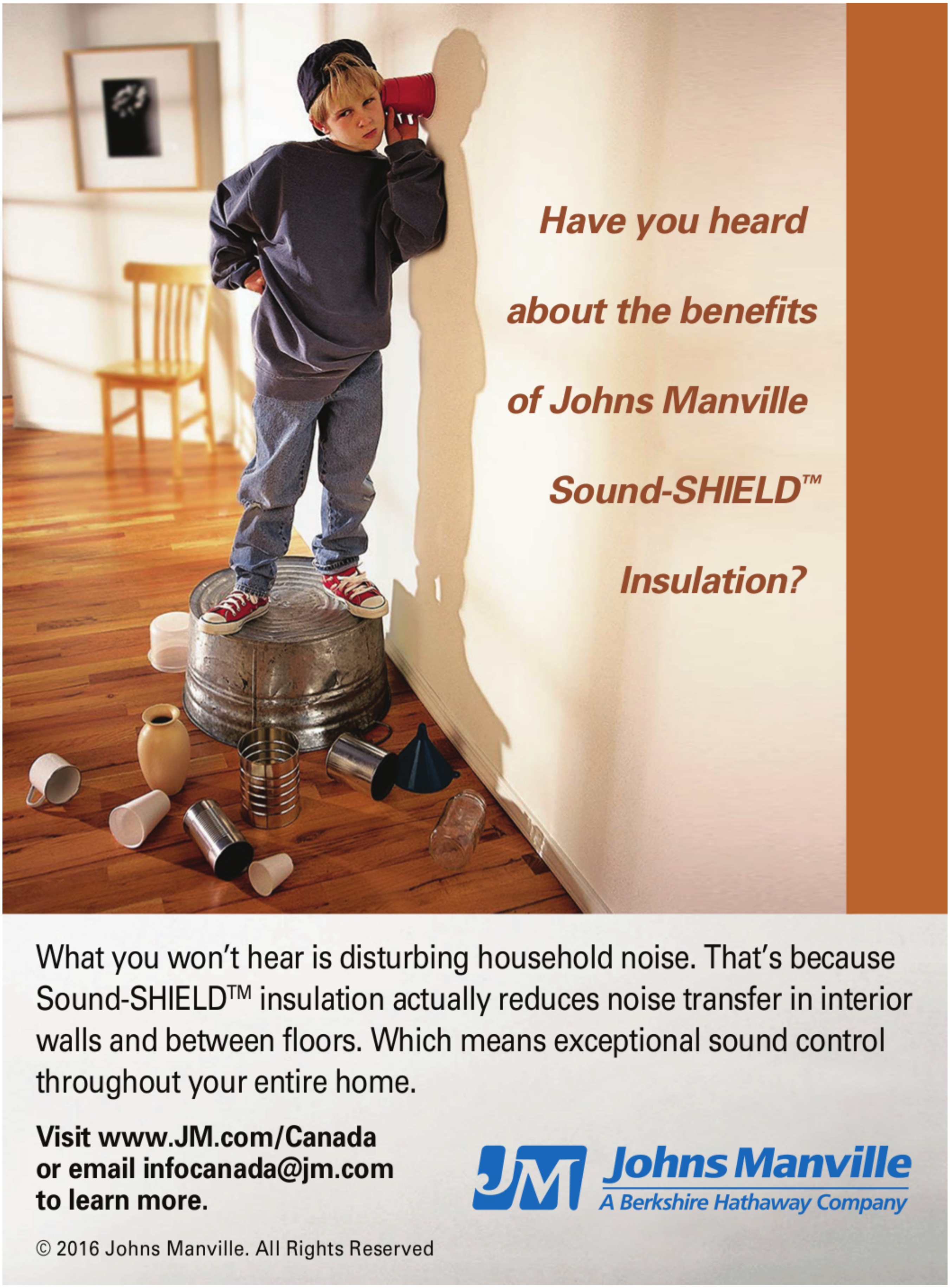
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Call for Papers

Acoustics Week in Canada 2017 – Guelph, Ontario

Your participation is invited for Acoustics Week in Canada 2017 to be held **October 11-13, 2017**. The Canadian Acoustical Association is calling for papers to be presented at the conference hosted at the Delta Hotel and Conference Centre in Guelph Ontario.

This conference highlights the state of the art in acoustics by bringing together leaders, researchers and thinkers. **Keynote speakers** include:

Elliot Berger: Bang! Damage from impulse noise and the effectiveness of hearing protection

John Bradley: A Rationale for a National Classroom Acoustics Standard

Samir Ziada: Flow-Excited Acoustic Resonances

The National Research Council will conduct a special session presenting tools and data available to consultants and designers to address acoustic changes in the National Building Code.

The technical presentations will be organized by topic. The following is a partial list of sessions that are planned:

- Aeroacoustics
- Architectural and Building Acoustics
- Bio-Acoustics and Biomedical Acoustics
- Hearing Conservation
- Musical Acoustics
- Noise and Noise Control
- Physical Acoustics and Ultrasonics
- Psycho- and Physio-Acoustics
- Shock and Vibration
- Signal Processing
- Speech Sciences and Hearing Sciences
- Standards and Guidelines in Acoustics
- Underwater Acoustics

Special sessions on more narrowly-defined topics are being planned. If you are interested in organizing a special session, please contact the Technical Chair – Christian Giguere. Check the conference web site for details.

Key Dates

- Submit **abstracts** for proposed presentations on or before **June 15, 2017** via the conference web site.
- Submit a **two-page paper by August 1, 2017** for publication in the conference proceedings.

Students are strongly encouraged to apply for:

- Conference bursaries available to student presenters; and
- Three $500 prizes awarded to the best student presentations.

Apply before June 1, 2017. Details and application forms are in the Students section of the conference web site.

CALL FOR PAPERS

ACOUSTICS WEEK IN CANADA 2017 – GUELPH, ONTARIO

Registration

	Member	Non-member
Full conference registration	$ 495	$ 615
Student conference registration	$ 275	$ 335

For further details, please refer to the conference web site. Rates go up after September 11, 2017.

Venue and Accommodation

The conference will be held at Marriot's Delta Hotel and Conference Centre in Guelph.

Enjoy the convenience of staying at the conference venue. The hotel has set aside a block of rooms for the conference at a special rate of **$129 per night** for reservations made until September 11^{th}. Claim the special rate by reserving at 519-780-3700 or 1-800-268-1133 and identifying the group Canadian Acoustical Association (Group Code CAN101017_001). Extend your stay and enjoy the local area at the same special rate. Guests have free access to the large Movati Athletic fitness centre next door.

Exhibition

You will have opportunities to look for new products and try the latest in equipment from key suppliers to the acoustic community. Look for them at the conference exhibition for in-person and hands-on interaction!

Suppliers who have not yet reserved their spot should do so by contacting the Exhibits and Sponsorship coordinator – Bernard Feder.

Key Contacts:

Conference Chair: Peter VanDelden(conference@caa-aca.ca)

Technical Chair: Christian Giguère(cgiguere@uottawa.ca)

Exhibits and Sponsorship: Bernard Feder (bfeder@hgcengineering.com)

Registration: Dalila Giusti(treasurer@caa-aca.ca)

Conference Web Site: Kyle Hellewell(kyle.hellewell@rwdi.com)

http://awc.caa-aca.ca

APPEL À SOUMISSIONS

SEMAINE CANADIENNE DE L'ACOUSTIQUE 2017 - GUELPH, ONTARIO

Vous êtes invités à participer à la Semaine canadienne de l'acoustique 2017 qui aura lieu du 11 au 13 octobre 2017. Les articles soumis à l'Association canadienne d'acoustique seront présentés lors de la conférence qui se tiendra dans l'hôtel Delta et au centre de conférences de Guelph Ontario.

Cette conférence met en lumière l'état de l'art en acoustique en réunissant des meneurs, des chercheurs et des intellectuels. Les principaux conférenciers seront :

Elliot Berger : Bang ! Dommages causés par les bruits impulsifs et l'efficacité de la protection auditive

John Bradley : Une raison pour une norme nationale en acoustique des salles de classe

Samir Ziada : Résonances acoustiques excitées par un flux

Le Conseil national de recherches du Canada (CNRC) tiendra une session spéciale sur les outils et les données disponibles pour les consultants et concepteurs afin de présenter les derniers changements au Code national du bâtiment (CNB).

Les présentations techniques seront organisées par thème et la liste partielle des sessions planifiées sera la suivante :

- Aéroacoustique
- Acoustique architecturale et du bâtiment
- Bioacoustique et acoustique biomédicale
- Conservation de l'audition
- Acoustique musicale
- Bruit et contrôle du bruit
- Acoustique physique et ultrasons
- Psycho et physio-acoustique
- Chocs et vibrations
- Traitement du signal
- Sciences de la parole et sciences de l'audition
- Normes et réglementations en acoustique
- Acoustique sous-marine

Des séances spéciales sur des sujets plus étroitement définis sont prévues. Si vous souhaitez organiser une session spéciale, veuillez contacter le président technique - Christian Giguere. Pour plus de détails, veuillez consulter le site Web de la conférence.

Dates clés

- La soumission des proposions des **résumés** des présentations est à effectuer au plus tard le **15 juin 2017** via le site Web de la conférence.
- La soumission des **articles de deux pages** est à effectuer au plus tard le **1er août 2017** pour publication dans les actes de la conférence.

Les étudiants sont vivement encouragés à envoyer leur candidature pour :

- Les bourses de conférence offertes aux étudiants effectuant une présentation ;
- Les trois prix de 500 $ attribuées aux meilleures présentations étudiantes.

Toutes les candidatures devront être parvenues avant le 1er juin 2017. Les détails et les formulaires de candidature se trouvent dans la section Étudiants du site Web de la conférence.

Appel à soumissions

Semaine canadienne de l'acoustique 2017 - Guelph, Ontario

Inscription

	Membre	Non-membre
Inscription à la conférence complète	495 $	615 $
Inscription à la conférence - forfait étudiant	275 $	335 $

Pour plus de détails, veuillez consulter le site Web de la conférence. Veuillez noter que les frais d'inscriptions seront majorés en cas d'inscriptions effectuées après le 11 septembre 2017.

Lieu et logement

La conférence se tiendra au Marriot Hotel Delta et au centre de conférence de Guelph.

Profitez de la commodité de séjourner au lieu de la conférence. L'hôtel a réservé plusieurs chambres pour la conférence à un tarif préférentiel de **$129 par nuit** pour les réservations faites avant le 11 septembre. Pour bénéficier de ce tarif, n'oubliez pas de mentionner que vous êtes membre de l'Association canadienne d'acoustique (Code de groupe CAN101017_001) lors de votre réservation par téléphone au 519-780-3700 ou au 1-800-268-1133. Il est également possible de prolonger votre séjour pour profiter davantage de la région, tout en continuant à bénéficier du tarif préférentiel. Durant votre séjour, vous aurez la possibilité d'accéder gratuitement au grand centre de fitness Movati Athletic situé juste à proximité de l'hôtel.

Exposition

Durant la conférence, vous aurez la possibilité de découvrir et d'essayer les nouveaux produits et les derniers équipements proposés par les principaux fournisseurs de la communauté acoustique. N'hésitez pas à venir les rencontrer en personne durant l'exposition de la conférence !

Les fournisseurs qui n'ont pas encore réservé leur place doivent le faire en contactant le coordinateur des expositions et commandites - Bernard Feder.

Contacts clés :

Président de la Conférence: Peter VanDelden (conference@caa-aca.ca)

Président technique: Christian Giguère (cgiguere@uottawa.ca)

Expositions et commandites: Bernard Feder (bfeder@hgcengineering.com)

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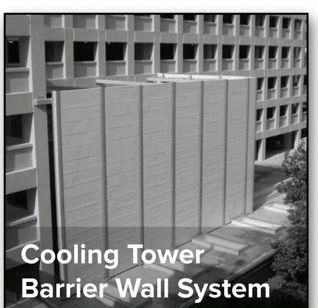

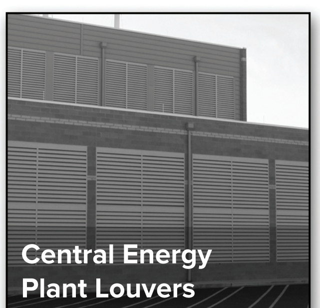

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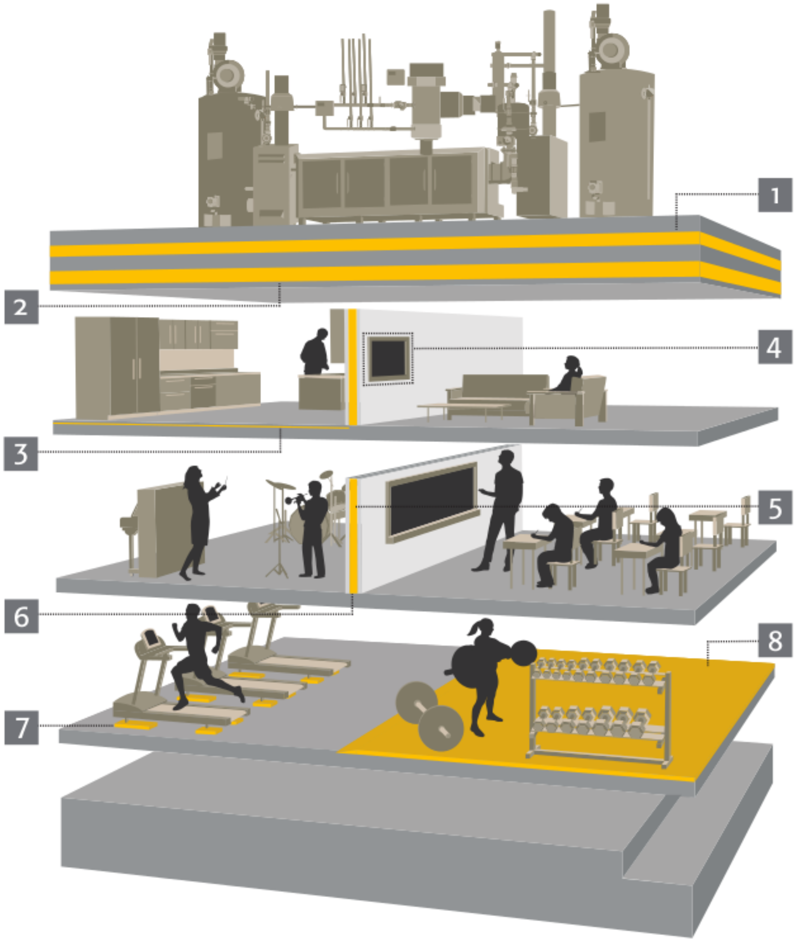

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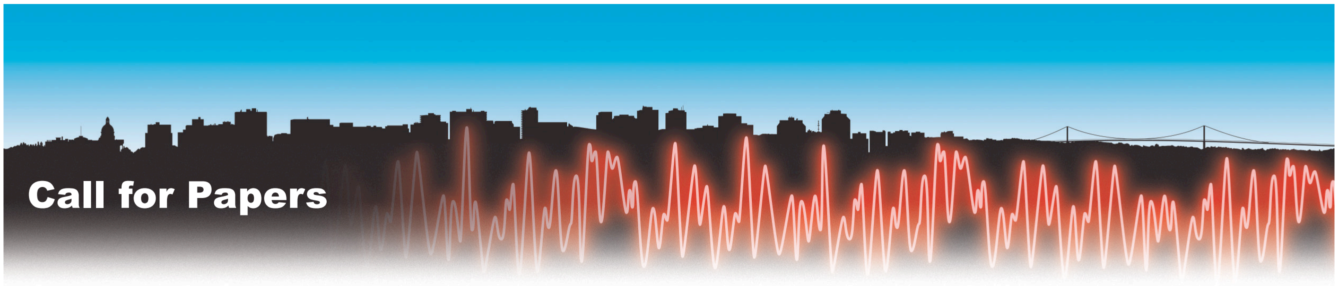


HALIFAX

Special issues with regional topics and articles

Acoustics is a broad subject matter, as you know, that currently employs hundreds of us across the country in fields as different as teaching, research, consulting and others. To reflect such diversity and to -maybe- help each of us discover a new professional in the neighborhood, the Canadian Acoustics journal is currently inviting submissions for a series of special “regional” journal issues from individuals, groups and companies located within the greater-areas of major cities in Canada.

Special issues of the Canadian Acoustics journal have been tentatively programmed for June 2015 (Montreal), June 2016 (Toronto), and June 2017 (Halifax) while other dates will later be added for the other cities.

How to be part of it?

To contribute to these special “regional” journal issues, authors are invited to submit their manuscript (2 pages maximum), in English or in French, under “Special Issue” section through the online system at http://jcaa.caa-aca.ca before **April 30th** of the publication year. The first author must be located in the greater area of the targeted city. Two versions of the same article can be published in the two official languages.

Each manuscript will be reviewed by the Canadian Acoustics Editorial Board that will enforce the journal publication policies (original content, non-commercialism, etc., refer to Journal Policies section online for further details) while welcoming promotion of authors’ expertise, companies services, and consultants' success stories and the like.

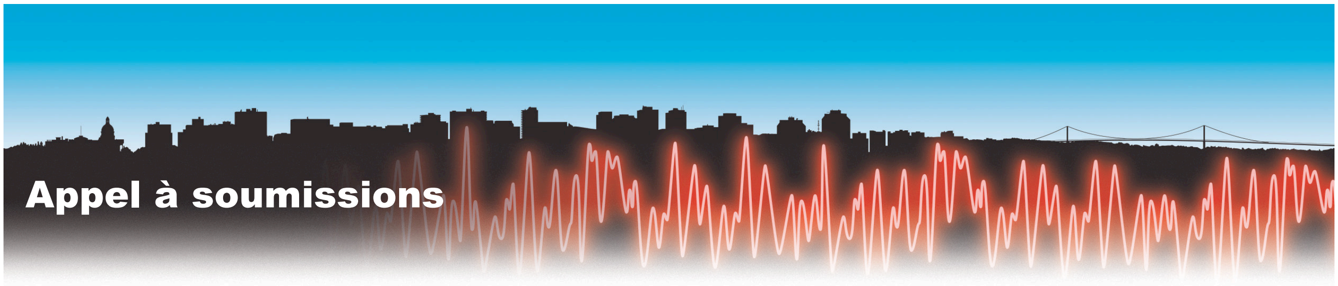
A true “regional directory” you want to appear in!

Each of these regional local issues of the journal can be considered as a local directory book for acoustics. They will be published in hardcopies, sent to all CAA national and international members, while electronic copies will be made available in open-access on the journal website. The content of these issues will be entirely searchable and comprehensively indexed by scholar engines as well as by major internet search engines (Google, Bing, etc.). Authors are invited to carefully select their keywords to maximize the visibility of their articles, while ad-hoc advertisement opportunities will be given to pair each article with a one-page full advertisement.

For any questions, please contact Sean Pecknold (pecknold.s@gmail.com) or Mikael Kiefte (mkiefte@gmail.com). To secure an advertisement for this special issue, please contact our coordinator (advertisement@caa-aca.ca).

Such an offer will only repeat in 7 to 9 years – be sure to submit now!

http://jcaa.caa-aca.ca



HALIFAX

Numéros spéciaux portant sur des sujets régionaux

Comme vous savez, l'acoustique donne matière à plusieurs sujets d'ordre général et créer des centaines d'emplois au pays, et ce, dans différents secteurs tels que l'éducation, la recherche, la consultation professionnelle et autres. Afin de bien refléter cette diversité et peut-être même à faire connaître davantage les professionnels de notre voisinage qui œuvrent dans le domaine, l'Acoustique canadienne fait un appel à soumettre une série d'articles provenant de personnes, groupes ou compagnies qui font partie d'une même grande région du Canada.

Pour le moment, la programmation provisoire des numéros spéciaux régionaux de l'Acoustique canadienne va comme suit : juin 2015 (Montréal), juin 2016 (Toronto), et juin 2017 (Halifax). D'autres dates et villes seront ajoutées au fil du temps.

Comment en faire partie?

Pour contribuer à un de ces numéros « régionaux », les auteurs sont invités à soumettre un article (de 2 pages maximum), sous la rubrique « Numéro spécial » dans notre système en ligne au http://jcaa.caa-aca.ca avant le **30 avril** de l'année de publication. Le premier auteur devra faire partie de la grande région de la ville concernée. Il est possible de soumettre un même article dans les 2 langues officielles.

Chaque article sera révisé par le comité éditorial de l'Acoustique canadienne qui veillera à ce que les politiques de publications de la revue soient respectées (contenu original, contenu non commercial, etc. – voir les politiques de la revue pour de plus amples détails) tout en accueillant les articles qui font la promotion de l'expertise des auteurs, des services offerts par les compagnies, les réussites de consultants et autres sujets du même ordre.

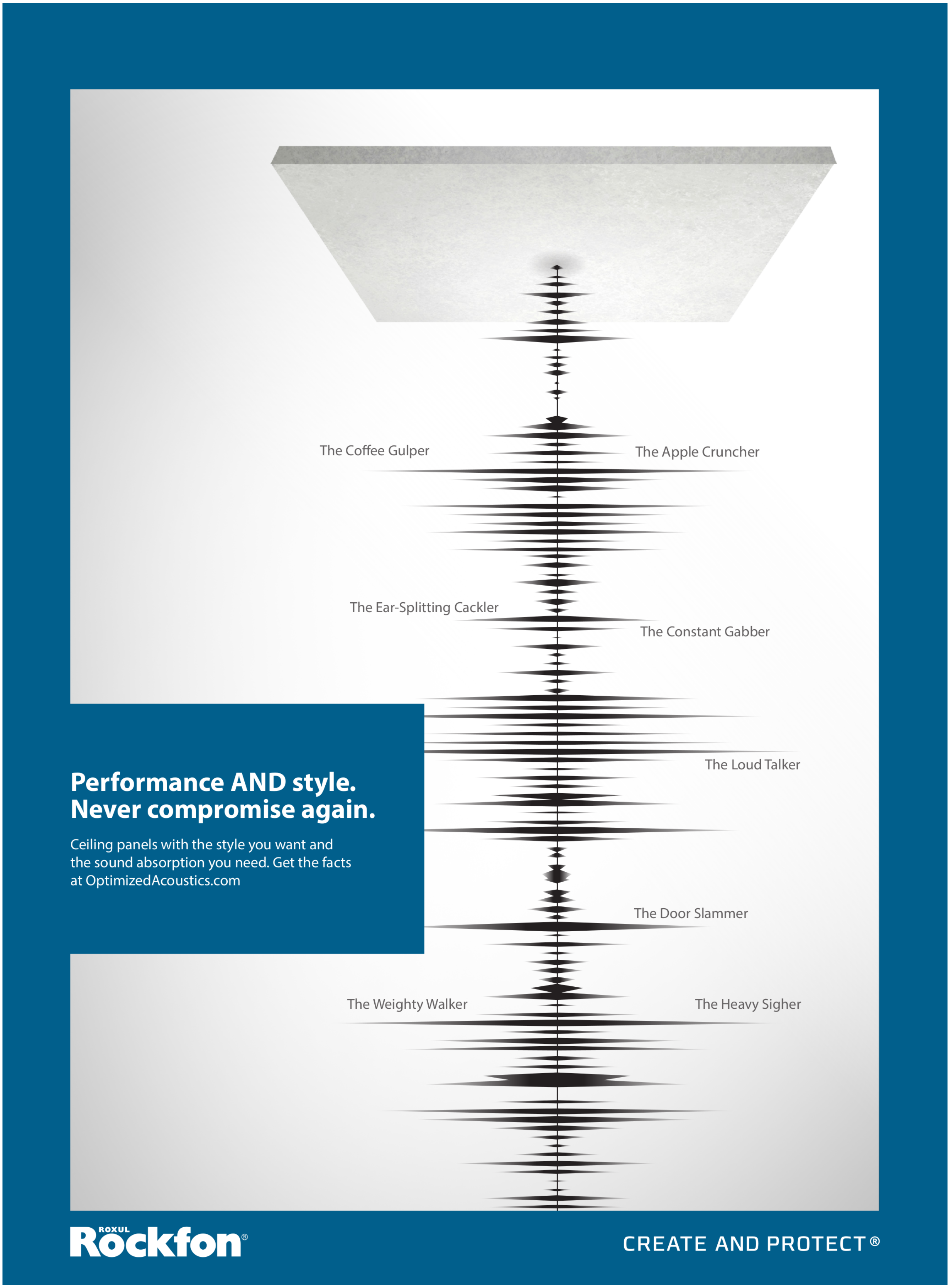
Un vrai « répertoire régional » dans lequel vous voulez paraître!

Chacun de ces numéros spéciaux régionaux pourra être considéré comme un répertoire des noms et services locaux liés à l'acoustique. Ils seront publiés en format papier et envoyés à tous les membres nationaux et internationaux de l'ACA. Une version électronique sera aussi disponible en ligne sur le site internet de la revue. Le contenu de ces numéros sera indexé, donc facilement trouvable au moyen de moteurs de recherche majeurs, tels Google, Bing, etc.). Les auteurs sont invités à bien choisir les mots clefs pour maximiser la visibilité de leur article. Des opportunités de publicité ad hoc seront offertes pour jumeler chaque article avec une page complète de publicité.

Pour toutes questions, vous pouvez communiquer avec Sean Pecknold (pecknold.s@gmail.com) ou Mikael Kiefte (mkiefte@gmail.com). Pour réserver un espace de publicité dans un de ces numéros spéciaux, veuillez communiquer avec notre coordonnateur (advertisement@caa-aca.ca).

Une telle offre ne se reproduira pas avec 7 ou 9 ans, assurez-vous d'en profiter maintenant!

http://jcaa.caa-aca.ca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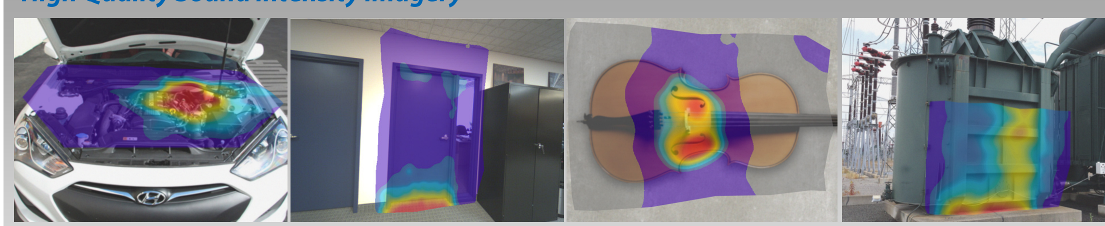

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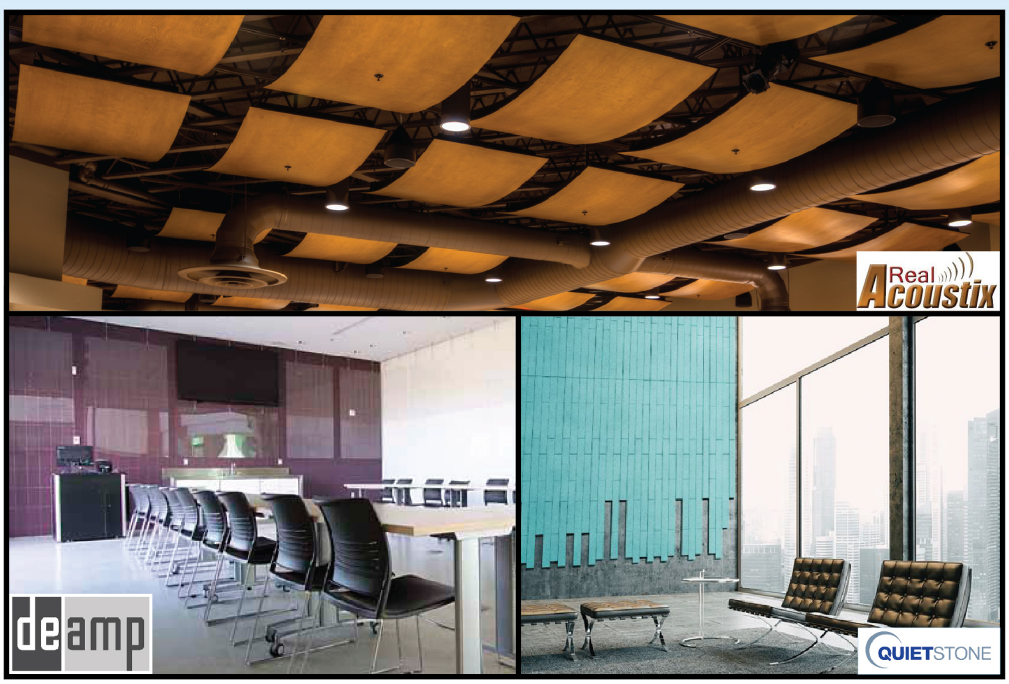

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Looking for a job in Acoustics?

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

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

August 5th 2015

CAA is now social!

Canadian Acoustical Association is moving to the social media!

Find us on social media: - Twitter: CanAcoustical - Facebook: facebook.com/canadianacousticalassociation

December 14th 2015

Prof. Michael Kiefkte appointed as Associate Editor for Speech Sciences

Prof. Michael Kiefkte, has recently accepted the position of Associate Editor for Speech Sciences for Canadian Acoustics.

Prof. Michael Kiefkte, has recently accepted the position of Associate Editor for Speech Sciences for Canadian Acoustics.

November 5th 2016

Philip Tsui appointed as webmaster for Canadian Acoustical Association

Philip Tsui, has recently accepted to act as our new webmaster, and will be in charge of our core website, the journal website and the conference website. -

The Canadian Acoustical Association would like to tank again Dr. Sean Pecknold for all his service over the years.

November 5th 2016

Acoustics exhibition at the Musée de la Nature et des Sciences in Sherbrooke (QC)

The Musée de la Nature et des Sciences in Sherbrooke will feature an exhibition on Acoustics.

A group from the Université de Sherbrooke led by Dr. Olivier Robin approached the CAA with a request for support of a new exhibition they are planning entitled 'Musée de la Nature et des Sciences'. This exhibit is intended to disseminate knowledge about acoustics to the general public, including information about sources of sound, sound propagation and sound reception. This initiative aligns well with our interest as an Association in education and outreach, as well as with activities being planned by the International Commission of Acoustics (of which the CAA is a member) for the proposed UNESCO "Year of sound" in 2019 (http://www.sound2019.org). The board agreed to commit up to $2000 of financial support along with promotional assistance. We expect that the group will be able to present elements of the exhibition in the journal and at an upcoming Acoustics Week in Canada.

November 5th 2016

INTER-NOISE 2017: Conference Updates

INTER-NOISE 2017, the 46th International Congress and Exposition on Noise Control Engineering, will be held in Hong Kong, China, between 27 and 30 August 2017. The Congress is organised by the Hong Kong Institute of Acoustics and the Hong Kong Polytechnic University, in conjunction with NVH Branch, Society of Automotive Engineering China and the Acoustical Society of China. - -

- INTER-NOISE 2017 will provide the best opportunity for engineers and scientists in all fields of acoustics to learn about and share their work with colleagues from around the world. More than hundred technical sessions would be arranged for exchange of views and sharing of experience. Please be reminded that the abstract submission deadline is 31 March 2017.

March 2nd 2017

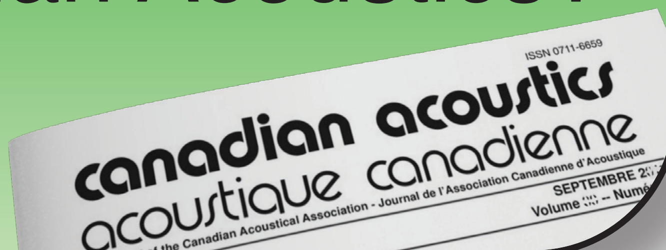
À la recherche d'un emploi en acoustique ?

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

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

August 5th 2015

Why publish in Canadian Acoustics?



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