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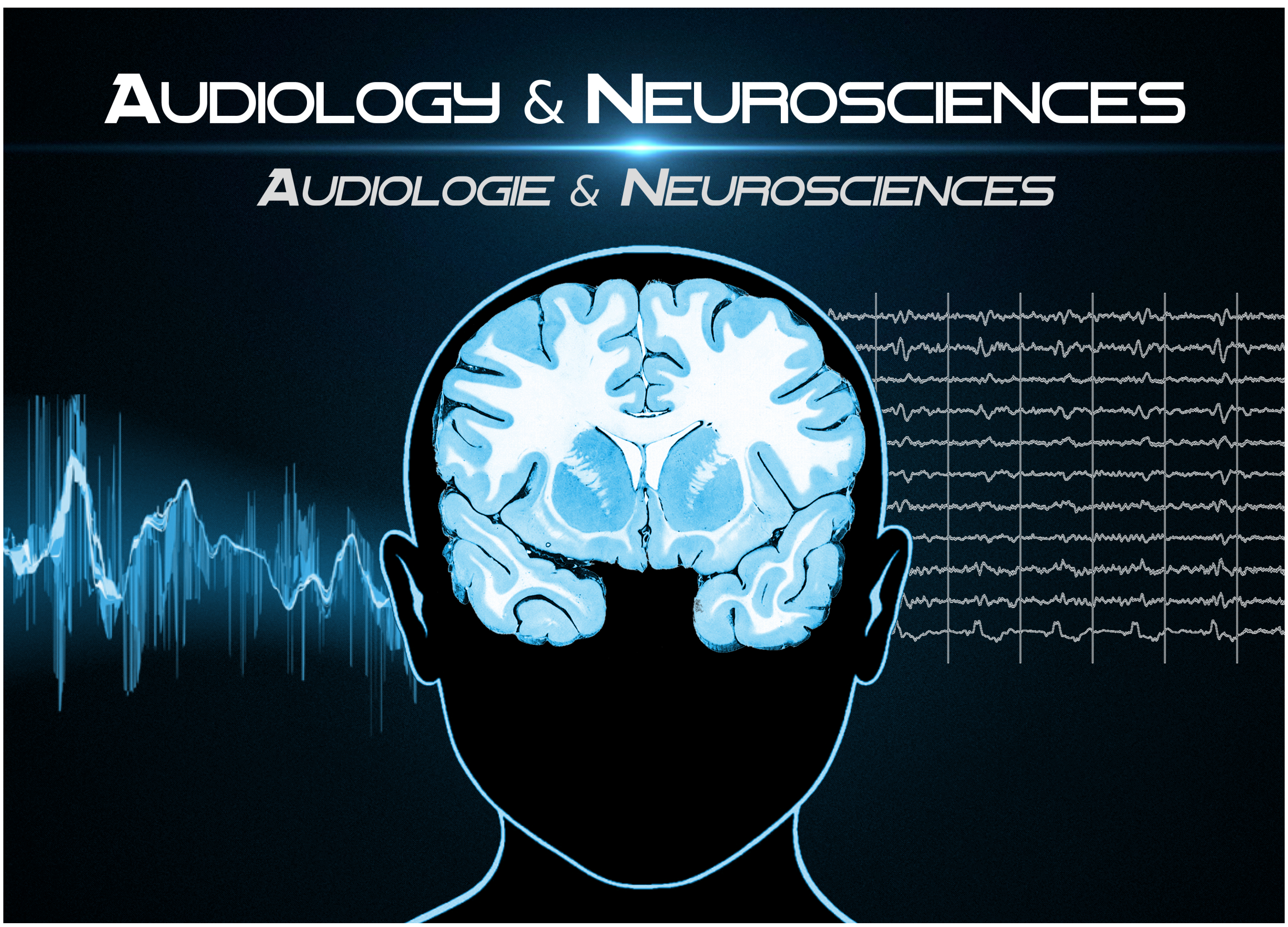

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Acoustique canadienne est publié quantre fois par an, en mars, juin, septembre et décembre. Cette revue trimestrielle est envoyée gratuitement aux membres individuels de l'Association canadienne d'acoustique (ACA) et aux abonnés institutionnels. L'Acoustique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

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Editor's note
Éditorial

Special Issue: Audiology and Neurosciences

Acoustics is a broad subject matter that currently employs hundreds of us across Canada in fields as different as teaching, research, consulting and others. To reflect such diversity the Canadian Acoustics has been regularly publishing over the last 40 years a series of special journal issues to highlight thematic topics related to acoustics. Therefore, it is my pleasure to present this special issue which includes research topics on audiology and in neurosciences related to acoustics and/or music.

Among the articles included in this special issue, you will find: a contribution aiming to raise the awareness of the damage to the integrity of the peripheral auditory system, an article about the development of an acoustical beamformer based on eye movements recordings and several articles investigating the effect of bilingualism, musical training, and intermittent noises on the auditory brainstem responses.

I would like to thank all the authors whose contributions are the essence of this special issue. I would also like to acknowledge the reviewers for their support and their promptness during this busy time of the year. This was much appreciated.

Before closing this editorial, I would like to welcome Pierre Grandjean, PhD student at Université de Sherbrooke, who kindly accepted to be our new Copyeditor, as I am stepping down from this role.

I wish you a pleasant reading, and a pleasant summer!

Olivier Valentin
Guest editor-in-chief

Édition spéciale : Audiologie et Neurosciences

L'acoustique est un vaste domaine qui offre des centaines d'emplois à travers le Canada, et ce, dans différents secteurs tels que l'éducation, la recherche, la consultation professionnelle, et bien d'autres. Afin de bien refléter cette diversité, l'Acoustique Canadienne a publié régulièrement au cours des 40 dernières années une série de numéros spéciaux pour souligner les divers champs d'applications de l'acoustique. C'est donc avec plaisir que je vous présente ce numéro spécial portant sur des thématiques recherche en audiologie et en neurosciences en lien avec l'acoustique et/ou la musique.

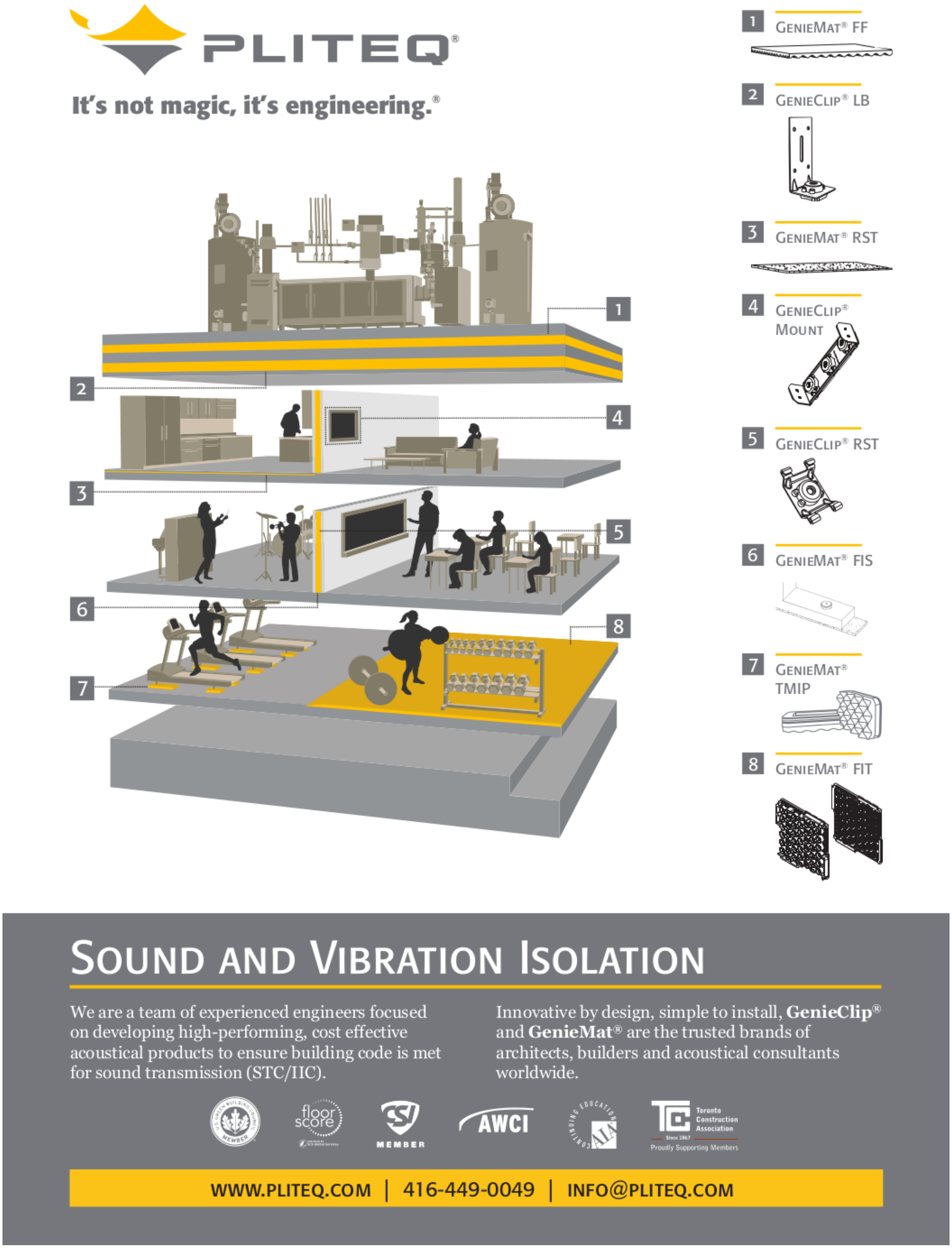
Parmi les articles de ce numéro spécial, vous trouverez : un article de sensibilisation sur les principales atteintes du système auditif périphérique, un article traitant du développement d'un *beamformer* basé sur l'enregistrement des mouvements oculaires et plusieurs articles portant sur l'effet du bilinguisme, de l'apprentissage musical et des bruits intermittent sur les potentiels évoqués du tronc cérébral.

Je tiens à remercier tous les auteurs dont les contributions sont l'essence même de ce numéro spécial. Un grand merci également aux évaluateurs pour leur support et leur promptitude en cette période de l'année souvent très chargée.

Avant de terminer cet éditorial, je tiens à souhaiter la bienvenue à Pierre Grandjean, étudiant au doctorat à l'Université de Sherbrooke, notre nouveau relecteur-réviseur.

Je vous souhaite, à toutes et à tous, une bonne lecture et un été agréable !

Olivier Valentin
Éditeur-en-chef invité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AUDITORY FUNCTIONS OF THE PERIPHERAL HEARING SYSTEM AND THE COMMON CONDITIONS AFFECTING SOUND CONDUCTION

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Résumé

Le système auditif périphérique combine une transmission mécanique et électrique via les différentes structures de l'oreille externe, moyenne et interne. L'Organisation Mondiale de la Santé estime que 6,1% de la population présente une atteinte auditive bilatérale. Cet article résume le rôle des différentes composantes du système auditif périphérique et présente les causes les plus communes de perte auditive touchant la transmission mécanique des sons chez l'humain. Quelques causes fréquentes d'atteinte auditive touchant la transmission neurale sont aussi abordées. Plus précisément, l'occlusion du conduit auditif externe, l'otite externe (dans le cas où l'enflure est si importante qu'elle bloque le conduit auditif), la dysfonction tubaire (trompe d'Eustache), l'otite moyenne séreuse et aiguë, la perforation tympanique, le cholestéatome, la discontinuité ossiculaire, l'otosclérose, la maladie de Ménière, la presbyacousie et la perte auditive causée par l'exposition au bruit sont brièvement abordés dans cet article afin de sensibiliser l'ensemble de la communauté de l'Acoustique Canadienne à ces problèmes et pathologies.

Mots clés : système auditif, anatomie, physiologie, conduction mécanique, pathologies

Abstract

The peripheral hearing system combines mechanical and electrical transmission through the different structures of the outer, middle and inner ear. The World Health Organization estimates a prevalence of 6.1% of the world population living with a bilateral disabling hearing loss. Here, the roles of the different peripheral hearing system structures are reviewed and the most common causes of hearing loss related to mechanical transmission in the human ear are presented. Some common causes of sensorineural hearing loss are also discussed. More precisely, ear canal blockage, external ear infection (when the ear canal is blocked due to severe swelling), Eustachian tube dysfunction, serous and acute otitis, tympanic membrane perforation, cholesteatoma, ossicular chain discontinuity, otosclerosis, Meniere's disease, presbycusis and noise-induced hearing loss are briefly presented in this paper in an attempt to highlight these problems and pathologies to the Canadian acoustical community.

Keywords: hearing system**,** anatomy, physiology, mechanical transmission, pathologies

1 Introduction

The prevalence of hearing loss worldwide is difficult to estimate. Studies on the subject use different measuring tools, ranging from subjective questionnaires (completed by the subject or by someone in the household) to clinical evaluations in a sound-attenuating booth. Moreover, the criteria to conclude the occurrence of hearing loss vary in terms of intensity and frequencies.

For example, Goman and Lin (2016) determined the prevalence of hearing loss in the US by using an average criterion to sort the impairments by severity. This average criterion was computed using pure-tone thresholds estimated at 500, 1000, 2000 and 4000 Hz in a sound-attenuating booth. If the average criterion was superior to 25 dB HL, individuals were considered to present a hearing loss [1]. Using such methodology, Goman and Lin concluded that the prevalence of hearing loss in the US for 12 year olds and older is estimated at 23% [1]. Their study also reported that mild hearing loss was more frequent (estimate of 25.4 million cases), except for individuals aged 80 years or older for whom a moderate hearing loss (mean threshold between 41 and 60 dB HL) was more frequent than a mild hearing loss (mean threshold 26 to 40 dB HL). Using the same severity criterion and average frequency method, Feder et al. (2015) estimated that 19.2% of Canadians aged between 20 and 79 years old presented a hearing loss and that 12% of Canadian adults suffer from a mild hearing loss [2]. Their study also reported that the prevalence was more important in younger subjects (less than 10%) and reached 50 to 65% in 70-79 years old [2].

As for children and teenagers, Feder et al. (2017) studied 2434 individuals aged between 6 and 19 years old with valid audiometric results. In this study, they defined the hearing loss as a pure-tone average (for each ear separately) of more than 20 dB HL in individuals aged between 6 and 18 years old and of more than 25 dB for individuals aged 19 years old, using different pure-tone average frequencies. A global average was computed using thresholds estimated at 500,

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1000, 2000 and 4000 Hz. A high frequency average was computed using thresholds estimated at 3000, 4000, 6000 and 8000 Hz. A low frequency average was computed using thresholds estimated at 500, 1000 and 2000 Hz [3]. Hearing losses were found by using at least one of the pure-tone averages in 7.7% of the individuals aged between 6 and 19 years old, and 4.7% for the 4 frequencies pure-tone average [3]. The majority of these hearing losses were unilateral and the most frequent severity was mild. The authors report a possible underestimation of the true prevalence since many subjects were excluded because no audiometric valid results could be measured or because the ear canal showed excessive earwax or pus [3]. In newborns, the prevalence of permanent hearing loss is estimated to 133 per 100 000 live births [4].

The World Health Organization estimates that 6.1% of the world population has a disabling hearing loss (defined as a 40 dB and 30 dB hearing loss in the better ear in 15 years or older and 14 years and under respectively) [5].This paper aims to report the more frequent hearing loss etiologies affecting the mechanical transmission of the sounds in the peripheral hearing system, in an attempt to sensitize the Canadian acoustical community to the various origins of such hearing impairments that are widely reported in the literature. The first part of the article describes the normal function of the peripherical hearing system and the common hearing dysfunctions are presented in the second portion. Pathologies affecting the sound transmission, rather than the mechanical transmission part, were excluded in this paper, except for the most prevalent ones: NIHL and presbycusis. Rare afflictions and malformations will also be excluded.

2 Hearing function

As can be seen in figure 1, from the time a sound wave enters the outer ear to the time it reaches the inner ear and is processed by central auditory pathways, many mechanical and electrical functions (neural transmission) are required.

2.1 External ear

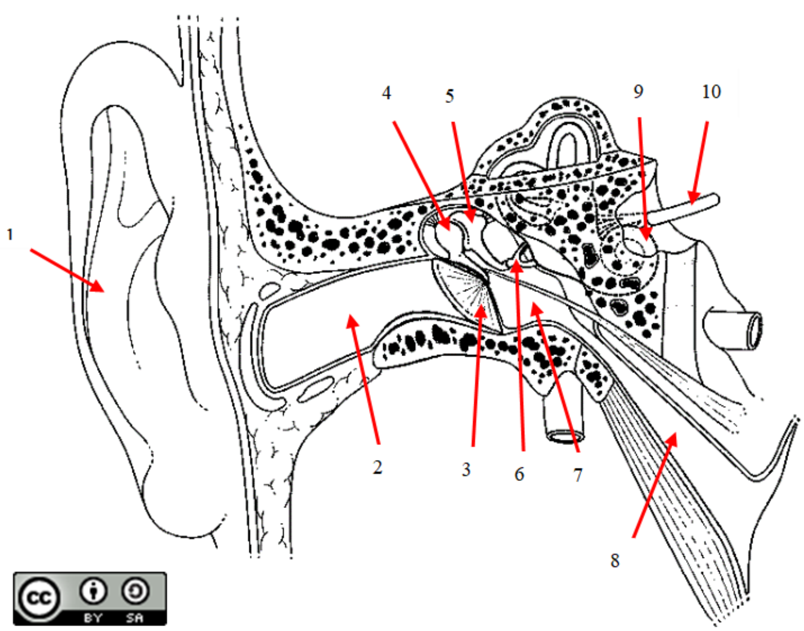
When a sound reaches a normally functioning ear, it first meets the external ear. The external ear is comprised of the pinna and the external ear canal (figure 1) [6]. The pinna has a peculiar shape that allows both sound localization in the vertical plane and sound amplification: the mid frequencies from 2000 and 7000 Hz are slightly amplified [6, 7]. The sound then travels in the ear canal, another source of sound amplification composed of an external cartilaginous portion and an inner bony portion [8].

2.2 Middle ear

At the end of the external auditory canal, the sound reaches a thin translucid membrane called the tympanic membrane, or eardrum (figure 1, figure 4a) [7, 8]. The tympanic membrane is the first structure of the middle ear and is composed of three layers. The condensations and rarefactions of the sound make the tympanic membrane vibrate, and the three middle ear ossicles (called malleus, incus and stapes) are put into motion as well, transforming the acoustical energy into mechanical energy [9]. The three ossicles are linked with one another and the ossicle chain is suspended in the middle ear cavity by ligaments [10]. The last ossicle of the chain, the stapes, transfers the movement to the oval window, a small opening in the inner ear which is covered with a flexible membrane.

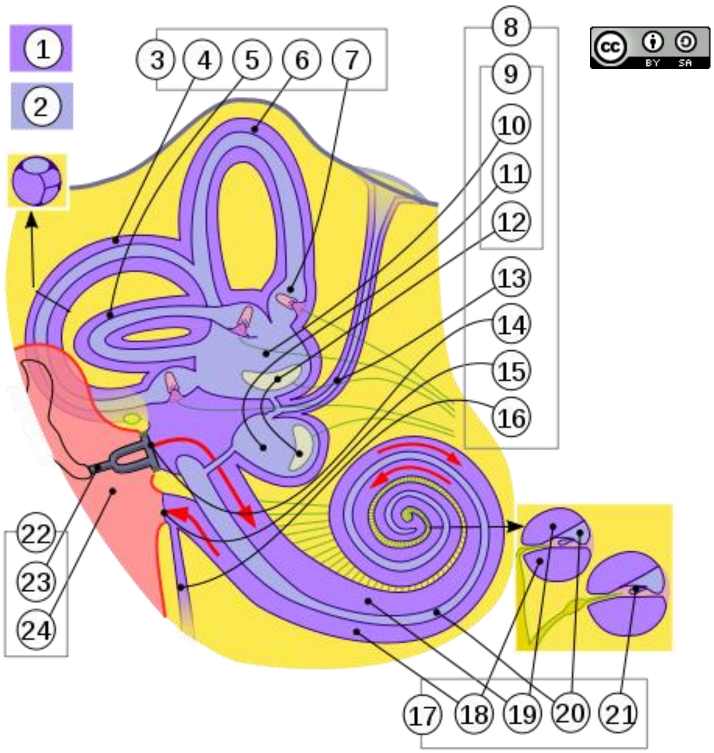
During the transfer of the movement to the oval window, the ossicles also amplify the movement, mainly around 1-2 kHz [9, 11, 12]. When the stapes presses on the oval windows, it causes the liquid of the inner ear (the perilymph) to move.

During this change in medium, the middle ear uses two principles to match the impedance: firstly the tympanic membrane has a much larger surface than the oval window, and secondly the lever action of the incus and malleus [9].



1- Pinna
2- External auditory canal
3- Tympanic membrane (eardrum)
4- Malleus
5- Incus
6- Stapes
7- Tympanic cavity (middle ear)
8- Eustachian tube
9- Cochlea (inner ear)
10- Auditory nerve

Figure 1: Peripheral hearing system. Modified by adding arrows and numbers from the original drawing by Didier Descouens, licensed under CC BY-SA.



1 Perilymph
2 Endolymph
3 Semicircular canals
4 Posterior semicircular canal
5 Horizontal semicircular canal
6 Superior semicircular canal
7 Ampula
8 Vesibule
9 Otolith organs
10 Utricule
11 Saccule
12 Vestibular maculae
13 Endolymphatic duct
14 Oval window
15 Round window
16 Perilymphatic duct
17 Cochlea
18 Scala tympani
19 Scala vestibuli
20 Cochlear duct
21 Oran of Corti
22 Middle ear
23 Stapes
24 Tympanic cavity (middle ear)

Figure 2: Inner ear. Original drawing by Jmarchn, licensed under CC BY-SA.

Middle ear pressure

The equalization of the air pressure in the middle ear is ensured by the Eustachian tube [13]. This structure is a small tube (24 mm long, with a bony and cartilaginous portion) between the nasopharynx and the middle ear which has a protective role: protection against self-generated body sounds such as voice, breathing and heartbeat (also called autophony), protection against infections and protection against inner body sudden pressure change (like when coughing) [14-16]. Most of the time, the Eustachian tube is closed. It normally opens when swallowing or following jaw movements or yawning [15]. These occasional openings allow one to equilibrate pressure outside and inside the middle ear, and to bring in fresh air and oxygenate the walls of the middle ear, recovered with mucosal tissue [17].

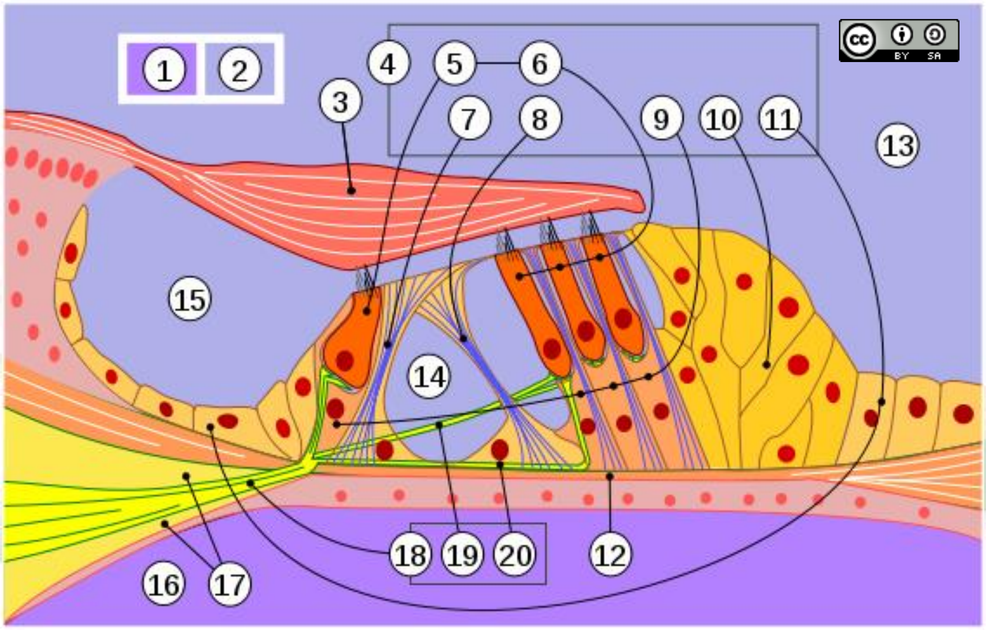
Reduction of loud noises

In the middle ear, the stapedial muscle (not shown on Figure 1) contracts in the presence of a loud noise (generally 85 to 100 dB SPL for pure tone stimuli), thus stiffening the ossicular chain and reducing the intensity of the noise reaching the cochlea [9, 18]. In order for this reflex to occur, other structures need to be functioning well, such as the cochlea, auditory nerve, facial nerve and brainstem structures [18]. However, this reflex has a few limits: it does not protect for long noise exposures, has a small activation delay which does not protect against impact noises and mostly protects against low frequency noises [7, 9].

2.3 Inner ear

The inner ear, also called the cochlea, is filled with two different kinds of fluids: perilymph and endolymph. These liquids travel in three canals all along the two and a half spires of the cochlea: the endolymph in the cochlear duct and perilymph in the scala vestibuli and scala tympani (Figure 2) [7]. The scala vestibuli and the scala tympani are connected at the apex of the cochlea, a point named helicotrema [7]. Along with the oval window, the round window allows perilymph to move when the stapes moves. The movement of the stapes and the presence of the two windows allow a movement of the fluids, resulting in a vibration of the basilar membrane, on which the Organ of Corti rests [7, 9]. Even if the organ of Corti is similar along the two and a half turns of the cochlea, the properties of the basilar membrane differ. It is narrow and stiff at the base. At the apex the basilar membrane is wider, more flexible and has more mass. These properties allow a frequency distribution (low-frequencies being perceived with the stimulation of the apex and high-frequencies being perceived with a base stimulation of the cochlea) [7, 9].

In the organ of Corti, there are hair cells and supporting cells: hearing sensitivity depends on the good function of those cells, and more specifically on inner and outer hair cells [7]. The hair cells are in contact with two different fluids with different ionic composition: perilymph and endolymph. These fluids have a 80 mV potential difference (endocochlear potential) [7].



1 Perilymph
2 Endolymph
3 Tectorial membrane
4 Organ of Corti
5 Inner hair cells
6 Outer hair cells
7 Inner pillar
8 Outer pillar
9 Deiter's cells
10 Hensen's cells
11 Claudius cells
12 Basilar membrane
13 Cochlear duct
14 Inner tunnel (Corti)
15 Internal spiral tunnel
16 Scala tympani
17 Bony (osseous) sprial lamina
18 Auditory (cochlear) nerve
19 Efferent fibers
20 Afferent fibers

Figure 3: Organ of Corti. Original drawing by Jmarchn, licensed under CC BY-SA.

The tip of the hair cells bathes in endolymph and the base bathes in perilymph, allowing a passive entrance of potassium ions (K^+) as well as a passive exit of the same ions, following the concentration gradient [7]. This way, rapid successive stimulations are possible in the hair cells [7]. The stria vascularis needs energy to create the endolymph, which is rich in K^+, but the presence of the different fluids allows hair cells to save ATP [7].

Inner hair cells have stereocilia at their apex and, when there is a vibration, the stereocilia move in the stria vascularis' direction (driven by the movements of the basilar and tectorial membranes, see Figure 3) and pull open potassium channels, allowing for the cell to depolarize [7]. There is a release of neurotransmitters in the synaptic space, thus transforming a mechanical energy into an electrical energy: the sound travels through many auditory relays up to the brainstem or the brain [7]. Those higher functions are beyond the scope of this paper.

In the inner ear, outer hair cells also depolarize by the stereocilia movement. Unlike the inner hair cells, the outer hair cells' electric message feeds energy back to the cochlear partition [7]. The outer hair cells play an amplification role for faint to moderate sounds. These cells contract (by electro-mechano transduction), allowing less powerful soundwaves to stimulate the inner hair cells more easily [7]. Lost external hair cells do not regenerate in humans, nor for all mammals [7].

3 Conductive & mixed hearing dysfunctions

There is a large number of hearing loss etiologies. Some only affect the mechanical transmission of the sound to the cochlear hair cells: this origin of hearing loss is called "conductive hearing loss". In this particular case, patients have good hearing thresholds when measured with bone conduction (stimuli are presented with a bone vibrator placed on the mastoid), but not when measured with air conduction (stimuli are presented with earphones) [7]. Other causes lead to sensorineural hearing losses, a hearing loss affecting the cochlear or auditory neural pathways; in these cases, bone and air-conduction are similarly affected [7]. Finally, a mixed hearing loss is when there is both a bone-conduction hearing loss and an air-bone gap in the hearing thresholds [7].

The focus of the present paper is on the more prevalent causes of hearing loss affecting the mechanical transmission of sounds, from the external ear to the cochlea. The choice of presented conditions was inspired by Isaacson & Vera (2003) [19]. Some pathologies will change the structure's mass or stiffness and may therefore alternate the perception of sounds in different ways by modifying the transfer function of the middle ear.

By definition, the resonant frequency of a vibrating object depends on mass and stiffness: mass is an obstacle to high-frequency sound transmission and stiffness is obstacle to low-frequency [9]. Therefore, if the middle ear is considered as a mass-spring system, the stiffness resides in the tympanic membrane (it's elasticity), the ligaments of the ossicles and the pressure changes in the middle ear during the tympanic membrane vibration [9]. For example, the tympanic membrane may become stiffer when the air pressure in the middle ear is very different than the ambient pressure [9]. Changes in stiffness may also come from a modification in the tendons and ligaments linked to the ossicular chain, or by changes in the ossicular chain itself.

The mass of the mass-spring system of the middle ear resides mainly in the ossicles and the tympanic membrane modifications. Changes in the ossicles' mass may affect transmission of high frequencies [9]. Additionally, changes in the mass of the tympanic membrane may also change the middle ear function. Frictions may also occur in the middle ear due to the viscosity of the mucous membranes or the presence of narrow passages [20].

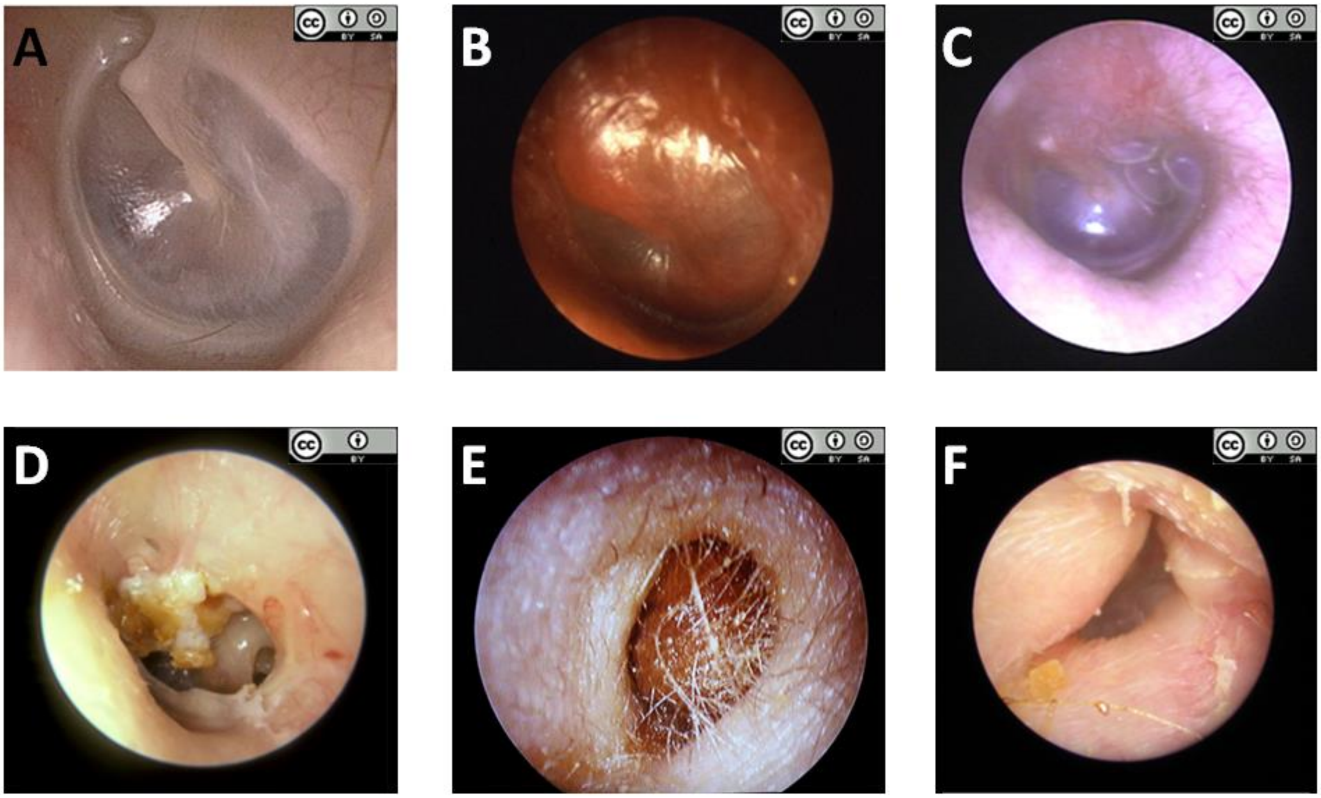


Figure 4: External ear and middle ear

A- Normal tympanic membrane. Original picture by B. Welleschik, licensed under CC BY-SA.
B- Acute otitis media. Original picture by B. Welleschik, licenced under CC BY-SA.
C- Serous otitis media. Original picture by B. Welleschik, licensed under CC BY-SA.
D- Tympanic membrane perforation with cholesteatoma. Original picture by Michael Hawke, licensed under CC BY-SA.
E- Cerumen (earwax) blockage. Original picture by Didier Descouens, licensed under CC BY.
F- Exostosis. Original picture by B. Welleschik, licensed under CC BY-SA.

Additional hearing dysfunctions may modify the natural external ear transfer function, such as when the ear canal is blocked or when the tympanic membrane is perforated [6].

3.1 Ear canal blockage

There are many causes for a temporary or permanent ear canal partial or total blockage: cerumen (earwax) accumulation, an external ear malformation, a foreign body (e.g. necklace pearl, blueberry), etc. [8]. A partially occluded ear will generally have a high frequency hearing loss, while a total occlusion will also affect middle and low frequencies [21]. Such hearing loss is conductive.

Cerumen is produced in the outer third of the ear canal, where hair and ceruminous glands are found. It is constituted of ceruminous glands secretions and oily sebaceous secretions [10, 22]. The cerumen forms a protective coating with antibacterial properties [23]. The ear is generally self-cleaning; in some cases, a partial or total obstruction of the ear canal is noted (Figure 4e) [22]. This situation is temporary if the ear canal is cleaned.

Another slightly less frequent cause of partial blockage is exostosis (figure 4f). The exostosis is a benign bony outgrowth, often noted in patients with a history of cold water swimming [8]. This problem is generally bilateral [24]. While often asymptomatic, in rare cases the ear canal may be completely blocked or cause repeated infections or cerumen impaction [8, 24].

3.2 External ear infection

Also known as swimmer's ear, the External ear infection or otitis externa is an infection of the external ear (often of the ear canal) [25]. The cerumen coating generally creates an acidic environment in the ear canal, but frequent swimming (bath, shower) may rinse it off and make the ear more vulnerable to ear canal infection, especially when contaminated water stays in the ear [23, 25].

Early on, the patient notices rather sudden itching and swelling of the ear canal, as well as pain [24]. Moreover, movements such as mouth opening or touching the pinna may be painful [24]. In most cases, there is also generally an ear discharge that may be thick or serous.

If there is an important accumulation of ear discharge and debris or if the tympanic membrane is thicker, a conductive hearing loss might be noted [24]. This infection is generally treated with eardrops since the more common cause is bacterial [24]. A fungus or a virus may also be the cause. This condition may be prevented by the use of ear drops changing the acidity in the ear canal [25].

3.3 Eustachian tube dysfunction

While an Eustachian tube may have a closing dysfunction, the most prevalent trouble is an obstruction or occlusion of the Eustachian tube. This problem is often temporary, like in the case of nasal congestion or in young children. The obstruction of the Eustachian tube may result in a serous otitis, as will be discussed later.

In an occlusive dysfunction, the forces that maintain the Eustachian closed (pressure from surrounding structures, cartilages elasticity, surface tension offered by mucous in the Eustachian tube, some muscle contraction and relaxation) and those which allow opening (mainly muscle contraction) are unbalanced [16]. The cause may be in the Eustachian tube itself, like in an upper respiratory tract infection with acute inflammation in the Eustachian tube (edema, mucus change), or located nearby (hypertrophy of adenoids blocking the nasopharyngeal opening) [26]. Allergic rhinitis may also cause a nasal inflammation and an edema in the nasopharynx [26]. Another frequent and permanent cause is malformations affecting the muscles in charge of the Eustachian tube opening or the tube itself. For example, cleft palate is a malformation that often affects the Eustachian tube function [14].

In the presence of Eustachian tube dysfunction, a negative pressure in the middle ear is frequent and may cause a rise in the middle ear stiffness and a conductive hearing loss, mainly in low frequencies [9].

Vila et al. (2017) estimated the US number of consultations to more than 2 million per year in patients under 20 years old, and a similar number of consultations in patients of 20 years old and older, for Eustachian tube dysfunction and related complications (otitis media with effusion and tympanic membrane retraction) [27].

3.4 Acute otitis media

When there is an acute inflammation of the middle ear, it is called an acute otitis media (figure 4b) [28]. The symptoms generally appear suddenly: ear pain, impression of ear fullness, fever, hearing loss and, in some cases, ear discharge (if the tympanic membrane is perforated) [15].

Acute otitis generally causes a temporary conductive hearing loss present at all frequencies and is more prevalent in children [15, 29].

In most cases, the infection is viral and resorbs by itself in less than 48 hours [29]. When the condition persists or in the presence of a perforated tympanic membrane, antibiotics are generally prescribed. An untreated bacterial infection may have serious complications such as mastoiditis and meningitis.

By their first birthday, 62% of children have had at least one acute otitis media episode and 83% before their third birthday, with 46% having at least three episodes [30].

3.5 Serous otitis media

If the Eustachian tube is occluded or is not able to open for a prolonged period, the middle ear mucosal walls use all the oxygen available and a negative pressure builds up in the middle ear, causing a tympanic membrane retraction in the middle ear direction [17]. Once this pressure is important enough, the body mucosal walls of the middle ear transudate a serous liquid in the middle ear [13, 27]. The presence of this serous liquid, in the absence of infection, is called serous otitis media (figure 4c) [31]. This condition is very common in children in whom the Eustachian tube is shorter and closer to a horizontal orientation [14].

There are causes for serous otitis other than Eustachian tube dysfunction. For example, serous otitis may follow an acute otitis, if the infection was treated but the middle ear remains filled with fluid [14, 28]. Following an acute otitis media diagnosis, a middle ear effusion is often present for 1 to 3 months (45% and 10% of the cases respectively) [30]. There is also a possibility that the effusion may have been present before the infection causing the acute otitis media [14]. Malformations of the skull base, ear or Eustachian tube (including the muscles that allow it’s opening) may also cause frequent serous otitis [14].

Once the middle ear fills with fluid, the mass and the stiffness of the tympano-ossicular system changes, and a conductive hearing loss is typically present at all tested frequencies [9].

This condition in children must not be taken lightly because it can delay language acquisition if present for a prolonged period [32]. In many cases, the serous otitis will resorb by itself [29]. However, the presence of residual uninfected fluid in the middle ear is a risk factor for another episode of acute otitis [14, 28]. Also, if the serous fluid persists many months, the Ear, Nose and Throat doctor (ENT) will often place ventilation tubes to restore the hearing sensitivity [13]. It must be noted that fluid that persists in the middle ear for years may cause an ossicular erosion over time [33].

The serous otitis media has a prevalence in adults of approximately 0.6% and a prevalence in children of 20% (for 2-year-olds), with more than 90% of the children having a first occurrence of serous otitis media before the age of two [31, 34].

3.6 Barotrauma

A barotrauma is a trauma caused by extreme air pressure changes and affects particularly enclosed cavities. The Eustachian tube has elastic properties, but may block in the presence of a sudden pressure change [15]. If the pressure difference between the middle ear and the environment becomes severe, particularly if the extra-tympanic pressure increases rapidly, there is a risk for barotrauma [15]. The trauma may cause middle ear transudation in the lighter cases, with an obstruction persisting up to several weeks. In more severe cases, hemorrhages in the middle ear, ossicular dislocation, tympanic perforation or perilymphatic fistula (opening in the round or oval window resulting in perilymph loss from the inner ear, accompanied by a hearing loss and vertigo) may occur [24, 35].

The impact of barotrauma on the hearing thresholds will vary according to the type of consequences: middle ear fluid, tympanic membrane perforation, etc.

The time of recovery and the number of medical interventions vary as well.

3.7 Tympanic membrane perforation

The main causes of a tympanic membrane perforation include the use of an ear swab or the insertion of a foreign body in the ear, a barotrauma, an acute otitis or a head trauma [8]. The presence of tympanic membrane perforation consecutive to chronic suppurative otitis media is estimated to 1.78% [36].

The impact on the hearing sensitivity varies greatly according to the perforation localization and size [8]. For example, ventilation tubes are known to cause little to no hearing changes. In most cases however, a conductive hearing loss is measured in the presence of a tympanic membrane perforation [37].

The recovery is often spontaneous but depends on the size of the perforation, the cause and the presence of constant ear discharge [24, 36].

3.8 Cholesteatoma

The cholesteatoma is a non-cancerous tumor which develop in the middle ear (figure 4d). It is often a consequence of otitis media or tympanic perforation [36]. The cholesteatoma is formed of accumulated epithelial debris and keratin in the middle ear (often beginning on the tympanic membrane) and can destroy surrounding structures, even bone, by erosion and compression [15, 36]. The presence of this mass in the middle ear leads to an augmentation of the impedance. It causes a hearing loss and it is generally accompanied by a strong scented ear discharge [38].

The treatment for cholesteatoma includes ear surgery to remove all of the tumor and to prevent recidivism [15]. If the mass is large, a mastoidectomy – removal of bone in the skull, behind the ear – can be necessary. Since the surgery often leads to a predominantly conductive hearing loss (for example in the case of ossicle removal), a reconstructive surgery may be offered to regain some hearing sensitivity.

The prevalence of cholesteatoma is estimated to be 0.34% in the population of 4 year olds and older [36]. The retraction pocket in the tympanic membrane, a condition that may follow tympanic membrane perforation and is a risk condition for cholesteatoma, has an estimated prevalence of 1.21% in the population of 4 years old and older [36].

3.9 Ossicular chain discontinuity

The three middle ear ossicles are normally linked one to another to transmit the sound vibration from air (outer ear) to a liquid medium (inner ear). However, sometimes two ossicles may lose their link from one another, or the malleus with the tympanic membrane, or even the stapes with the oval window [15, 39]. One of the possible etiologies is the cholesteatoma, especially after a surgical tumor removal. Other causes include congenital malformations of the ossicles (often with atresia – a permanent occlusion of the ear canal), head trauma, otitis media (with important erosion), barotrauma or penetrating object in the middle ear. Depending on the cause, sometimes a fibrous joint may remain between the ossicles even if they are detached [39].

In the case of a complete discontinuity, a conductive hearing loss is noted on all frequencies [39]. Partial discontinuity is known to cause a hearing loss more important on the high frequencies [39].

3.10 Otosclerosis

Otosclerosis is a disease of the temporal bone that leads to a progressive hearing loss [40, 41]. It consists of bone resorption, followed by new bone formation, often causing a partial or total mechanical blockage of the stapes footplate movement on the oval window (the mobility slowly decreases with time) [42, 43]. Mechanical blockage also may touch the other middle ear ossicles. The presence of otosclerosis stiffens the ossicular chain, leading to a conductive hearing loss more important in the low frequencies [9, 37].

The prevalence of this disease is of 0.3 to 0.4% in Caucasians [42]. It is one of the more frequent etiology for hearing loss apparition in adults, and the more common conductive hearing loss in Caucasian adults [42, 43].

Women are twice more often affected than man by otosclerosis, and the evolution of the pathology is faster in women due to their hormonal changes [44]. Otosclerosis progress faster with endocrine activity, for example during puberty, pregnancy and menopause. In some cases, the cause of otosclerosis is genetic. An autosomal dominant transmission with incomplete penetrance have been identified in some cases [42, 43].

Many patients suffering from otosclerosis undergo a stapes replacement surgery to regain some hearing sensitivity [40]. The extension of the pathology to the inner ear leads to a sensorineural component in the hearing loss, in addition to sound transmission alterations [41, 42].

4 Sensorineural hearing dysfunctions

4.1 Meniere's disease

Meniere's disease is characterized by an excessive presence of endolymph, or hydrops of the inner ear [45, 46]. A hydrops is an excessive accumulation of fluid. There are several hypotheses about the apparition of the hydrops: either too much endolymph produced by the stria vascularis or not enough (absorbed by the endolymphatic sac), or there is a circulatory problem of the endolymph [47]. Meniere's diseases is characterized by three main symptoms: a fluctuating sensorineural hearing loss (generally in low frequencies), intermittent tinnitus (whistling, buzzing, but most frequently a humming in Meniere's disease) and intermittent episodes of vertigo [48]. Symptoms manifest in the form of crisis that may last from a few minutes to many days, and are often accompanied by an aural pressure [47, 48].

Since some patients present an incomplete expected symptoms portrait, the prevalence of Meniere's disease is not well known. Estimations vary between 8 and 218 cases per 100 000 individuals [49, 50]. In the US, the estimation is 73 per 100 000 individuals and the prevalence is lower for men than women [50].

Therapeutic treatments include sodium intake restriction and medication (betahistine, intratympanic gentamicin, steroids) [46, 51].

4.2 Presbycusis

It is well documented that hearing loss is more frequent in older individuals. Ageing will impact the neural transmission of sounds by auditory neurons loss, vascular changes in the cochlea and central hearing pathways' function [7, 52]. However, it also impacts the mechanical transmission of sounds.

In the external ear, the cerumen becomes drier, harder and impactions are more frequent [52]. In the middle ear, the tympanic membrane may become stiffer, thinner and less vascularized [52]. The joints between the ossicles may show calcification and arthritic changes. Middle ear muscles and ligaments show atrophy and degeneration [52]. However, despite all these changes the impact on ageing in the audiometric results are typically of sensorineural predominance [7, 52, 53].

In the inner ear, ageing will lead to hair cells loss, support cells loss, basilar membrane rigidity and calcification of some structures in the cochlea [52]. The organ of Corti is the most susceptible structure to age changes. The hearing loss is generally sloping in the high frequencies [21, 52].

Homans et al. (2017) found a prevalence of 33% of men and 29% of women with a hearing loss ≥ 35 dB HL (pure tone average: 500, 1000, 2000 and 4000 Hz) [53]. Lin et al. (2011) estimated that 63.1% of the US population of age 70 and older present a hearing loss (pure tone average > 25 dB HL in the better ear) [54].

4.3 Noise-induced hearing loss (NIHL)

Noise exposure is known to cause a hearing loss, affecting importantly the outer hair cells function, and eventually the inner hair cell function [55]. At first, a noise-exposed individual may experience a temporary threshold shift (TTS), where symptoms such as hearing loss, tinnitus and impression of ear fullness last from a few hours to a few days [55]. These effects were believed to be temporary until recently. Animal studies however suggest that there may be permanent effects on the neural processes of supra-threshold signals [56]. In the case of exposure to very intense noise (e.g. the noise of a gunshot nearby), the hearing damage may be immediate and even affecting the middle ear - this situation is known as an acoustic trauma [55]. The acoustic trauma is less frequent than the permanent threshold shift (PTS) observed in most noise-exposed workers: 10% of the world's population would be exposed to noise levels associated to a noise-induced hearing loss risk [57]. Typically, the PTS occurs progressively, is permanent and impacts more importantly the hearing thresholds at and near 4000 Hz [55]. The hearing loss is sensorineural and affect both ears in most cases [57]. Sensorineural hearing loss or progression may be prevented in reducing the noise exposition time and the noise intensity [55].

5 Conclusion

This overview of the peripheral hearing function and dysfunctions focuses on the most prevalent etiologies affecting mechanical transmission. Such mechanical changes may touch the ear canal, the tympanic membrane, the middle ear ossicles and/or the cochlea. Presbycusis and noise-induced hearing loss are also discussed because of their high prevalence. Other hearing loss causes that are less prevalent or related to the auditory nerve or higher auditory pathways are not included in this paper.

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USING THE AUDITORY BRAINSTEM RESPONSE ELICITED BY WITHIN-CHANNEL GAPS TO MEASURE TEMPORAL RESOLUTION

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Résumé

Les potentiels auditifs du tronc cérébral (PÉATC) peuvent être utilisés pour mesurer l'activité temporelle précoce du système auditif. Des PÉATC des bruits intermittents ont été développés pour mesurer la réponse électrophysiologique à la stimulation auditive sans l'attention active. Dans la présente étude, des jeunes adultes ont écouté passivement des stimuli avec les périodes de silence de différentes largeurs dans des séquences séparées. Pendant une seule séquence, deux bruits à bande étroite identiques de 15 ms, avec une fréquence centrale de 750 ou 3750 Hz, ont été présentés avec une période de silence (durée de 2, 5, 10, 20, 30, 40 ou 50 ms) avec un deuxième bruit suivi par un intervalle interstimulus de 50 ms ou plus. Des PÉATC ont été enregistrés à l'activation du premier bruit avant et au début du deuxième bruit (à la fin de la période silencieuse). L'amplitude de l'onde V après l'intervalle augmentait avec la durée plus longue de la période silencieuse. Ceci contrastait avec la vague V avant l'intervalle, le contrôle, qui restait relativement constant. Une différence significative a été constatée entre l'amplitude de la vague V évoquée avant et après l'intervalle, pour des durées d'intervalle égales ou inférieures à 20 ms et à 5 ms, pour 750 et 3750 Hz, respectivement. Les PÉATC évoqués par le bruit intermittent peuvent fournir des informations spécifiques à la fréquence pour l'étude de la résolution temporelle chez les populations avec divers problèmes auditifs.

Mots clefs : PÉATC, électrophysiologie, résolution temporelle, discrimination temporelle

Abstract

The Auditory Brainstem Response (ABR) can be used to measure the early temporal activity of the auditory system. A gap-in-noise ABR has been developed to measure the electrophysiological response to auditory stimulation without attending to the task. In the present study, young adults passively listened to stimuli of various gap widths in separate sequences. In a single sequence, two identical 15 ms filtered noise bursts, with a center frequency of either 750 or 3750 Hz, were presented separated by a gap (2, 5, 10, 20, 30, 40 or 50 ms in duration), with the second noise burst followed by an interstimulus interval of no less than 50 ms. An ABR was recorded at the onset of the first noise burst, before the gap (pre-gap), and at onset of the second noise burst, after the gap (post-gap). The gap duration had a suppressive effect on the amplitude of wave V for the noise burst following the gap. In contrast, wave V amplitude before the gap (i.e. the control) remained relatively constant. A significant difference was found between the amplitude of wave V elicited before and after the gap for gap durations equal to and below 20 and 5 ms, for 750 and 3750 Hz, respectively. The gap-in-noise ABR can potentially provide frequency-specific information for the study of temporal resolution in populations with a variety of hearing disorders.

Keywords: ABR, electrophysiology, temporal resolution, gap detection

1 Introduction

Temporal resolution refers to the ability to detect changes in the envelope of a sound over time [1]. It is used for comprehension of speech by detecting the separation between words. The mechanism of temporal resolution is modelled in Moore (1995) in 4 phases: 1) bandpass filtering, 2) compressive nonlinearity, 3) a sliding temporal integrator, and 4) a decision device. As a stimulus enters the cochlea, it engages a specific location of the basilar membrane that is most sensitive to the stimulus frequency. The basilar membrane then displaces in response to the stimulus and triggers a nerve spike [2]. The neural spikes are then processed in a sliding temporal integrator where the window builds when the stimulus is turned on and decays when it is turned off. It is believed this process occurs after the auditory nerve [1], possibly linking the peripheral temporal information to cortical rules that determine if the input originating from the temporal integrator is qualified as a "gap". Indeed, studies where the auditory cortex was ablated bilaterally in rats showed elevated gap detection thresholds [3].

Behavioural gap detection thresholds are often used to investigate temporal processing. Gap detection methodologies determine the threshold of detecting a gap, or a just-noticeable silent interval, within a sound by altering

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the length of the interval [4-6]. These studies, using broadband noises, determined normal hearing participants could detect gaps as small as 2 to 3 ms in length [4], however its perceptibility can vary with changes to intensity [4, 5] and stimulus bandwidth [7-9]. In addition to this, performance is affected by the level of attention, concentration, motivation, and the response criteria used [10, 11]. It is thus of interest to use alternative measures that are more objective to mitigate the potential effects of performance on the detection of gaps.

Objective measures such as auditory event-related potentials have been demonstrated as an alternative method of measuring neural gap detection [12-19]. The advantage of such neural measures is that they are often elicited passively, in the absence of attention, while a participant is reading a book or watching a film.

The auditory brainstem responses (ABR) have been used clinically to assess the summed activity of auditory nerve [20]. The ABR is an acoustically stimulated electrophysiological response that represents synchronized activity that appears as a five-peak waveform generated less than 10 ms following the onset of a stimulus [21]. These voltage changes are recorded using 3 to 4 electrodes placed on the scalp of the head. One of the advantages of the ABR is that it is inexpensive, non-invasive and routinely used in clinical practice.

ABRs using gapped stimuli have been explored to measure temporal discrimination in animal models, pediatric populations, and the elderly [22-24]. The ABR elicited by gaps was investigated using two identical noise bursts separated by a silent interval. The ABR to the first noise represents a typical response that would be similar to a non-gapped ABR. The ABR to the second noise is an altered response that is reflective of the length of the silent interval. Boettcher et al. (1996) used Mongolian gerbils to identify latencies of waves I, II, III and IV for the second noise occurring 1.4 to 2.0, 2 to 3, and 4 to 7 ms, respectively, following the offset of the gap. The amplitudes were measured from the peak of wave II to the trough following wave III, and the peak of wave IV to the trough following wave V. The amplitudes for the second noise burst were generally smallest for the narrowest gaps and grew as the gap size widened. The latency changes after the gap were small but consistently shorter as gap duration increased, particularly for gerbil wave IV. Both Werner et al., (2001) and Poth et al. (2001), showed the amplitude of human wave V, occurring at a similar latency following the gap as in gerbils, increased with widening gap size. Werner et al. (2001) found measureable differences in wave V amplitude for gap sizes as small as 4 ms. It was demonstrated that when the ABR is used as a measure of gap detection threshold in humans, the results correspond well with established psychophysical measures [22].

We are interested in further exploring the early impairments that may be responsible for impaired gap detection by differentiating the ABR gap-in-noise elicited by higher and lower frequency filtered stimuli. The gap-elicited ABR has been investigated using broadband noise bursts, which does not provide information on the effects of varying the spectral characteristics of the carrier stimulus. Behavioural responses to large gaps do not change with the carrier frequency [25], however increasing the center frequency can decrease the gap detection threshold [26, 27]. Shailer and Moore (1987) interpreted this effect as the result of inherent fluctuations in the low frequency noise that resemble the embedded gap, making detection of the gap more difficult. It is unclear whether this confusion occurs at the level of auditory bandpass filters or later in the higher-order decision device.

The present experiment aims to investigate the use of the ABR gap in noise paradigm in normal hearing participants, as a means of validating the methodology for use with frequency-specific stimuli. Noise burst center frequency and gap duration will be varied and ABR wave V amplitudes will be measured and compared before and after the gap similar to Poth et al. (2001), and Werner et al. (2001). We hypothesize that the amplitude of the ABR wave V following increasing gap lengths will show similar recovery for both center frequency stimuli as previous reported for wave V elicited by the post-gap stimulus.

2 Method

2.1 Participants

Fifteen normal hearing participants ages 18-30 years old (7 males and 8 females, mean age=21.1) were recruited for this study. All participants completed a questionnaire on their auditory health and noise history to ensure that none of the participants were exposed to more than 3 hours of noise per week. Based on these questionnaires, none of the participants reported any known hearing difficulties. Participant hearing thresholds were measured using an audiometer (AC40, Interacoustics) and with supra-auricular headphones (TDH39P, Telephonics). All participants had auditory thresholds of 15 dB HL or lower at 250, 500, 1000, 2000, 3000, 4000, 6000 and 8000 Hz. All procedures and testing were approved by the University of Ottawa Research Ethics Board and written and verbal consent was given by the participants prior to the testing.

2.2 Electrophysiology

Preparation

Participants were tested while resting in an inclined armchair in a sound isolated Faraday cage. The ABR was acquired from a one-channel montage of high forehead to ipsilateral mastoid. The contralateral mastoid served as a ground using an Amplitrode™ (Vivosonic). All electrodes were disposable pre-gelled adhesive electrodes (Neuroline 720, Ambu) and each surface was prepared using an abrasive gel (NuPrep, Weaver and Company) and an alcohol wipe to ensure optimal electrode contact. Prior to recording, the electrical impedance of each electrode was below 5 kΩ.

Stimulus

In a single sequence, two identical 15 ms filtered Gaussian noise bursts were presented, separated by a gap, with the second noise burst followed by an interstimulus interval of no less than 50 ms. Each noise burst was filtered using a 2nd order Butterworth filter with a 1 ms Blackman ramp on and off (within the 15 ms noise). The filters were set from 500 to 1200 Hz, for the low frequency condition, and 3500 to 4000 Hz, for the high frequency condition. Stimuli were presented at 100 dB pe SPL through an insert tube earphone (Etymotics, ER-3) placed in the right ear. Each test session ran multiple gap lengths: Δt = 2, 5, 10, 20, 30, 40 and 50 ms, presented in descending order. The stimulus rate was held constant at 12.2 Hz, causing the interstimulus interval (ISI) to range from 50 ms (for a gap of 50 ms) to 100 ms (for a gap of 2 ms).

Recordings

ABR waveforms were recorded using the Vivosonic Integrity system which includes the Vivolink V500 (VN0266, Vivosonic) which communicates via Bluetooth connection to a laptop with the Vivosonic Integrity V500 software (version 8.3, Vivosonic). The system was calibrated according to manufacturer recommendations. Filter settings were 30 to 1500 Hz with a 12 dB/oct high pass and a 24 dB/oct low pass filter roll off. Polarity was set to rarefaction. For each subject and each test condition (gap/noise frequency), two ABRs were recorded: one corresponding to the onset of the first noise burst before the gap (pre-gap) and one corresponding to the onset of the second noise burst (i.e. post-gap). This was called the 'two-stimulus trial'. For 10 subjects, the pre-gap average was also recorded without the synchronization of the post-gap, a 'one-stimulus trial', in order to compare the pre-gap ABR with a control ABR. All recordings were conducted when the patient was at rest and the raw EEG was relatively flat. Kalman weighting was used in conjunction with the Amptrode™ for artifact rejection [28].

Responses were sequentially replicated for the first five participants up to 2000 sweeps for each gap width and frequency to ensure replicability of results. In other words, the trial was repeated a second time to ensure that the waveforms were not significantly different. For the remaining 10 participants, two buffer channels were used to separate the data into two grand average waveforms. The two buffers were compared to measure the replicability of the waves. After 1200 sweeps were collected, if the two buffers were correlated by 0.7 or higher, the recording was retained for further analysis. For correlations below 0.7, testing continued until the residual noise was below 0.035 μV or 2500 sweeps. A t-test determined this method had higher correlations and lower residual noise than the initial sequential method.

Data analysis

Waveforms before and after the gap were subjectively marked based on the average known latency of wave V as previously reported [22]. Two experienced judges decided on the presence or absence of the wave V. A response for the presence of wave V was retained if both judges agreed. The latency and amplitude of wave V was then computed using the Vivosonic Integrity software.

The latency was determined according to the local maximum of the expected latency range for waves I and V as reported in Boettcher et al. (1996) (see introduction).

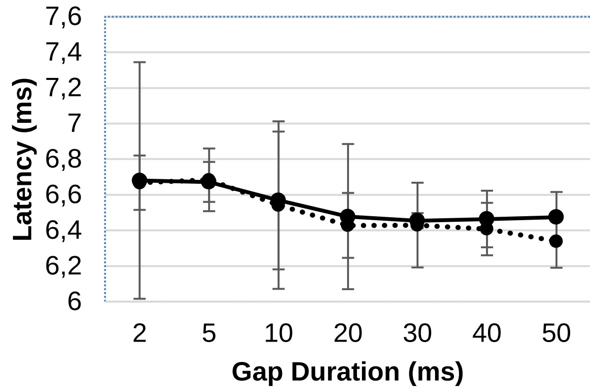

Figure 1: Latency of wave V following the gap for various gap durations. The solid line represents the latencies for wave V elicited by a 750 Hz stimulus. The dotted line shows the latencies for the ABR elicited by the 3750 Hz condition. Standard deviation is indicated by brackets.

The amplitude of wave V was measured as the amplitude difference between the peak to the following trough. A 3-way repeated measures ANOVA was performed on the amplitude of wave V using the measure of gap size (2, 5, 10, 20, 30, 40 and 50 ms), position (pre or post-gap), and frequency (750 or 3750 Hz). A post-hoc analysis using a pairwise t-test was applied to compare the amplitude before and after each gap. A one-tailed p-value was chosen as only positive amplitudes were considered valid wave V deviations. The two and one-stimulus trials were compared in a repeated measures ANOVA on frequency, stimulus (one or two-stimulus) and gap width.

3 Results

3.1 Effect of stimulus frequency on the ABR latency

The latency of the auditory brainstem response at wave V was consistent for both before the gap and following the gap. Figure 1 shows the latency responses were not significantly different between the two frequency conditions. The latency also did not significantly change with the increase of gap duration, however a slight decreasing trend is observed.

3.2 Effect of stimulus frequency on the ABR amplitude

The auditory brainstem response was analyzed using a peak-to-peak measure of the maximum (peak) of wave V to the immediate trough. In other words, the maximum positive deflection to the proceeding negative deflection at the latency range reported in previous studies [22, 23].

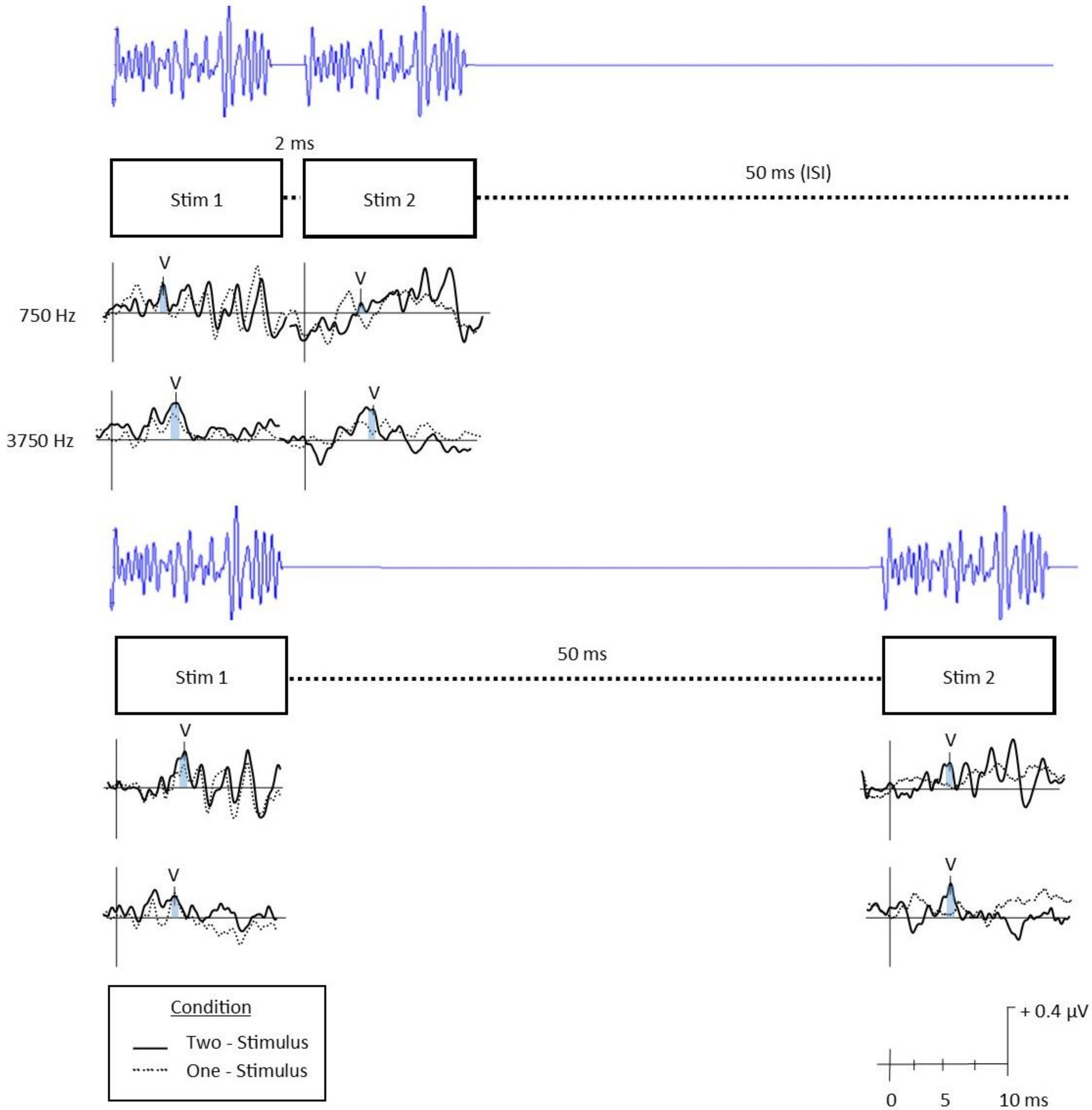

Figure 2: The two-stimulus design gaps of various widths separating stimulus 1 and 2. The stimulus rate was kept at a constant of 7.6 Hz and the ISI varied based on the length of the gap from a maximum of 100 ms (for the 2-ms gaps) to a minimum of 50 ms (for the 50-ms gaps). The ABR, shown for a single participant (subject 6), was elicited by the onset of stimulus 1 and the onset of stimulus 2 after the gap, shown with the solid lines. The dotted lines represent the ABR elicited by only stimulus 1 in the absence of stimulus 2 (i.e one-stimulus condition). The amplitude was measured peak-to-peak from the local maximum of wave V to the subsequent trough, therefore the baseline was set to the trough of wave V, or when the wave V was absent, to the trough where wave V is seen in the two-stimulus condition. For stimuli at 750 and 3750 Hz, there was a decrease in the amplitude of the post-gap wave V for 2-ms gaps, however when the gap was large as in the 50-ms gaps, the post-gap wave V amplitude were similar to pre-gap values.

This peak-to-peak measure was determined for both the onset of the stimulus before the gap and following the gap as shown in Figure 2.

A three-way repeated measures ANOVA revealed a three-way interaction between gap width, position, and frequency, $F(6.54)=2.78$, $MSE=.16$, $p=.02$. Larger amplitudes were recorded for wave V elicited by the low frequency stimulus (750 Hz) compared to the high frequency stimulus (3750 Hz), $F(1,9)=2.78$, $MSE=0.16$, $p=.002$. This can be seen in the average amplitude shown in figure 3.

However, the low-frequency condition showed smaller amplitudes for the smaller gap durations than the high frequency condition.

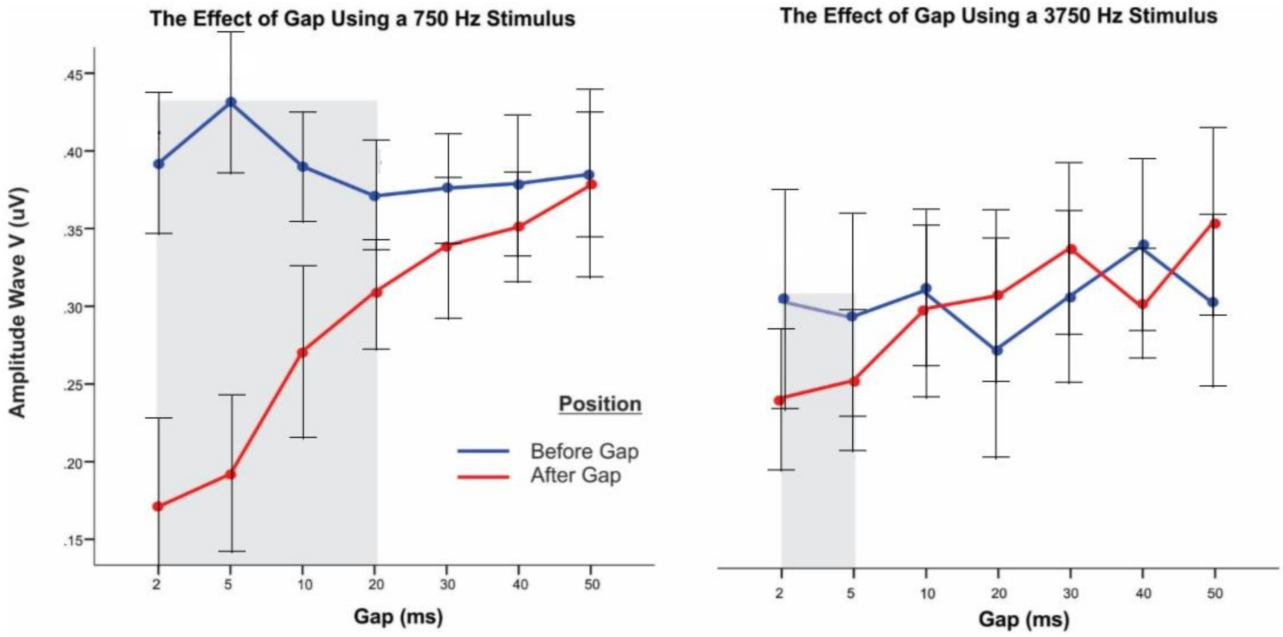

Figure 3: Mean peak-to-peak amplitude of wave V before and after a silent gap between two noise bursts (n=10) for the 750 Hz stimulus and the 3750 Hz stimulus. As indicated in the shaded grey area, the wave V amplitude before the gap (blue) is significantly larger than post-gap (red) for gap widths below 20 ms and 5 ms, for the 750 and 3750 Hz stimuli, respectively (one-tailed t-test, $p<0.05$). Brackets indicate standard deviation.

3.3 Effect of gap width on the ABR amplitude

Figure 3 and Table 1 show the post-gap amplitudes of wave V at lower gap widths were significantly smaller than the amplitudes for larger gap widths in both the high and low frequencies.

At 750 Hz, the post-gap amplitude was significantly smaller at and below 20 ms ($t(9)<2.3$, $p<.026$). While at 3750 Hz, only gap widths under 5 ms showed significant amplitude differences ($t(9)<2.8$, $p<.05$).

3.4 Effect of single and double stimulus averaging

The ABR was elicited with either a single stimulus, stimulus 1, or with two stimuli, stimulus 1 and 2. As seen depicted in Figure 2, the second stimulus elicits a change on the amplitude of the post-gap ABR, however there was no effect of the post-gap averaging on the pre-gap.

When the ABR amplitude was measured before the gap using either a single or two stimulus averaging within a recording, there was no significant difference to the amplitude of the pre-gap ABR, $F(1,9)=1.13$, $MSE=.012$, $p=.32$. There was also no interaction between gap duration and stimulus condition.

4 Discussion

Our results demonstrate the feasibility of using the ABR recordings to a gapped stimulus among normal hearing participants using a high and low-frequency noise carrier. The results show a significant suppression of the post-gap amplitude of wave V for small gap durations for low and high frequencies. For large gap durations wave V shows an unsuppressed amplitude that is not significantly different from the pre-gap ABR.

Table 1: Mean wave V amplitude before and after the onset of the gap at various widths for the 750 and 3750 Hz conditions. Standard deviation between parentheses. (*one-tailed t-test, p<.05)

Gap	Pre/Post-gap	Mean amplitude, µV (SD)	
		750 Hz	3750 Hz
2 ms	Pre	.39 (.09)	.31(.14)
	Post	.17 (.11)*	.24(.09)*
5 ms	Pre	.43 (.09)	.30(.13)
	Post	.19 (.10)*	.25(.09)*
10 ms	Pre	.39 (.07)	.31(.10)
	Post	.27 (.11)*	.30(.11)
20 ms	Pre	.37 (.07)	.28(.14)
	Post	.31 (.07)*	.31(.11)
30 ms	Pre	.38(.07)	.31(.11)
	Post	.34(.09)	.34(.11)
40 ms	Pre	.38(.09)	.34(.11)
	Post	.35(.07)	.35(.07)
50 ms	Pre	.39(.08)	.31(.11)
	Post	.38(.12)	.36(.12)

Previous studies on the ABR and gap detection have shown that the onset of the stimulus before a gap elicits a clear ABR with a latency that is similar to a regular click stimulus [22, 23]. This is similar to the findings in this study, which showed an average wave V latency across the 750 and 3750 Hz conditions of 6.0 to 7.3 ms post-gap. This is a more narrow range of latencies than the wave V latency post-gap to a broadband click of 6.0 to 8.4 ms [23]. All latencies before and after the gap were not significantly different which is supported by previous studies [22, 23]. In Poth et al. (2001), gaps of 4, 8, 32 and 64 ms were inserted within a 100-ms broadband click. When testing young subjects, a measurable wave V amplitude decreased post-gap with decreasing gap duration similar to the results of this study. In Werner et al. (2001), ABR gap detection was measured using gaps inserted in 30-ms, 7 kHz low-pass filtered noises. They determined an electrophysiological gap detection threshold of 2.4 ms which was the smallest gap length that elicited a detectable post-gap wave V. This implies the post-gap wave V amplitude also decreased with decreasing gap width similar to Poth et al. (2001) and the amplitudes reported in this study.

Suppression of the ABR following the gap may be related to the temporal representation of the early auditory system.Reliable neuronal phase locking is known to occur for frequencies less than 2000 Hz and not for higher frequencies [2], which may be the reason for fewer gap widths with significant post-gap wave V suppression than the lower frequency condition.

In other words, the afferent neurons that lock themselves to the phase of higher frequency sounds may not be able to discharge with enough efficiency as the lower frequency sounds. This has been discussed in previous literature regarding the encoding of the auditory nerve fibers using temporal fine structures and the slower temporal envelope information [29]. At higher frequencies, the auditory nerve fibers do not phase lock to the temporal fine structures, which means that auditory nerve fibers are unable to discharge at a rate that corresponds to the timing of the sinusoidal band-pass carrier fluctuations. It is thus possible that cortical processing uses the changes in discharge, as represented by the wave V amplitude suppression, as an indicator that there is no gap in the stimulus.

Studies on behavioural gap detection show roughly constant gap thresholds of 6-8 ms for frequencies 400 to 2000 Hz at intensity levels above 55 dB SPL [30]. This suggests that gap sizes that are undetected behaviourally (i.e. below the gap thresholds) may correspond with a greater suppression of the post-gap amplitude. If this were the case, then the higher frequencies where the amplitude suppression occurs for only 2 of the 7 gaps shows better gap detectability. Improved gap detection with narrower stimulus bandwidth has been reported [30]. Behavioural gap detection intra-subject variability increases with larger signal bandwidth [7]. As mentioned earlier, the low frequency stimulus in this study elicited significant post-gap suppression for larger gap widths, up to 20 ms, whereas it occurs for smaller gaps, up to 5 ms, for the high frequency stimulus. This suggests that the ABR suppression occurs for a smaller range of gap widths with a high-frequency carrier (10-50ms) than the low-frequency carrier (30-50ms). Unlike the behavioural gap detection, the variability of the ABR amplitude was roughly stable for the high and low frequency conditions.

5 Conclusion

This study demonstrates the utility of the ABR as a measure of the early, short-latency response to gaps within a high and a low carrier frequency stimulus. Several previous studies indicate that the wave V is an appropriate biomarker of post-gap amplitude changes that are related to psychophysical gap detection. This study demonstrates that the suppression of the post-gap wave V amplitude may be an indicator of the afferent information that allows the central system to determine the presence of a gap. The results from this study suggest that the ABR gap detection is different for low frequencies compared to high frequencies. Further studies comparing the amplitude changes to behavioural results using similar carrier frequencies may elucidate whether such ABR suppression is related to perceptual temporal resolution.

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The Effects of Bilingualism on Speech Evoked Brainstem Responses Recorded in Quiet And in Noise

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Résumé

L'objectif principal de cette étude était d'évaluer l'effet de l'enrichissement sensoriel, tel que le bilinguisme, sur le traitement auditif sous-cortical, dans deux types de conditions d'écoute : dans le silence et dans le bruit. Plus spécifiquement, le but de cette étude était d'identifier des marqueurs biologiques neuronaux, au niveau du tronc cérébral, qui distinguent les bilingues des monolingues. Quarante et un adultes âgés de 18 à 25 ans ont participé à l'étude: 19 monolingues et 22 bilingues. Leur maîtrise de la langue a été évaluée à l'aide d'un questionnaire LEAP (*Language Experience and Proficiency*). Les potentiels évoqués auditifs du tronc cérébral (PÉATC) ont été enregistrés en utilisant des stimuli de clics et des stimuli verbaux (/da/), dans le silence ainsi que dans le bruit (stimuli verbaux seulement). Aucunes différences significatives n'ont été observées entre les deux groupes avec les PÉATC enregistrés par les clics. Les ondes transitoires évoquées par les stimuli verbaux (V, C) et les latences de la région périodique (D et F) étaient plus longues pour le groupe monolingue que pour le groupe bilingue. La réponse soutenue en fréquence (*frequency following response*) F0 et F1 des PÉATC verbaux était similaire pour les deux groupes dans le silence et dans le bruit. Les résultats suggèrent que, les monolingues ont besoin de plus du temps pour traiter les stimuli verbaux que les bilingues. Très tôt dans le système auditif, on constate que le traitement neuronal de leurs réponses aux stimuli verbaux en absence ou présence de bruit semble moins robuste que celui des adultes maîtrisant les deux langues. Le bilinguisme pourrait stimuler les capacités de traitement automatique du son du système auditif de manière à améliorer son efficacité. De surcroît, cette étude confirme le potentiel d'utilisation des PÉATC en réponse à des sons de parole en tant qu'outil clinique pour la détection de marqueur biologique.

Mots clefs : potentiels évoqués auditifs sous-corticaux; potentiels évoqués auditifs du tronc cérébral avec stimuli verbaux; bilinguisme; plasticité dépendant de l'expérience; enrichissement sensoriel

Abstract

The main objective of the present study was to investigate the effect of sensory enrichment, such as bilingualism, on the subcortical processing in quiet and adverse listening conditions such as in the presence of noise. More specifically, the aim of this investigation was to identify some neural biomarkers at brainstem level distinguishing bilinguals from monolinguals. Forty-one 18- to 25-year-old adults participated in the study: 19 monolinguals and 22 bilinguals. Their language fluency was assessed with the Language Experience and Proficiency (LEAP) questionnaire. Auditory Brainstem Responses (ABRs) were recorded using click and speech /da/ stimuli in quiet and also in noise for the latter. No significant differences between the two groups were observed for click-evoked ABR. The speech-evoked ABR transient waves (V, C) and the periodic region (D and F) latencies were longer for the monolinguals compared to the bilingual group. The Frequency Following Responses (F0 and F1) of the speech-evoked ABR were similar for the two groups in quiet and in noise. Results suggested that monolinguals need more time to process speech stimuli than their bilingual peers. Early in the auditory system, the neural responses related to speech processing in the absence or the presence of background noise seem to be less resilient when compared to those of adults who are fluent in two languages. Bilingualism could stimulate the automatic sound processing abilities of the auditory system in a way that makes it highly efficient. Furthermore, this study demonstrated the applications of speech-ABR and its potential usefulness as a clinical biomarker.

Keywords: sub-cortical auditory evoked potentials, speech-ABR, bilingualism, experience-dependent plasticity; sensory enrichment

1 Introduction

Early life experiences and adversity have a powerful impact on the developing brain and influence on brain function [1-4]. Personal development and long life experience alter the brain's physical structure and shape its neural networks, allowing it to adapt to its environment [1-3, 5]. Neuronal plasticity is the idea that neural pathways can be strengthened through repetitive use [6]. Markham et al. (2004) [7] reported that experience-dependant plasticity is a dynamic interaction between one's environment (nurture) and the biological make-up of one's brain (nature).

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Experience-dependent plasticity is affected by how individuals adapt to the demands of their environment leading to reorganization of the brain at the cellular level [7].

The interaction between subcortical and cortical processes allows modifications of our perceptual system, changing how external sensory information is perceived [8, 9]. The cerebral plasticity is particularly evident in individuals who are in constant contact with auditory-enriched environments, such as musicians [10, 11], speakers of tonal languages [12, 13], children with rigorous auditory training [14] and bilinguals [15, 16]. Krizman et al. 2014 [16] recorded subcortical neurophysiological responses to speech sound in 14-year-old high school Spanish-English bilinguals and English monolinguals. The stimuli taken were the consonant-vowel (CV) phoneme /da/ of 170 ms in quiet and background noise which consisted of multi-talker babble. Krizman et al. (2014) [16] illustrated that in bilingual adolescents the efferent neural pathways that connect the executive system of the frontal cortex with the subcortical auditory system are more efficient than in monolinguals. The efferent pathways appear to optimize the perception and encoding of auditory stimuli based on what the auditory system is receiving from the environment [15, 16]. By using speech auditory evoked response, Krizman et al. (2012) [15] found that there exists a relationship between enriched linguistic environments - such as a bilingual environment in contrast to a monolingual environment - and the neural response of the auditory system. Although cortical and subcortical auditory evoked responses were present in both monolingual and bilingual groups, the two evoked potentials of the bilinguals were more pronounced (e.g., larger amplitude) than in the monolingual cohort [15, 16]. Moreover, in contrast to those who acquired a second language at a later stage, bilinguals from birth showed better encoding of the fundamental frequency of speech sounds /ba/ and /ga/ [17].

The speech-auditory brainstem response, Speech-ABR, is utilized as an objective tool to observe how subcortical structures of the auditory pathway encode speech sounds [9, 18, 19]. The chosen phonemes (e.g., /da/) are found in the majority of languages and no one group has a greater advantage over the other in processing that sound ([9]. When plotted on a time-amplitude domain, its peak amplitudes and latencies correspond with the acoustic features of its evoking acoustic stimulus [9, 18, 19]. Speech-ABR would provide an objective index of the brainstem and midbrain's representation of complex sounds [9, 18, 19].

The present study aims to determine whether subcortical neural biomarkers would distinguish between bilingual Canadian young adults who experience a linguistic environment composed of two or sometimes more languages, and monolinguals. For the current investigation, we hypothesized that bilingual adults exhibit more efficient auditory processing capacities in quiet and noisy conditions compared to monolinguals as has been observed in Krizman et al.'s study with high school children (2014) [16].

2 Materials and Method

All procedures were approved by the Office of Research Ethics and Integrity at the University of Ottawa. Participants provided informed consent before the experiments.

2.1 Participants

Forty-one 18-to-25-year-old students were divided into two experimental groups based on answers to the Language Experience and Proficiency (LEAP) [20] questionnaire as well as oral expression with native speakers: 19 monolinguals (mean 22.8 yrs, standard deviation (SD) 1.4, 11 females) and 22 bilinguals (mean 23.1 yrs, SD 0.79, 19 females). A hearing screening test was conducted to ensure that participant's hearing sensitivity was within normal limits (thresholds < 20 dB HL) between 250 Hz to 8000 Hz. Although more females were recruited than males in the present study, the two groups were matched in sex, age and hearing threshold.

2.2 Questionnaire

The participants' linguistic capabilities and environment were evaluated by the LEAP questionnaire, available in either the English or French (Marian, Blumenfeld, and Kaushanskaya, 2007) [20]. Participants responded to the questionnaire using a subjective rating scale from zero to ten, and provided information on the daily use of their spoken language (i.e. the proportion of each language spoken) and the age of language acquisition and fluency. The responses to the questions of language proficiency were evaluated to identify bilingual participants. Participants who rated their proficiency and fluency greater than six and spoke two languages were placed in the bilingual group. The participants in the monolingual group spoke either French or English. The bilingual group spoke both French and English.

2.3 Electrophysiology

Preparation

The electrophysiological protocols were run using both click and speech ABR. The BioMAP® software in the Biologic Navigator Pro System (Natus Medical Inc.) was used to collect and analyze the recordings. Participants were prepared for the electrophysiological testing by having three contact zones scrubbed with an abrasive gel and alcohol swaps. The data was recorded with an active electrode placed at the vertex and the reference placed on the right ear. The forehead acts as the ground. An intra-auricular earphone (EARLINK 3B) was placed into the participant's right ear. The impedance of each electrode was less than 5 kΩ and the impedance difference between the electrodes was never greater than 2kΩ.

ABR with click stimulus

Click-evoked ABR was conducted on all participants across both groups. Rarefaction 100 µsec clicks were presented to the right ear at an intensity of 80 dB peak SPL and were bandpass filtered on-line from 100 to 1500 Hz. The rate of presentation was 13.3 clicks/s. A block of 1500 artifact free sweeps was recorded. The entire procedure was presented a second time and the data collapsed across the two blocks (total of 3000 artifact free sweeps).

Data acquisition of speech ABR with and without competitive noise

The speech ABR was recorded to a 40 ms custom speech /da/ syllable from Bio-Logic software (Figure 1). The stimulus consisted of five formants with a transition between the consonant [d] and the vowel [a] [9, 21]. After the initial 5 ms, the fundamental frequency (F0) transitioned from 103 to 121 Hz between 0 and 35 ms, and reached 121.2 Hz between 35 ms and 40 ms [9, 21]. The stimulus was presented to the right ear at a rate of 10.9 stimuli per second at 80 dB SPL with an alternating polarity. The phoneme was presented in both quiet and noise conditions. In the latter, the phoneme was presented in continuous white noise with a signal-to-noise-ratio (SNR) of +10 dB. A total of 2000 artifact free stimuli were collected in each condition. The stimuli were presented a second time (i.e., the averages were based on 4000 artifact free presentations) and averaged using a 85.33 ms (including a 15-ms pre-stimulus time window). The responses were amplified 100,000 times, and were bandpass filtered on-line from 100 to 2000 Hz. Artifacts were rejected online at ± 23 μV and did not exceed 10% of the total number of sweeps. In all conditions, participants were asked to remain calm and relaxed, and the lights inside the audiological cabin were dimmed.

Data processing

Data processing and averaging were performed usingBioMAP® software in the Biologic Navigator Pro System. The two recorded waveforms (4000 sweeps) were weighted average. The weighted response was compared with normative template during analysis. All waves of the click and speech-ABR were identified and marked manually by three independent experienced scorers. Click-ABR waves were replicated twice and visually marked as waves I, III and V. The speech ABR waves (responses) consist of onset peaks labelled as A and V, a consonant–vowel transition peak C, and an offset wave O. In addition, three sustained frequency following response (FFR) waves D, E and F were observed. These responses were thus quantified in the speech-ABR weighted average waveforms.

In addition to the temporal analysis (Figure 2), spectral analysis, F0 and F1, (Figure 3) was performed on the sustained portion of the speech-ABR using the Brainstem Toolbox [9] under MATLAB v.8.1 (MathWorks, Natick, MA). Fast Fourier Transform (FFT) analysis of the response was performed, with zero padding, over the period of 11.4–40.5 ms to evaluate the spectral composition of the response. The magnitudes of frequency representation over the stimulus F0 (103–121 Hz) and F1 (454–720 Hz), were measured by taking the average of the amplitudes over the specified frequency ranges.

Statistical analysis

All statistical analyses were completed using IBM SPSS Statistics V24. Dependent measures included timing (i.e., the latencies in ms for waves V, A, C, D, E, F and O of the speech-ABR and the peak latency for peaks I, III and V of the click ABR), magnitude (the amplitudes of the waves) and the spectral representation (i.e., F0 and F1). For each dependent measure, ANOVA analyses of variance were used for the group factor (monolinguals, bilinguals) in the two conditions (quiet vs. noise). In all cases, p-values reflect two-tailed tests. Levene's test was used to ensure homogeneity of variance for all measures.

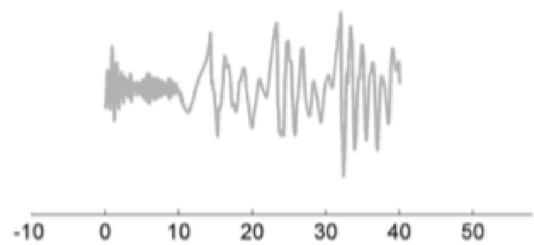

Figure 1. Time-domain representation of a 40 ms custom speech stimulus /da/.

3 Results

No significant differences were observed between the groups for ABR wave latencies ($p \geq 0.05$) and amplitudes ($p \geq 0.05$) in response to click stimuli.

3.1 Speech ABR

Figures 2 and 3 illustrate the grand average responses to speech stimuli in the two groups recorded in two conditions. Tables 1 and 2 show the latency and amplitude values for the speech ABR in the two groups of participants measured in two testing conditions.

Neural Timing (Latency)

Significant condition (with and without noise) effects were observed for all the waves (V, A, C, D, E, F and O). Longer latencies were observed in the noisy condition than in the quiet condition. The group factor (bilingual or monolingual) was significant for the V, C, D and F waves. Significant longer latencies were observed in monolinguals than in bilinguals. The interaction between condition X group factors was significant only for the wave C: [F (1, 39) = 7.5, p = 0.009, $\eta p2$ =0.16] (see Table 1). An analysis of simple effects for this significant interaction indicated that longer latency was observed in monolinguals when the stimulus was presented in +10 signal to noise ratio. Wave C latency was longer in monolinguals (mean 20.39, SD= 1.3 ms) than bilinguals: (mean 19.04, SD = .85 ms), [t (18) = 5.05, p = 0 .000].

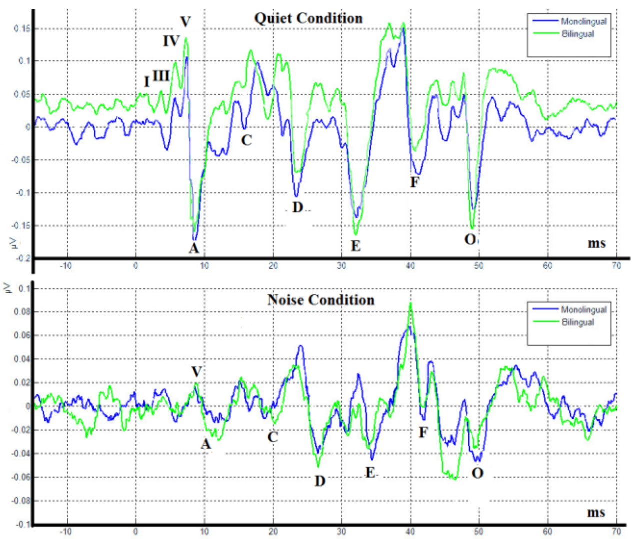

Figure 2: Grand average of subcortical responses (Speech-ABR) obtained from the two groups: monolinguals (blue) and bilinguals (green) recorded in quiet and in noise.

Neural magnitude (amplitude)

Regarding the amplitude value, significant effects were onlyobserved for the main condition factor for all of the waves except wave C (see Table 2). Wave amplitude was larger in quiet than in noise. No significant effect was observed for the main group factor or for the interaction between group and condition factor except for the wave E: [F (1, 39) = 4.2, p = 0.04, ηp2 =0.096] (see Table 2).

Spectral analysis

The amplitudes of the FFR are shown in Figure 3 and Table 2 along with their statistical significance. ANOVA results revealed a significant difference only for the main condition factor F0: [F (1, 38) = 62.8, p = 0.0001, ηp2 =0.62] and F1: [F (1, 38) = 72.76, p = 0.0001, ηp2 =0.66] (see Table 2). However, results revealed no significant differences between the groups or an interaction between groups and condition (p > 0.05 in all cases, see Table 2). T-tests for the condition factor revealed that the F0 and F1 amplitudes were larger in quiet than in noise.

Table 1: Results of a two-way, repeated-measures ANOVA, as a function of condition (noise and no noise) and group (monolingual, bilingual), for the mean latencies of waves V, A, C, D, E, F, O.

		Latency				
		df (between group)	df (within group)	F	*p*	SE
	V	1	39	45.7	0.001	0.54
	A	1	39	87.9	0.001	0.69
	C	1	39	41.1	0.001	0.51
Condition	**D**	1	39	149	0.001	0.79
	E	1	39	96.7	0.001	0.7
	F	1	39	75.8	0.001	0.7
	O	1	39	30.8	0.001	0.44
	V	1	39	3.6	0.07	0.08
	A	1	39	0.68	0.42	0.02
	C	1	39	7.5	0.009	0.16
	D	1	39	1.45	0.24	0.04
Group x Condition	**E**	1	39	3.1	0.08	0.07
	F	1	39	0.91	0.35	0.02
	O	1	39	0.49	0.49	0.01
	V	1	39	4.4	0.04	0.10
	A	1	39	1.63	0.21	0.04
	C	1	39	4.19	0.04	0.1
Group	**D**	1	39	9.4	0.004	0.2
	E	1	39	2.33	0.14	0.06
	F	1	39	3.9	0.05	0.09
	O	1	39	2.1	0.15	0.05

Table-2: Results of a two-way, repeated-measures ANOVA, as a function of condition (noise and no noise) and group (monolingual, bilingual), for the mean amplitudes of waves V, A, C, D, E, F, O, VA complex and spectral magnitude.

Amplitude						
		df (between group)	**df (within group)**	**F**	***p***	**SE**
Condition	**V**	**1**	39	99.9	0.001	0.7
	A	**1**	39	143.3	0.001	0.8
	C	**1**	39	2.13	0.15	0.05
	D	**1**	39	14.9	0.001	0.28
	E	**1**	39	163.8	0.001	0.81
	F	**1**	39	19.33	0.001	0.3
	O	**1**	39	54	0.001	0.6
	F0 amp: 103–121 Hz	**1**	38	62.8	0.001	0.62
	F1 amp: 454–719 Hz	**1**	38	72.8	0.001	0.66
Condition X Group	**V**	**1**	39	0.08	0.78	0.002
	A	**1**	39	0.93	0.34	0.02
	C	**1**	39	1.8	0.18	0.04
	D	**1**	39	0.43	0.5	0.01
	E	**1**	39	4.2	0.04	0.096
	F	**1**	39	0.1	0.76	0.002
	O	**1**	39	4.07	0.05	0.09
	F0 amp: 103–121 Hz	**1**	38	2.13	0.7	0.004
	F1 amp: 454–719 Hz	**1**	38	0.6	0.45	0.015
Group	**V**	**1**	39	0.08	0.78	0.002
	A	**1**	39	1.4	0.24	0.035
	C	**1**	39	1.3	0.26	0.033
	D	**1**	39	0.29	0.6	0.007
	E	**1**	39	3.7	0.06	0.087
	F	**1**	39	0.5	0.5	0.012
	O	**1**	39	3.3	0.08	0.08
	F0 amp: 103–121 Hz	**1**	39	0.5	0.48	0.013
	F1 amp: 454–719 Hz	**1**	39	3.2	0.08	0.077

4 Discussion

The aim of the current study was to compare neural responses of subcortical auditory potentials in both a quiet and a noisy listening environment using two groups of adults, monolingual speakers and bilingual speakers, who have an enriched sensory experience. Several neural biomarkers of speech-ABR were more sensitive, enabling us to distinguish between the two groups. In fact, the temporal analysis of the neural onset (wave V), the consonant transition (Wave C) and the harmonic region (D, F) responses showed longer latencies among the monolingual group compared to their bilingual peers. This would suggest that the wave's latency could be considered as a neural biomarker distinguishing the two groups. Moreover, when speech stimuli were presented in noise, the processing of the transition between consonant /d/ to /a/ required a longer time in monolinguals than bilinguals.

Part of the difficulty in perceiving stop consonants, such as /d/ in noisy situations, is the rapid production and the relatively low-amplitude transient features of speech [22]. Generally, increased peak latencies could be an indicative of a disruption of the encoding process [23-

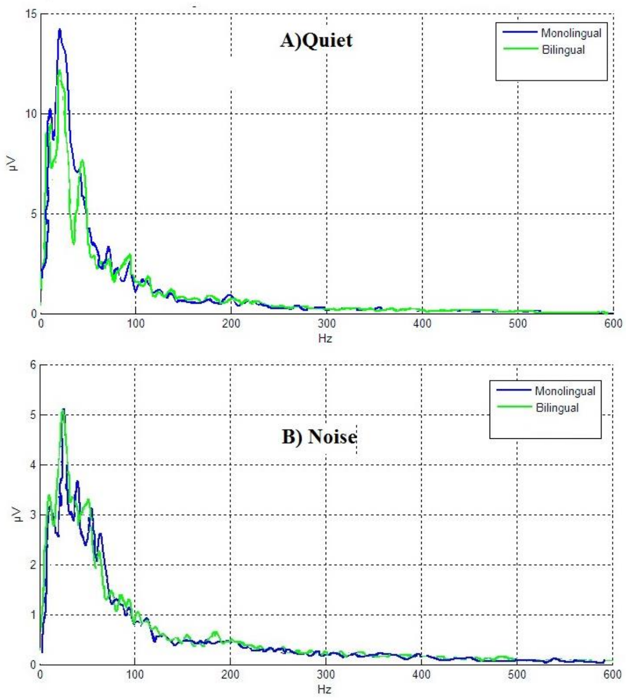

Figure 3: Grand average of fundamental frequency of subcortical responses of monolinguals (blue) and bilinguals (green) recorded in quiet (A) and in noise (B).

25]. Longer latencies have been observed in a number of clinical conditions, including specific language impairment, auditory processing disorder and hearing loss [23, 24, 26]. Although no clinical condition was observed in the monolingual participants, being bilingual could add extra advantages to the central auditory processing. In other words, enhanced experience in two languages could stimulate the automatic sound processing abilities of the auditory system in a way that make it highly efficient in regular and in challenging listening conditions.

It should be emphasized that a large change in the speech-ABR morphology of the waves was noted when comparing the noisy listening condition to the quiet condition in the two groups; waves with smaller amplitude and longer latency were observed in the noisy condition. The loss of the robust nature of the signal translates to an overall reduction of the amplitude peaks as well as increased latencies [8, 15]. A reduction in the amplitude of the response might serve as a manifestation of less efficient system processing [25]. Although the morphology of the neural responses obtained in noise was generally degraded in all participants, monolinguals demonstrated delayed neural subcortical encoding of transition of speech sound in the presence of background noise. The presence of background noise appears to greatly affect the coding of the stimulus in the monolingual group and to a lesser extent the bilingual group. The timing delays calculated for monolinguals contribute to the idea that individuals living in an enriched environment are better equipped to detect relevant sound characteristics more rapidly. Language experience in bilinguals limited the degradative effects of noise on neural timing in response to the formant transition of a speech syllable.

Although some studies have observed a deficit in speech-in-noise comprehension in bilinguals [27, 28], these studies assessed the non-native language in the bilinguals, and not the native or dominant language. Bilingual listeners have better speech-in-noise performance in their native rather than their non-native language [29].

Contrary to Krizman et al. (2012, 2014) [15, 16], none of the groups were found to have a fundamental frequency (F0) that was encoded more robustly than the others, in silent or noisy conditions. In noise, since vowels are less affected than consonants, the FFR is less degraded than the onset and the transition response [19]. A major difference between the onset and FFRs (F0 and F1) measured in this study was that neural encoding of onset features was delayed in the monolingual group, whereas the sustained FFR amplitude remained relatively similar in two groups. FFR refers to the later portion of the response evoked by the harmonic vowel structure of the stimulus [14]. The addition of ipsilateral noise predominately affected the latency of the several responses and also resulted in a reduction of the amplitude for all waves, as previously mentioned [14, 19]. The difference between the present study and Krizman et al.'s 2012 and 2014 studies could be explained, in part, by the differences in methodology and the method of analysis. Krizman et al. (2012; 2014) [15, 16] chose a 170 ms long stimulus and they studied the F0 after 50 ms of formant transition from /d/ to the FFR of /a/. In our case, /da/ was 40 ms long, with a 35 ms FFR. This may have potentially prevented the present study from finding any differences in the representation of F0 between the two groups. Moreover, no transient analysis had been performed for the first 50 ms of the stimuli in Krizman et al.'s 2012 and 2014 studies [15, 16]. Using a 40 ms stimulus, 7 distinct subcortical waves could be identified which is not the case with 170 ms. In terms of clinical application, Audiologists would be more familiar with speech ABR recorded with a 40 ms stimulus (due to similarities with click-ABR waves) than with a 170 ms stimulus. To be able to translate research findings to the clinical setting; 40 ms stimulus would be more suitable for clinical Audiologists seeking to identify neural biomarkers in clinical populations.

Though very little in the literature makes reference to the stimulus-encoding abilities of bilinguals using speech-ABR (with 40 ms /da/) in quiet and/or in noise, bilinguals could encode the auditory stimulus more efficiently due to enhancements of cognitive processes [16,17]. Krizman et al. (2012) [15] found that through experience-dependant plasticity, cortical regions of the brain that are responsible for processing language and executive control undergo modifications that lead to these enhancements. Therefore, bilinguals benefit from better inhibitory control, allowing them to better discriminate the characteristics of the desired stimulus, even if when the latter is presented in conjunction with an unrelated and disturbing signal, such as noise [15].

Limitations of the study

The participants in our study's bilingual group were not all bilingual to the same level of proficiency. It is difficult to ensure that second-language speakers have similar levels of language competency and frequency of utilization, which can be explained by the fact that there are many tools available to measure bilingualism. Each tool measures a specific capacity, and the literature does not clearly and/or accurately describe which tools were used to classify the relationship between levels of bilingualism based on individual proficiency. In addition, we did not take prior musical training into consideration. Since the effects of musical training on auditory processing are well known, this may have had an impact. Behavioral measures (such as the speech-in-noise test) could have been used for comparing behavioral and electrophysiological responses. Taken together, these limitations may affect the probative strength of the results in our study.

Future direction and clinical application

The speech-evoked ABR may be used as a tool to objectively measure and quantify the effects of noise, and may shed light on why some people have more difficulty in noise than others. Investigation of auditory evoked potentials in a population having specific difficulties understanding speech in background noise, such as children with auditory processing disorders, older adults, and individuals with sensory hearing loss shows excessive difficulty in noisy listening situations [30, 31]. Since Audiologists regularly use click-ABR in their clinical practice, this study supports the feasibility of using 40 ms /da/ to record Speech ABR in clinical setting.

5 Conclusion

Individuals speaking two or more languages are examples of lifelong acoustic exposure that may have an effect on the brain's functional organization. The results from this study show enriched language experience can lead to more efficient subcortical processing. ABR recorded with 40 ms /da/ provides an objective, multidimensional measure of sound encoding that could be different and/or abnormal in some individuals with different life experience or in clinical populations. This technique helps observe and might evaluate the effects of auditory activities and auditory processing and could serve as a sensitive biomarker.

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All authors contributed to this work. A.K. designed experiments, analyzed data, provided statistical analysis and wrote the paper; J.T. and G.Ch. performed experiments, collected and analyzed data, and contributed to the first draft of the paper. All authors discussed the results and implications and commented on the manuscript at all stages.

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THE EFFECTS OF SINGING LESSONS ON SPEECH EVOKED BRAINSTEM RESPONSES IN CHILDREN WITH CENTRAL AUDITORY PROCESSING DISORDERS

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Résumé

Cette étude a examiné l'impact de cours de chant sur le traitement auditif sous-cortical chez les enfants atteints d'un trouble du traitement auditif (TTA). Onze enfants de 7 à 11 ans ont participé à cette étude. Les potentiels évoqués auditifs du tronc cérébral (PEATC) ont été enregistrées en utilisant un stimulus auditif non verbal (clic) et un stimulus de parole (phonème /da/), avant et après six mois de cours de chant. Les leçons comprenaient un programme spécialement conçu pour remédier aux déficits de perception de la tonalité et du rythme observés chez les enfants ayant un TTA. Les résultats obtenus ont révélé des latences allongées chez les enfants présentant un TTA avant et après les leçons de chant par rapport aux valeurs normatives établis sur des enfants ayant une audition normale. Cependant, aucune différence de latence significative n'a été observée après six à huit mois de cours de chant. Des amplitudes significativement plus grandes ont été observées pour l'onde A et la pente VA après un entraînement musical. Une tendance vers une amplitude supérieure a également été observée pour l'onde O. Les expériences auditives enrichies ont une influence profonde sur la façon dont le son est traité dans le cerveau. Les données de cette étude suggèrent que l'efficacité des leçons de chant peut être quantifiée grâce aux PEATC enregistrés avec un stimulus de parole chez les enfants atteints de TTA. Après six à huit mois de formation musicale, l'amplitude de l'*onset* et de l'*offset* de la réponse physiologique s'est améliorée. L'amplitude des réponses sous-corticales pourrait donc être plus sensible que la latence pour démontrer l'effet positif des leçons de chant. Toutefois, cette durée reste insuffisante pour révéler une amélioration de la synchronisation neurale (latence).

Mots clefs : potentiels évoqués auditifs sous-corticaux ; potentiels évoqués auditifs du tronc cérébral avec stimuli verbaux ; trouble de traitement auditif, plasticité, intervention spécialisée, cours de chant

Abstract

This study investigated the effects of formal singing lessons on subcortical auditory responses in children with central auditory processing disorders (CAPD). Eleven school aged children (7-11 years old) participated in the study. Auditory brainstem responses (ABRs) were recorded using click and speech stimuli (/da/) before and after 6 months of singing lessons. The lessons included curriculum specifically designed to address deficits in pitch and timing perception as seen in children with CAPD. Results revealed delayed latencies in CAPD children before and after singing lessons compared to the normative data developed for children with normal auditory function. However, no significant latency differences were observed after the six to eight months of singing lessons. Significantly larger amplitudes were observed for Wave A and the VA slope after musical training. A trend for larger amplitude was also observed for Wave O. Enriched auditory experiences have a profound influence on how sound is processed in the brain. The data of the present study suggest that efficacy of formal singing lessons can be demonstrated by speech-ABR in children with CAPD. The magnitude of the onset and off-set of the speech-ABR response improved after the six to eight months of formal auditory (music) training. Subcortical response amplitude could be more sensitive than latencies to demonstrate the positive effect of singing lessons. However, this duration would be insufficient to reveal an improvement for the neural timing (latency).

Keywords: central auditory processing disorders, sub-cortical auditory evoked potentials, speech-ABR, plasticity, specific intervention, singing lessons

1 Introduction

An~auditory~centered~dysfunction,~a~prevailing~central auditory processing disorder (CAPD), has been outlined as a perceptual disorder which should be distinguished from peripheral hearing loss, cognitive, psychological and/or learning problems that are not auditory specific [1-4]. According to the Canadian Guidelines on Auditory Processing Disorder in Children and Adults (2012) [4], CAPD is defined as a persistent limitation in the performance of auditory activities. Children with CAPD have difficulties

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processing, tolerating, filtering and listening to sounds in background noise [1, 4]. Consequently, children with CAPD experience challenges in daily living which can make their school experiences extremely challenging and tiring [1, 4]. CAPD prevalence is not precisely known due to the lack of agreement about a 'universal standard' diagnostic test [5]. However, CAPD prevalence in the school-aged children is estimated to be between 2 and 3%, worldwide [6]. Besides high co-morbidity between CAPD and attention disorders [2], reading impairments [7], and language disorders [7], the behavioral test battery may be easily influenced by non-auditory factors like memory [8] or attention [9].

Research on therapeutic interventions specifically for CAPD is emerging [10-12], however, there is still much work to be done to identify evidence-based approaches which have demonstrable success as the results of the existing research have been limited. A meta-analysis by Fey et al. (2011) [13] explored the efficiency of several auditory and language interventions, such as Dichotic listening, Fast ForWord, Earobic, modified auditory integration, comprehension in noise training and other specific interventions, in school-aged children with CAPD (for more information and details about the interventions, see [13]). Based on the meta-analysis results, there was little evidence to support the effectiveness of existing intensive interventions [13]. Kraus and Banai (2007) [14] also noted that existing interventions generally do not show remarkable improvements. As such, there is currently little direction for clinicians working with children with CAPD and there is a marked need for deficit-specific interventions.

Given the impact that CAPD-related deficits can have on the daily life of children and the limited results of existing interventions, the need to explore possible interventions for CAPD is pressing. Preliminary studies on the use of music as auditory processing training show promising results in improving functions across several domains, such as enhancements in speech perception [11, 15], reading acquisition [11], socialization and emotional self- regulation [16, 17], numeracy and general attainment [18]. Moreover, changes in the brain become evident after mere months of music training, especially in children [11, 15]. The indirect benefits of music training have also been observed in special populations, including children with learning difficulties [19]. Music-making can improve general auditory function [11] and language processing [14, 20]. Studies show that there is a link between musical perception, phonological awareness and early reading development [15] and between perception of musical meter and phonological development [21]. Specific music training has also been shown to improve neural differentiation in speech sounds [11], and phonological awareness and auditory memory [15]. While music training has not been shown to provide an advantage in clinical speech-in-noise tests [22, 23], there is significant evidence of improved pitch perception and processing in musicians versus nonmusicians as seen in both behavioural and electrophysiological measures [23- 27]. The promise shown in these preliminary explorations of the effect of music on CAPD-related deficits encourage further research on music-related interventions.

Several studies investigated whether certain electrophysiological tests could be used as an objective and non-invasive neurophysiological tool to explore the impact of specific auditory intervention, such as music training, in diverse clinical populations [10, 11, 28, 29]. Recording auditory brainstem responses (ABRs) to nonverbal sounds such as a click has long been established as a valid and reliable clinical tool to assess the integrity of the neural transmission of acoustic stimuli [30]. The ABRs are auditory subcortical evoked responses originating from the distal portion of the eighth nerve and extending up to the auditory brainstem [31, 32]. ABRs consist of five distinct positive peaks (I to V) originating from the brainstem; the first peak, wave I, occurring 1.5 to 2 ms, and together IV and V form normally the largest peak, occurring about 5.5-6 ms after the onset of a click stimulus [30, 32]. Although the clinical ABR evoked by nonverbal stimuli, click or tone burst provides information regarding hearing sensitivity, it would not provide specific information regarding auditory processing.

Additional methods have been developed to analyze ABR information obtained from the presentation of speech stimuli such as /da/ that are spectrally and temporally more complex than click stimuli [33]. As described in Skoe and Kraus (2010) [34], ABRs recorded from presentation of a 40 ms stimuli to a stop consonant-vowel /da/ are composed of seven evoked waves (peaks); V and A are related to the onset response corresponding to the burst release of the stop consonant, peak C is the transition from consonant to vowel, peaks D, E, and F correspond to the speech-evoked frequency following responses (FFR) and peak O is the response to the stimulus offset.

ABRs evoked by speech stimuli were used in several clinical populations, such as children with hearing loss and/or reading difficulties, with the aim of finding neurophysiological markers [29, 35- 38]. For example, Strait et al. (201l) [29] tested 42 participants ages 8 to 13 years with different reading abilities. The objective was to define common biological underpinnings for music and reading abilities. Auditory working memory, attention, musical aptitude, reading ability, neural sensitivity to acoustic regularities, and auditory brainstem measures were investigated. The authors concluded that the multimodal quality of musical training promoted neuroplasticity and the enhancement of specific mechanisms such as auditory discrimination or temporal processing – pitch, timing or rhythm – essential abilities in speech processing. Therefore, biological markers and shared qualities promote the positive correlations between literacy and music, positioning the latter as a forthcoming reading – improvement approach [29].

Based on reviewed investigations, music training would improve auditory functioning and there would be a possibility that music training could be a viable option for CAPD intervention. This would fill the noted gap in effective interventions for CAPD. The purpose of this study was to explore this possibility by developing and delivering a music training intervention that targeted specific deficits seen in CAPD. We hypothesized that music-based intervention would be an effective intervention for CAPD. As playing a musical instrument requires intense coordination of skills, we opted to remove the challenge of motor coordination and focus purely on auditory skills by using singing lessons as the vehicle of training. We also sought to explore the clinical value of speech-evoked ABR, and potentially increase evidence for its use as part of the test battery required to diagnose CAPD.

2 Method

The experiment was conducted at the APD Ottawa clinic and at Lotus Centre for Special Music Education. All procedures were approved by the Office of Research Ethics and Integrity at the University of Ottawa.

2.1 Participants

Data were collected from 11 Canadian English-speaking school-age children (8 boys and 3 girls) that were between the ages of 7 and 12 years (mean age: 9 years, 11 months; SD: ±1 year and 3 months). Hearing threshold was within normal limits (pure tone thresholds ≤ 15 dB HL for octave frequencies from 250 to 8000 Hz and tympanometry was normal as well (admittance curve with a single peak between +50 to -100 daPa using a 226 Hz probe).

The participants were recruited from the APD Ottawa clinic in Ottawa, Canada and were diagnosed with auditory processing difficulties before enrolling in the present study. The diagnosis was given independently from the study. Since there are no universal criteria for the diagnosis of CAPD, the Canadian Guidelines on Auditory Processing Disorder in Children and Adults [4] were followed by APD Ottawa's audiologists to establish diagnosis. Within the parameters of these guidelines, children have a hypothesis or working diagnosis of CAPD when their performance is at least two standard deviations below the mean on a minimum of two tests. The test battery included the following tests: Staggered Spondaic Words [39], the Dichotic Digits Test [40], Pitch Pattern Test [41], Random Gap Detection Test [42] the Filtered Words test [43] and the Bamford-Kowal-Bench Speech-in-Noise Test [44-46] or Quick Speech-in-Noise Test [47]. To be part of the present study, the participants were required to have failed the Pitch Pattern Test [41] and the Random Gap Detection Test [42], as well as the other mentioned criteria (See Table 1).

2.2 Materials

Stimuli

Click stimuli and the speech syllable /da/ were used to elicit the auditory brainstem responses. All the responses were elicited and collected using a BioMARK system (Biological Marker of Auditory Processing, BioMARK software, NavigatorPro AEP system, Bio-logic Systems Corp.). The stimuli used was a five-formant speech syllable /da/ (provided with the BioMARK) comprised of an initial noise burst and a formant transition between the vowel and the consonant (for more information about the formant, see [34]).

Table 1: Results of eleven participants with Auditory Processing Difficulties on six tests evaluating the key functions of the central auditory system in two different moments. The age of the participants at the first singing session is also indicated.

CAPD	Gender	Age at the beginning of singing lessons (yr; month)	Specific information	Tests failed 1st evaluation	Tests failed 2nd evaluation
1	M	7;11	Diagnosed with: learning disability -difficulty reading	SSW, BKB-SIN, PPST, RGDT, FS, ACPT (borderline)	SSW, BKB-SIN FS:LE,
2	F	10;1	Difficulties in school consistent with apraxia and short attention span	SSW, BKB-SIN, DD, PST, PPST, RGDT, CST	SSW, BKB-SIN, DD, PST, PPST, RGDT
3	M	8;9	-Intellectual functioning in the upper end of the average range with great variability	FS:LE, PST, PPST, RGDT	N/A
4	M	8;9	-Diagnosed with: speech disorder	SSW, PPST, RGDT, CST:LE ACPT, DD:LE (borderline)	N/A
5	M	7;7	Difficulties with ocular function and challenges with overall motor skills	SSW, PPST, RGDT, DD:LE, CST :LE, BKB-SIN :LE and ACPT (borderline)	N/A
6	M	7;9	Concerns with attention and focus	SSW, PPST, RGDT, FS:RE	None
7	M	8;4	Difficulties in school	SSW, FW, CST:LE PPST, RGDT, DD, FS:RE	N/A
8	F	10;10	Difficulty with reading comprehension	SSW, PPST, RGDT, Quick SIN, PST, FS, DD:LE, CST :LE ACPT (borderline)	None
9	F	8;4	-Difficulties with reading	SSW, RGDT, PPST, PST, CST, FS, DD:LE	N/A
10	M	7;4	-History of non-verbal learning disability and ongoing school difficulties	SSW, PPST, RGDT, DDT=LE, FW= LE, CST= LE	N/A
11	M	11;6	-Diagnosed with ASD	SSW, PPST, RGDT, PST, CST, DD:RE	SSW, PST, TCS, CST:LE, DD:RE Quick-SIN,

Legend: SSW = Staggered Spondaic Word test, BKB-SIN (Bamford-Kowal-Bench) Speech-in-Noise Test, PPST = Pitch Pattern Sequence Test, RGDT = Random Gap Detection Test, FS = Filtered Speech, ACPT = Auditory Continuous Performance Test, *DD* = Dichotic Digits, PST = Phonemic Synthesis Test, CST = Competing Sentence Test, FW = Filtered Words, Quick SIN = *Quick* Speech in Noise *test*, *TCS* = Time-Compressed Speech *Test*, RE = Right Ear, LE = Left Ear, N/A = not applicable (not tested yet)

The speech syllable was 40 ms synthesized at a sampling rate of 10 kHz.

2.3 Procedures

A consent form was reviewed and signed by the parents, and the children also agreed to participate in the study. The study was conducted in three distinct steps over the course of six to eight months. The first and third steps were respectively the pre- and the post-test via electrophysiological recordings. The second step was the singing lesson intervention.

Electrophysiological recordings

Participants were seated comfortably with closed eyes during the recordings and the experimenter was in the room. The stimulus was delivered to the right ear through a Bio-logic® small foam insert earphone. The left ear was kept non-occluded for the entire recording. The single channel montage consisted of three disposable adhesive scalp electrodes (Natus Medical Inc, Mundelein, IL, USA): an active Cz (vertex), a reference (ipsilateral earlobe), and a grounded electrode (contralateral earlobe). The clicks were presented with rarefaction polarity at a rate of 13.3 clicks/sec. Two blocks of 1500 sweeps were collected from the right ear and were averaged using a 10.6 ms time window, band-pass filtered on-line from 80 to1500 Hz using a 12 dB/octave filter roll-off. The /da/ syllable was presented at alternating polarities at a rate of 10.9 cycle/sec. A total of 4000 artifact-free responses (two sub-averages of 2000 sweeps) were collected and averaged using an 85.33 ms (including a 15-ms pre-stimulus time window) band-pass filtered on-line from 100-2000 Hz. For the click and /da/ recordings; electrical impedances at each electrode tended to be ≤ 5 kΩ and did not exceed a 2 kΩ difference between electrodes throughout the recordings. Trials with an artifact exceeding ±23.8 µV indicating movement artifacts and baseline noise contamination were excluded from the average. The total recording time lasted between 30 and 45 minutes, including the time required for electrode placement.

Singing lesson intervention

Participants received 24 lessons of 30 minutes each, once per week, which were completed within a six to eight-month range. All participants attended 24 lessons by the end of the intervention period, which was sometimes interrupted by holidays or participant vacation.

A preparatory singing lesson curriculum was used as the intervention, with specific activities designed to develop rhythmic abilities, pitch awareness and discrimination, and auditory memory. The curriculum was specially designed for this investigation based on prior research in vocal instruction [48] and was adapted by the researchers of this study to target specific deficits in participants with auditory processing disorder. The curriculum was developed to be accessible to music educators and not as a comprehensive therapeutic approach. The objective was to determine whether singing lessons with targeted rhythm and pitch development activities delivered by music educators could be an effective intervention in improving CAPD-specific deficits. For this reason, the progress of each participant was allowed to flow naturally and the instructor was encouraged to follow the curriculum in a way that was participant-led and would be replicable by music educators. An identical lesson structure was used for each participant, however individual progress was encouraged, meaning that students progressed through the lesson material at individual rates. The lessons were collaborative and involved active participation from both the participant and the teacher providing the intervention. This removed the rigidity that would be present in traditional therapeutic interventions, but as the goal here was to explore the effectiveness of singing lessons that would be delivered by a music educator, the intervention was allowed to proceed in a natural manner that would reflect typical music lessons while providing activities to improve student deficits that could be implemented by any experienced music educator.

The singing lesson plan was highly structured and followed the same set of activities in the same order in each lesson. The lessons first activity was an introductory song to create structure and develop rote-learning skills. The song was led by the instructor and echoed by the student. It also involved rhythmic movement in the form of waving to reinforce the musical beat.

The second activity aimed to achieve rhythmic accuracy through full-body movement. A medium-sized ball was rolled between the instructor and participant to the predetermined tempo set on a metronome. This required attention to and awareness of the tempo. The tempo increased incrementally at and between each lesson, beginning at 40 beats per minute and capping off at 180 beats per minutes. The rate at which the tempo increased was individual based on the development of each participant.

The third activity served the purpose of developing pitch awareness, pitch differentiation, and intonation (ability to sing in tune). It also aimed to foster creativity and musical improvisation skills, as well as the exploration of a wide range of pitches. The instructor and student took turns playing single to double note patterns on a glockenspiel. Participants chose any pitch between a predetermined range appropriate for his/her voice, as determined by the teacher. After playing and listening to the pattern once, participants sang his/her name, word of choice, or solfege syllable to the pitch(es) of choice.

The fourth activity was vocal warmups to prepare for the repertoire. Warm-ups included repetitive melodic patterns that increased in length and range throughout the intervention in accordance with each participant's musical development and progress. Freedom was given to the instructor when determining the specifics of each warm-up, particularly to address vocal technique issues specific to the student. The final step of the warm-up involved participants using solfege syllables in a call-and-response activity using three-note melodies sung to a specific rhythmic pattern with simple, chorded piano accompaniment.

The fifth step of the lesson was to apply the above skills to larger-scale repertoire. The repertoire was selected from a compilation of preparatory-level voice repertoire prepared by the Royal Conservatory of Music, Resonance: A Comprehensive Voice Series [49]. The pieces were introduced to each participant in a predetermined sequence, however the pacing was individualized. The process of learning the repertoire was the same for every participant, starting first with reading reading the text; second, speaking the text to rhythm; third, singing the melody on a pure vowel; fourth, singing the melody with the text; finally, singing the song in its entirety with piano/CD accompaniment.

The final portion of the lesson was a rhythm activity for learning rhythmic notation and developing rhythmic accuracy. The instructor and student reviewed notated rhythm by using colour-coded and sized rhythm cards, and then worked together to build rhythmic patterns that increased in complexity as the lessons progressed. The participant practiced clapping the rhythm both with and without a metronome. The lesson concluded with a good-bye song to the same melody as the introductory song.

3 Results

All statistical analyses were completed using IBM SPSS Statistics software (Version 25) (SPSS, Inc. Chicago, IL). For each dependent measure, one-way analyses of variance ANOVA were used for pre- and post singing training. In all cases, p-values reflect two-tailed tests ($p \leq 0.05$). Levene's test was used to ensure homogeneity of variance for all measures.

All waves of the click and speech-ABR were identified and marked manually. Click-ABR waves (I, III and V) and Speech-ABR waves (V, A, C, D, E, F and O) were replicated twice and visually marked.

3.1 Electrophysiology measurement

Electrophysiological recordings

No significant differences were observed between the two pre- and post singing training sessions test conditions for ABR wave latencies ($p \geq 0.05$) and amplitudes ($p \geq 0.05$) in response to click stimuli. For the speech-ABRs, dependent measures included timing (i.e., the latencies in ms) and the magnitude (amplitude in uV) of waves V, A, C, D, E, F, O and VA slope).

Figure 1 illustrates the participants' grand average responses to speech stimuli recorded in the two pre- and post singing training sessions. No significant differences were found between the two conditions for speech ABR neural timing (peak latencies) of any of the waves ($p \geq 0.05$). However, the neural magnitude (amplitude) revealed somewhat different results. Significant differences were found between the two conditions for the speech ABR wave peak amplitude: A (on-set): [$F(1, 19) = 5.4$, $p = 0.03$, $\eta p2 = 0.22$] and VA slope (on-set): [$F(1,19) = 6.5$, $p = 0.02$, $\eta p2 = 0.25$]. A trend was observed for peak amplitude O (off-set) [$F(1,19) = 3.4$, $p = 0.08$, $\eta p2 = 0.15$]. The peak (A, O) amplitudes and VA slope were bigger post- singing lessons compared to the pre-lesson session.

Participant individual data

In order to have a better understanding of the pattern of results in relation to wave amplitude, the individual data of participants with CAPD was explored. Three categories were identified: A) noticeable amplitude changes for almost all waves after singing training; B) a mixed pattern of noticeable changes for some waves and no remarkable changes for other waves; and C) minor amplitude changes for the several of the speech-ABR waves after singing training. Twenty per cent of the participants were classified in category A; twenty in category B; and sixty per cent of participants were included in category C (See Figures 2, 3 and 4).

4 Discussion

The goal of this study was to evaluate the degree to which neurophysiological subcortical response morphology, timing and magnitude would be modulated by a 6-month block of singing lessons for children identified with CAPD. The main neurophysiological findings of the present study suggest that the magnitude (amplitude) of several subcortical responses demonstrated a positive effect from the music training.

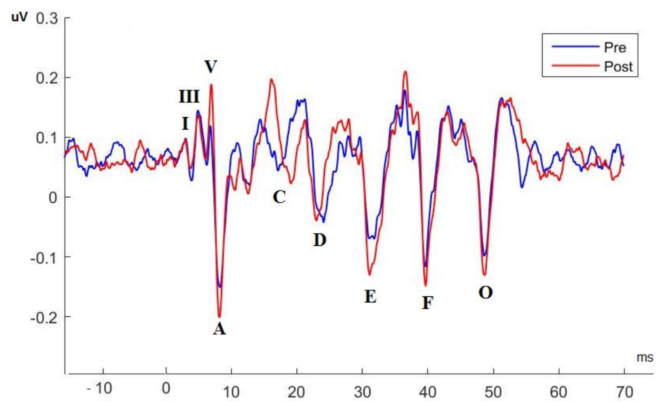


Figure 1: Grand average of subcortical responses (speech-ABR) obtained from children with auditory processing difficulties recorded before and after singing lessons (Pre, presented in bleu, and Post, presented in red). Click-evoked ABR peaks (I, III, and V) and the major speech- ABR peaks V, A, C, D, E, F, and O are labeled

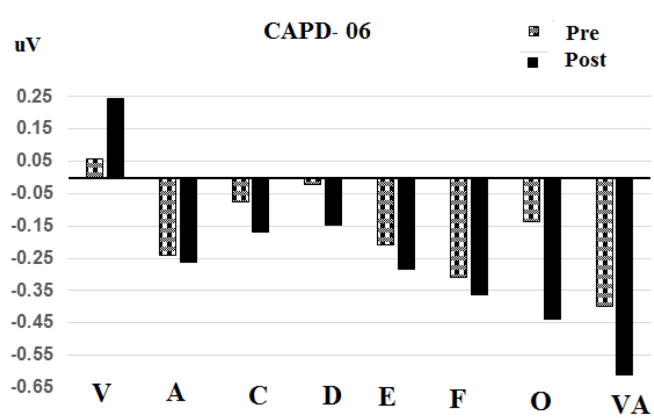
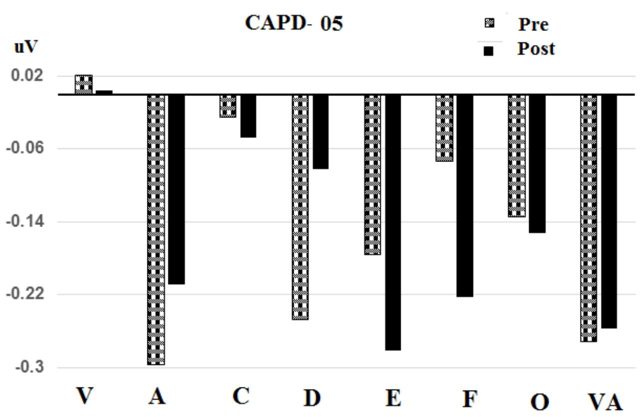


Figure 2: Category A. subcortical responses (speech-ABR) obtained from a participantparticipant with auditory processing difficulties (CAPD 6) recorded before and after singing lessons (Pre and Post). The amplitude of the six waves (V, A, C, D, E, F, O) and the VA slop were improved after the singing training.



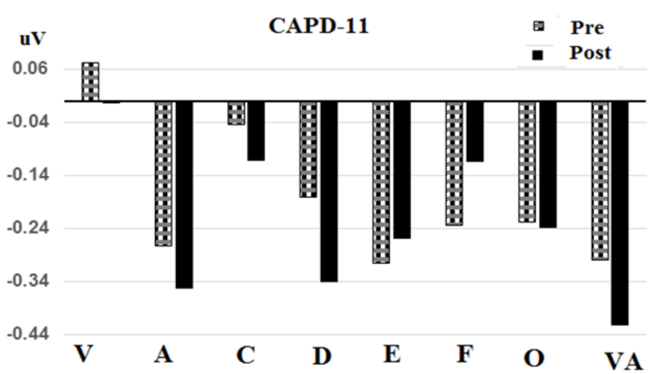


Figure 3: Category B. subcortical responses (speech-ABR) obtained from two participants with auditory processing difficulties (CAPD 05 and 11) recorded before and after singing lessons (pPre and pPost). The amplitude of waves C, E, F and O was improved for CAPD 05 and the amplitude of waves A, C, D and VA slop was improved for CAPD 11 after the singing training.

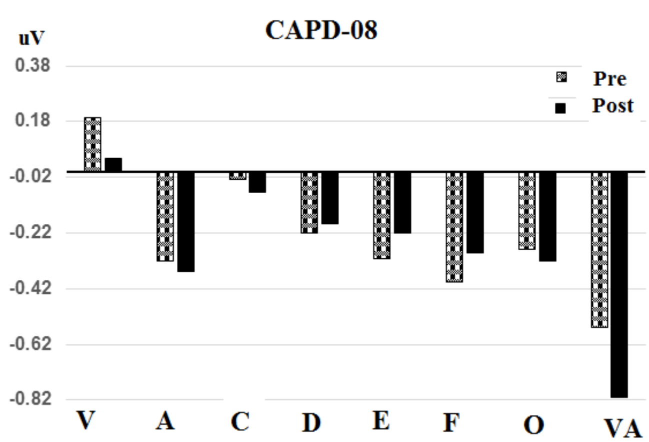


Figure 4: Category C. subcortical responses (speech-ABR) obtained from a participantsparticipant with auditory processing difficulties (CAPD 8) recorded before and after singing lessons (Pre and Post). The amplitude of majority waves (V, C, D, E, F, O) were not changed after the singing training, except VA slop which improved after the training.

The amplitude representation of several waves improved with singing lessons; at the early processing stage, onset level, and to the certain extent at the end of processing (offset). The larger amplitude responses could be a sign of more efficient auditory processing as a result of the singing lessons intervention. The amplitude of a waveform represents the magnitude of processing by the central auditory system [50]. Although the exact mechanisms of auditory learning – related plasticity remain unclear, the amplitude increase of some subcortical responses could indicate changes in the number of contributing neurons (such as synaptic density).

Musical training would shape the central auditory system [17, 51] and neuronal plasticity is the idea that neural pathways can be strengthened through repetitive use [52]. As noted by Ohl & Scheich (2005) [53], the effect of learning can be observed at different regions of the central auditory system from subcortical to cortical. Moreover, an increased amplitude of the physiological responses to the trained sound would be one of the learning manifestations in animal and in humans [53]. However, it remains puzzling that significant changes related to the training were not observed for all waves. How does the positive effect of singing lessons manifest mainly at the on-set and the offset (two waves A, VA slop and some trend on O) and not at the FFR region (Waves D, E, F)? Little is still known about the specific generator of the ABRs evoked by speech stimuli and the underlying neural mechanisms of these responses.

Since significant group results may not imply clinical significance, individual data of participant with CAPD for waves amplitude were explored in the present study. The examination demonstrated that the participants had different individual responses to the auditory (singing) training. The most revealing results showed that a fifth of the participants exhibited changes documented by neurophysiological recording. However, some of the participants had similar results before and after the training, showing no measurable benefits with the tests used. The majority of the participants demonstrated a larger amplitude for some neural responses. This could be due to heterogeneous characteristics of the CAPD participants in that they did not all demonstrate the same large amplitude patterns for the neural responses.

Children with auditory processing difficulties from a similar age group were tested with speech-evoked ABR before and after singing lessons and showed different amplitude patterns based on the individual data. Speech-ABR could therefore provide insight into a precision-assessment approach for CAPD individuals pre – and post – singing lessons. However, even children of the same age group diagnosed with auditory processing difficulties may present heterogenous results after singing lessons as a "reflection" of the differently altered auditory abilities. A recent review by Joshi and Light (2018) [54] proposed using an umbrella trial paradigm instead of a basket trial paradigm for individuals with schizophrenia. Generally, basket trials evaluate the effectiveness of a potential drug based on the mechanism of the disease. On the other hand, umbrella trials would take a more precise approach in which an intervention would be tailored to nuanced patient factors [54]. Authors proposed a tailored umbrella method for treating the cognitive impairment in schizophrenia (candidate illness) and the electroencephalogram measure of mismatch negativity as the candidate biomarker for identifying the patients' particularities [54]. Although the umbrella method has not been explored in audiology and/or in the CAPD domain, it would be worth exploring the potential of this method. By having a larger sample size and using ABRs evoked by speech stimuli (as a biomarker), it might be possible to identify CAPD children who would benefit from singing lessons.

Regarding the neural processing timing (latency) of the subcortical responses, these latencies continued to be delayed both before and after the training in participants when compared to the norm developed by Russo, Nicol, Masacchia and Kraus (2004) [55]. In other words, the speech-ABR waves for the children identified with auditory processing deficiencies had longer latencies than the norm. However, contrary to our hypothesis, neural timing was not improved after six to eight months of singing lessons. Although musical experience could shape the central auditory system [15, 17, 51-53], the exact training duration or form of the training remains unclear. This lack of change in latency could be interpreted as an insufficient duration of training, or that our investigation tool, speech-ABR, was not sensitive enough to show changes after the short training period. Moreover, a study by Kraus and Banai (2007) [14] demonstrated no latency changes in any peaks of speech-ABR responses after auditory training. In another example, speech-ABR was recorded in school age children before musical training, after one year, then again after two years [11]. No changes were observed after one year of training. However, results demonstrated a difference after two years of training. Authors explained that the number of hours of lessons after one year was not sufficient to produce a neurophysiological change [11]. When the duration of music lessons increased from two to four hours per week and was more focused on a single instrument, the positive effect of musical training was measurable by speech-ABR [11].

It should be emphasized that the children in the present study also failed several behavioral CAPD tests including timing processing (PPT, RGDT). Although the timing of the subcortical representation of speech in participants with CAPD did not show improvement with musical training, these children might have needed longer musical training, or more intensive repetition, instead of once per week, in order to observe timing changes at the subcortical level. Moreover, the small participant sample could explain this unexpected finding, to a certain degree.

Study limitations and future directions

A major limitation of the current study was the small sample size, which prohibits making any strong conclusions based on the obtained results. However, to the best to our knowledge, this is the first study showing preliminary data on the effect of singing lessons on subcortical auditory responses in children with auditory processing difficulties. We aim to present the results from a larger cohort in the future since these disorders are heterogeneous and characterized by overlapping symptoms. A larger sample size will also allow the examination of any correlation between behavioural and electrophysiological results. Moreover, a study with a larger sample size would help to determine the sensitivity and the specificity of the present auditory training protocol in order to identify which children would benefit from this type of training. Another limitation of the study was the absence of a control group; the latency data were compared only to the norm. It would be interesting to compare the results pattern between children with and without auditory processing difficulties. Moreover, it might be important to have an active control group of children with APD who do some other type of activity that matches the singing training in time and in interaction with another person.

5 Conclusion

The present study explored the capacity of the central auditory system to change through musical training in children with identified auditory processing difficulties. This study demonstrates that children with auditory processing disorders exhibit abnormal timing of subcortical responses to speech stimuli. Six to eight months of auditory training through singing lessons was shown to improve the magnitude, though not the timing of some subcortical responses in these children. Additionally, ABRs evoked by speech stimuli offers a method for objectively monitoring the neurophysiological effects of auditory training programs.

Acknowledgments

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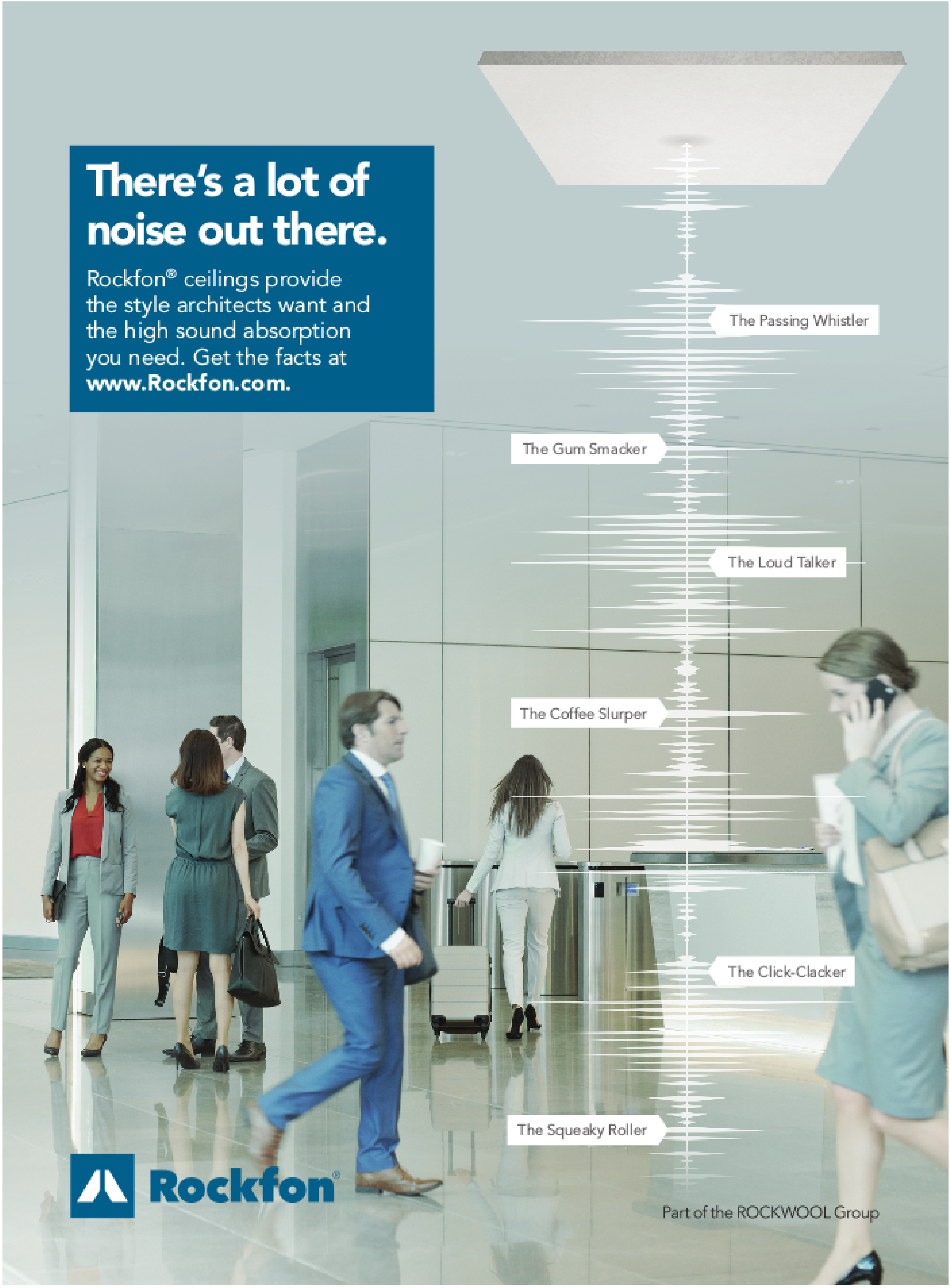
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DEVELOPMENT OF A REAL-TIME EOG-BASED ACOUSTICAL BEAMFORMER ALGORITHM FOR BINAURAL HEARING DEVICES

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Résumé

L'électro-oculographie (EOG) est une technique permettant, notamment, de mesurer les fonctions de la motricité occulaire grâce à des électrodes périorbitales enregistrant la différence de potentiel entre la cornée (positif) et la rétine (négatif). Cet article présente la preuve de concept d'un algorithme de *beamforming* acoustique utilisant l'angle de déplacement occulaire obtenu à partir d'enregistrements EOG pour optimiser la localisation et la perception des sons. Un tel algorithme permettrait d'optimiser l'expérience utilisateur des personnes utilisant des dispositifs auditifs binauraux tels que des audioprothèses ou des protecteurs auditifs numériques, en améliorant, par exemple, la reconnaissance de la parole en présence de bruit.

Mots clefs : beamforming acoustique, audioprothèse, électro-oculographie (EOG), simulink, binaural

Abstract

Electro-oculography (EOG), a technique that can be used to evaluate ocular motility, uses periorbital electrodes to record the difference in potential between the cornea (positive) and the retina (negative). This paper presents a proof of concept for an acoustical beamforming algorithm using the gaze angle obtained from EOG recordings to optimize sound localization and perception. This algorithm could enhance the user experience for binaural hearing devices such as hearing aids or digital hearing protectors by improving, for example, speech recognition in noise.

Keywords: beamforming, hearing aids, electrooculography (EOG), simulink, binaural

1 Introduction

Hearing aid users often complain about the difficulty of listening to a given sound source, for instance, speech from their interlocutor, in the presence of disturbances, such as concurrent babble, the so-called "cocktail party effect". To help hearing aid wearers, the devices are now designed to simultaneously reduce background noise and increase speech intelligibility without adding artefacts or distortions to the signal. Two main features are considered to achieve this goal, signal processing algorithms, and directional microphones [1].

Directional hearing aids currently on the market are based on the assumption that people listen to what is in front of them. Such devices usually include more than one microphone to increase the signal-to-noise ratio through spatial consideration: the signal of interest from the frontal hemispheres is considerably amplified while the signal coming from rear azimuths is less amplified [1, 2]. Still, Thorpe *et al.* [3] and Srinivasan *et al.* [4] have concluded that head and eye orientations are the most obvious indicators of attentional orientation. Srinivasan *et al.* [4] mention that listeners may also pay attention to a direction that they are not actually facing, which is called, covert attention. Numerous characteristics associated to the aids, as well as to the environment, must be taken into consideration in the evaluation of directional hearing aid benefits. Chung *et al.* relate some of these characteristics [1]. Notably, the directivity index of the microphone, characteristics of the sound sources (quantity, spatial location and type), characteristics of the environment (room, environmental acoustics), relative distance between the sound source of interest and the user as well as the location of the background noise, relative to the user. For example, Chung *et al.* [1] and Killion *et al.* [5] demonstrate that reverberation reduces the advantages of the hearing aids' directionality; the sounds are reflected from different surfaces in every direction, making it impossible to discriminate the sound source of interest from its spatial origin [1, 5]. Directional hearing aids also present disadvantages when the signal of interest is behind the user or when a surrounding wind noise is present [6, 7].

On the other hand, omnidirectional hearing aids amplify sounds coming from all directions equally. Gnewikow *et al.* [5] show that directional hearing aids give better speech-intelligibility performances than omnidirectional aids, but also that the difference decreases as the degree of hearing loss increases. Gnewikow *et al.* also reported that people with mild hearing loss mostly prefer directional hearing aids whereas people with moderate and severe hearing loss seem to prefer omnidirectional hearing aids. Generally, the omnidirectional mode is preferred in quiet environments, when the sound source of interest is not located in front of the user, or when the sound source is moving, while the directional mode is preferred when the sound source is

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located in front of the user, or close enough to the user, and if there is a consistent presence of background noise [8]. As a result, hearing aids that are both omnidirectional and directional have proven more successful, and are more commonly used. Also, it has been demonstrated in clinical studies that such aids can lead to good results when the user is able to switch properly between both functionalities [6].

Algorithms embedded in hearing aids can localise sound sources surrounding the hearing aid users. However, such algorithms remain unable to identify which is the source of interest.

Bulling *et al.* argue that eye movements can supply information on visual tasks and on cognitive processes of visual perception such as attention [9]. According to them, electrooculography (EOG) is a method well suited for mobile eye tracking, and is relatively inexpensive. They also qualify this method as reliable, easy to use, and unobtrusive, when compared to common eye tracking systems that use cameras. In their study, Bulling *et al.* use EOG to detect three specific eye movement patterns, namely saccades, fixations and blinks. The algorithms used to detect fixations use the fact that the gaze remains stable during a fixation [9]. Their results show an average precision in pattern detection of 69-93% for six out of eight participants, and less than 50% for the two last participants.

Joyce *et al.* developed a method based on EOG signals to track where an individual's gaze is directed on the surface of a flat screen (x, y coordinates) [10]. They obtained a mean error of 1-2 degrees on a 30-degree amplitude position (15 degrees on each side of the screen centre). However, according to them, the relationship between the EOG output and the angle of gaze stays linear within a limited range of up to +/- 70 degrees. Unfortunately, this method needs a calibration step before being usable, which means the participants had to sit at a precise distance from the screen and perform a few specific eye movements. If an electrode is displaced during the insertion of such an instrumented hearing aid device, the system would need to be recalibrated before being once again usable. Consequently, EOG-based eye tracking might not be well suited for real-world situations. However, the proposed system described in this paper might not necessarily require such recalibration since it can accommodate a certain range of error without altering the measurement of the eye gaze.

The paper is structured as follows: the design of the EOG-based beamforming is described in section 2. Section 3 contains preliminary results used to validate the proposed model. Conclusions and future works are presented in section 4.

2 Design of the EOG-based beamformer

The present study aims to develop a proof-of-concept of an EOG-based acoustical beamforming algorithm for improving speech discrimination in noisy environments and optimizing sound localization for users wearing binaural hearing aids.

2.1 Overview of fixed beamforming techniques

The objective of a fixed beamformer is to obtain spatial focusing on the desired speech source, thereby reducing background noise not coming from the direction of the speech source [11]. Different types of fixed beamformers exist, e.g. delay-and-sum beamforming, superdirective beamforming, differential microphone arrays and frequency invariant beamforming [12-17]. Fixed beamformers have mainly been used for monaural hearing aids [18-20]. Fixed beamforming techniques have also been proposed for binaural hearing aids combining spatial selectivity and noise reduction with the preservation of the speech source's binaural cues [21-23].

2.2 Design and implementation

Figure 1 shows a schematic of the proposed EOG-based beamformer prototype. The EOG signals recorded using electrodes F7 and F8 of the Emotiv (San Francisco, CA, USA) EPOC® headset are supplied to the EOG block, which calculates the corresponding angle. The angle is supplied to the beamformer for Interaural Time Difference (ITD) and Interaural Level Difference (ILD) calculations. The model takes stereo sound input from the left and right microphones, processes it in real-time and sends it back to the stereo headphones to create the binaural effect.

Figure 2 presents the block diagram of the model implemented on Simulink [24]. Four inputs are needed to perform the beamforming: the left and right in-ear microphone inputs, which are given by the *Audio processing* group of blocks, and the left and right delays, which are computed by the *EOG processing* group of blocks. Several steps are required to obtain the left and right delays.

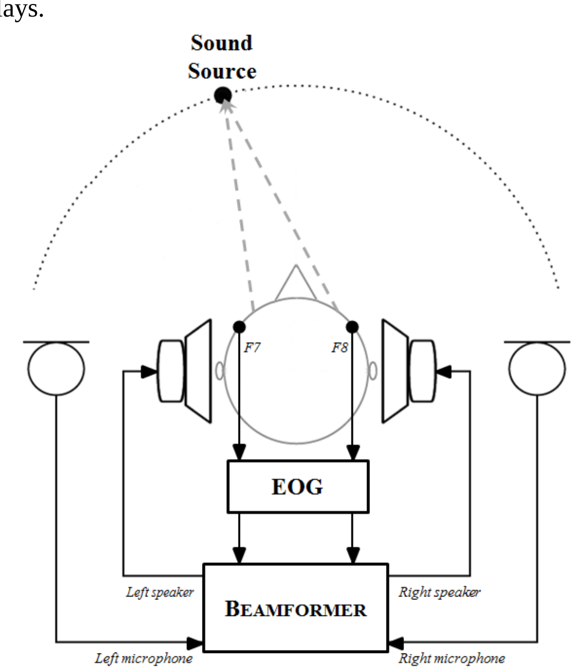

Figure 1: Schematic of the proposed EOG-based beamformer

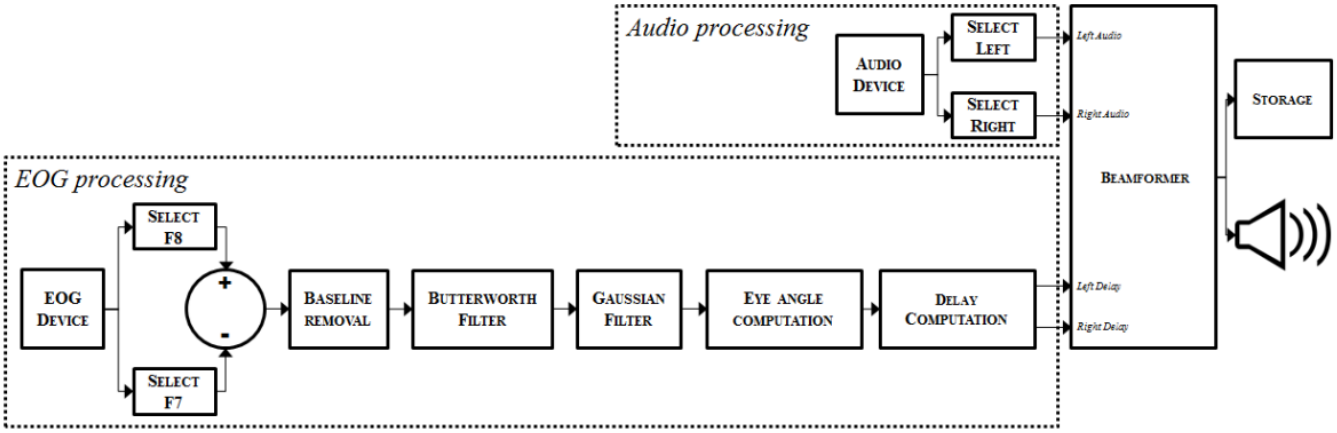

Figure 2: Simulink Block Diagrams of the proposed EOG-based beamformer.

First, EOG raw data obtained at F7 and F8 positions are selected from the output data given by the Emotiv headset and are formatted into a one-column format per electrode. These data are then subtracted to get the horizontal raw signal before being weight-averaged to remove the baseline from the horizontal raw signal.

Then, the signal is filtered and the corresponding horizontal angle is estimated mathematically. A MATLAB [25] function finally computes the delays corresponding to the given angle required to produce the binaural effect and stores the output into a multimedia file, for validation purposes.

The algorithm was first implemented completely in an offline mode using MATLAB and post-processing scripts. This offline mode includes scripts for EOG processing and angle calculation using windowed treatment.

Once the algorithm had been validated offline, a real-time model, with real-time input EOG signals and real-time inputs from the microphone, was developed using Simulink. The major advantage of Simulink was to facilitate the implementation of sample-by-sample real-time processing while MATLAB scripts used windowed treatment.

EOG recordings

EOG recordings, a technique used to evaluate ocular motility, can be used to assess the horizontal eye movements that are the most obvious indicators of where people are trying to direct their hearing attention. To obtain these horizontal eye movements, EOG signals were recorded on one subject using two electrodes of the Emotiv EPOC® headset placed on the external canthi (the bone on the side of the eye).

Minimal skin preparation was deliberate, to reproduce the limitations of acceptability as are to be expected of any device that is to be worn in social settings. Figure 3 shows the electrode placements used to measure EOG and Figure 4 presents a section of the raw EOG signal recorded on one subject.

Baseline removal

During electrophysiological recordings, drifts and/or direct current offsets due to sweating and skin conductance variations or other noise sources can compromise the quality of the recorded signals. Therefore, a common procedure is used to relativize the signal of interest with respect to a control (baseline) signal, shortly recorded before a stimulus event. Such procedures require offline data processing. Consequently, two methods were developed to perform the baseline removal on the data recorded on one participant, without doing offline data processing.

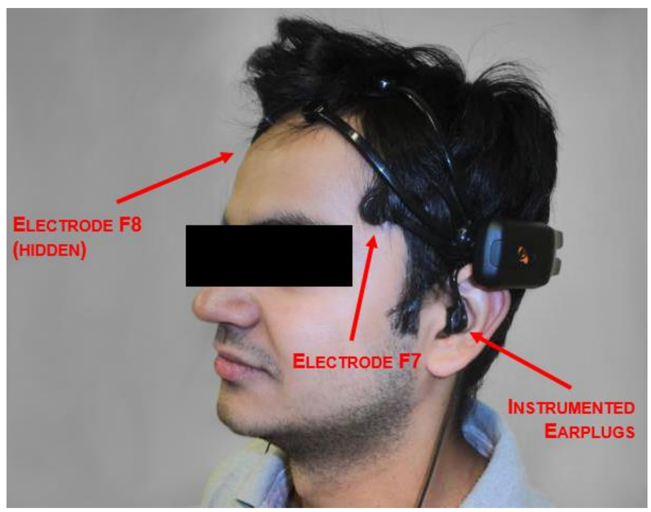

Figure 3: Electrode placement used for EOG recordings with the Emotiv EPOC® headset.

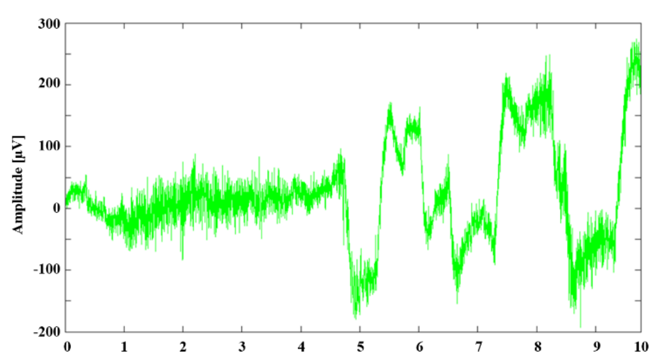

Figure 4: Raw EOG signal of F7-F8 signals, as recorded on one subject using electrode placement illustrated in Figure 3.

The first proposed method subtracts the mean amplitude value of the signal computed on three consecutive data windows of 10 ms to the data window being processed. The second proposed method subtracts the mean amplitude value of the signal computed from the first point of the first data window to the first point of the data window being processed. This method requires more data to compute the arithmetic mean since the number of data points being considered in the calculation increases as the data process moves forward.

Figure 5 presents the results obtained with the conventional baseline removal method (top) and the results obtained with the two proposed methods for baseline removal (middle and bottom). Figure 5 indicates that the results obtained with the second proposed method (bottom) are closer to those obtained with the conventional method (top) than those obtained with the first proposed method (middle).

Filtering

After the baseline removal, data were low-pass filtered using a fifth order Butterworth filter (-3dB cut-off at 10 Hz) before being filtered with a Gaussian filter to remove high frequency components since this type of filtering method requires fewer calculations than a frequency cut performed in the frequency domain. Figure 6 shows the filtered data from a subsection of the EOG signal presented in Figure 5.

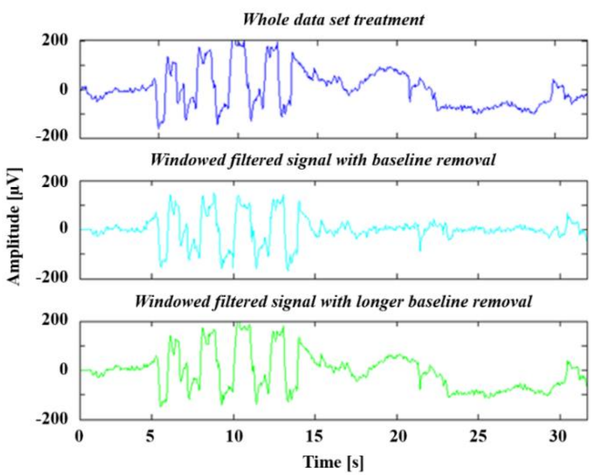

Figure 5: Baseline removal results obtained with a conventional method (top), with the first proposed method (middle) and with the second proposed method (bottom).

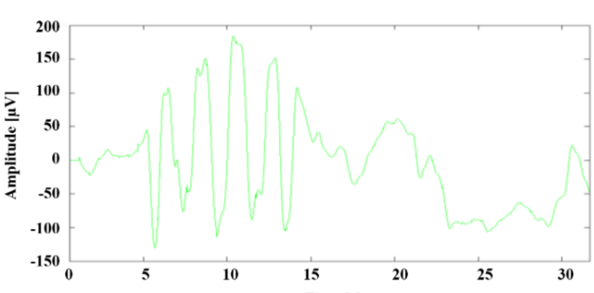

Figure 6: EOG signal filtered with a Gaussian filter, after baseline removal.

Horizontal eye angle computation

The EOG filtered results were used to establish the relationship (1) between the horizontal eye angle and the amplitude of the EOG signal, assuming that the angular movement of the eyes is linearly related to the amplitude of the signal, within a given angle interval.

$$\theta(i) = \frac{A(i)}{4.44\mu V} \quad (1)$$

Where Θ is the angle in degrees, A is the EOG signal amplitude in µV and i is the index of the sample.

Delay-and-sum beamforming

The beamforming method presented here, relies on spatial coherence. Signals that reach the two binaural microphones are delayed in time (in number of samples), following the desired beamforming angle, and are summed, so their amplitude is doubled if they are perfectly in phase, and diminished, to a different extent, if they are not in phase [26].

Figure 7 shows schematically the different steps used to execute the delays and summations. In the example illustrated in Figure 7, the imposed delay consists of three signal samples received on the right microphone. Consequently, the signal that is to be amplified is the one coming from the left side of the user and which reaches the left microphone some time before the right microphone (with a delay of approximately three samples). The last step illustrated at the bottom of Figure 7, corresponds to the shift of the matrices' sum, formatted as the original data.

In this step, data that were originally present in the right and left matrices are replaced by the ones that have been summed: signals that were not in phase (such as random noise) are therefore subtracted. Once all these steps are executed, the two matrices are presented to the test subject, through the miniaturized speakers embedded inside the earpieces.

However, the presence of numerous discontinuities in the signal creates important artefacts in the signal that are sent to the user's ears.

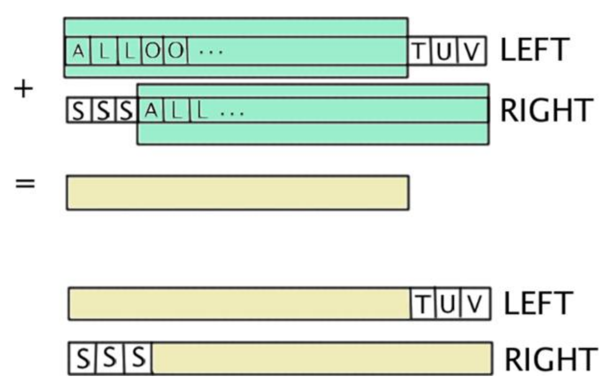

Figure 7: Steps in delay and summation, for a signal delayed by three samples (S) on the right microphone, while a signal starting with "ALLOO" is being played. "TUV" indicates the trailing audio message received on the left microphone but not yet picked-up by the right microphone.

At the beginning of a data window, when there is a difference between the amplitude of the last window's data and the amplitude of the first data of the processed window, an artefact may be generated. Also, at the limit between the section of the data window that has been summed and the rest of the data window, there can be a discontinuity that generates artefacts.

Figure 8 shows three successive data windows as well as the places where the discontinuities can be found.

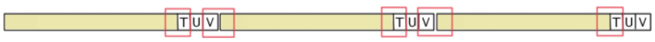

Figure 8: Discontinuities.

With this method, which consists of using only one window of data at a time, the main problem is not related to the discontinuities between summed values and original values, but to the discontinuities between two different windows of data, where an interpolation is necessary because it is impossible to filtrate (i.e., filtrated data that have already been sent to the user's ears). With interpolations, the results generally give better results, but the artifacts are persistent. Also, an interpolation between every single window implies a heavy calculation task. Another method was thus explored, and consists of using two data windows at a time instead of only one. This method is presented in Figure 9.

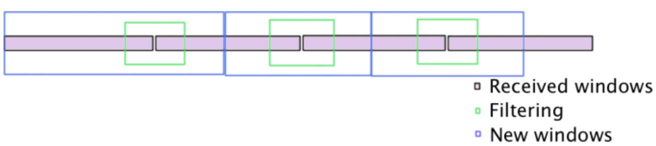

Figure 9: Reducing discontinuities.

3 Preliminary results

Gaze detection

Figure 10 presents the plot of the gaze angle versus time. As can be seen on this figure, the proposed EOG-driven beamforming algorithm was able to assess the movements generated by the eyes of the participant.

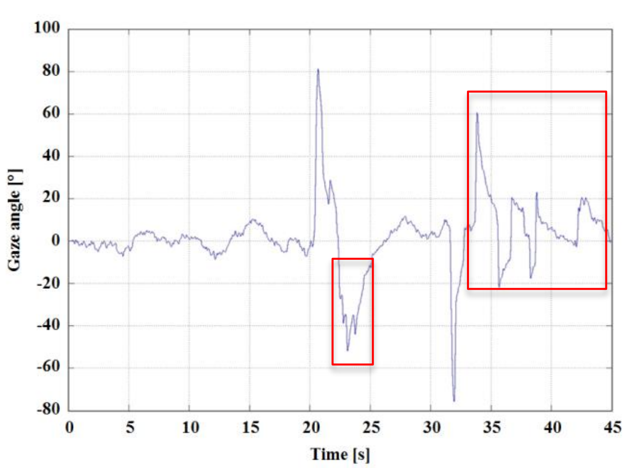

Figure 10: Gaze angle vs time plot in a Simulink scope.

Acoustical beamforming

With this proposed delay-and-sum method, a single filtering operation comprises one filtering operation and one interpolation. The filtering that is executed between two windows includes 50 samples. If a delay of 14 samples corresponds to a 45° angle, 25 samples on each side, included in the filtering, means that all the discontinuities are treated by this same filtering step. In other words, this filtering reduces the number of discontinuities present between two windows of data as well as the discontinuities present between the summed data and the original data in a window. This method reduces the complexity of calculation and at the same time, the time required for the calculation, and the interpolation generated artefacts. A drawback of this method is that two windows are required for processing instead of only one, which means that the delay between the time when the signals are sampled and the time when the signals are sent to the user's ears is increased. For 1500 samples per window and a sampling frequency of 44,100 Hz, the delay related to the proposed processing method is 0.068 seconds, excluding computation time.

Figures 11 and 12 show the results of a simulation that point out this phenomenon. In this simulation, the sound sources are localized all around the user, spaced at 1-degree intervals, and at a distance of one meter from the hearing aid user. For this, the beamformer is steered at 90° on the figures, which corresponds to the front of the user.

The reason why the lines are not smooth on Figures 11 and 12 is that the imposed delays are calculated in terms of samples instead of exact time. For a certain distance interval from the source, the imposed delay stays the same, which creates a "step" on the plot.

As can be seen from Figures 11 and 12, the proposed binaural beamforming approach only uses spatial coherence and does not provide the same enhancement across all the frequency range.

4 Conclusion and future work

This study presents an EOG-driven beamformer proof-of-concept. This real-time model is able to correct the audio signals recorded from the left and right in-ear microphones using EOG signals recorded from two electrodes, and present the optimized audio signals to the left and right in-ear speakers.

Further research is needed to overcome several limitations of this proposed EOG driven beamformer. Regarding the beamformer algorithm, further improvements could be achieved by using the resulting filtered signal to calculate the spectral weight to be applied on the head-related transfer function (HRTF) rather than being directly used as playback signal to be sent to the in-ear headphones. For the EOG gaze-detection algorithm, several filtering techniques that were applied in the post-processing mode are not implementable in a real-time embedded system. Therefore, alternate solutions must be applied to smooth the fast temporal transitions after each eye movement. Another limitation of this model remains the baseline removal method.

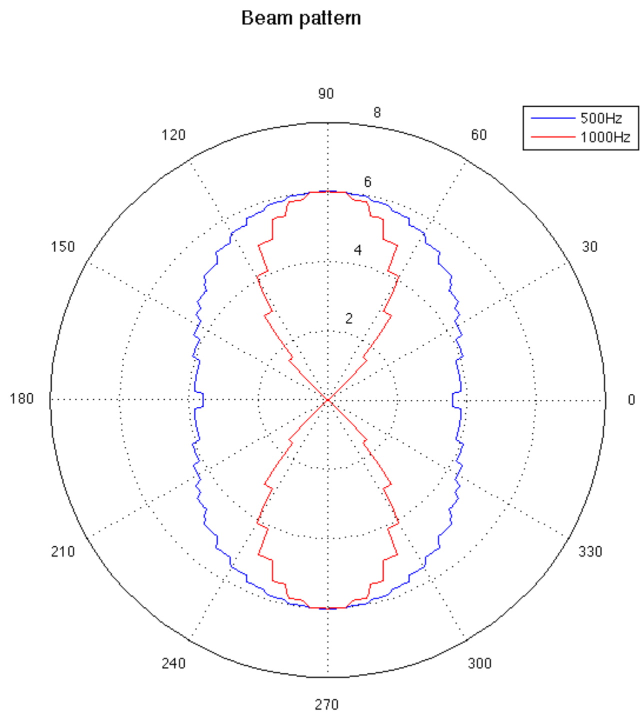

Figure 11: Simulation results of proposed beamformer in low frequency, at 500 and 1000 Hz showing clear improvement on front and back grains.

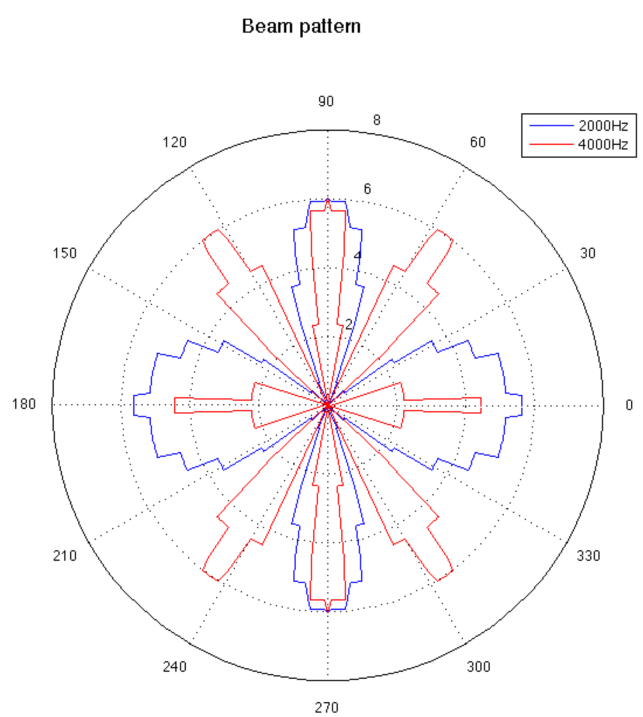

Figure 12: Simulation results of binaural beamformer in medium frequency, at 2000 and 4000 Hz showing the limits of the proposed delay-and-sum approach, with multiple side-lobe amplifications.

As can be seen in Figure 8, there is an immediate opposite spike whenever there is a large angle on either side. Also, the angles are not as stable as those derived from the MATLAB post-processing code. The most probable source of error seems to be the baseline removal method. The beamformer requires validation through an '8-Plot diagram' as well. EOG processing could also be further validated by a camera-based eye tracker.

Furthermore, eye angle estimates rely on two essential values, which are maximal amplitude of the signal and the maximum angle corresponding to that amplitude. These two values have been approximated here with the help of the complete set of data. A method needs to be found that would allow us to measure these two fundamental values first, within the initial sampled data, and second, with a method that ensures valid values that are user representative. To do so, one option is to perform a calibration at the beginning of every recording session, when the user puts the hearing device on. It could be in the form of two successively emitted sounds, one coming from the right, and the other from the left, to which the user would answer by looking towards the presented sound sources. Thus, the user's maximum possible reachable angle can be obtained, as well as the related maximum and minimum amplitude of the EOG signal.

Finally, as the focus of listening is not given by eye movements or by head movements alone, but by some optimal combination of the two, the proposed EOG-based beamformer might also be improved with the adjunction of a head-tracking feature.

Acknowledgments

The authors would like to thank Marc Schöenwiesner, from the International Laboratory for BRAin, Music and Sound Research (BRAMS) for the original idea and Marie-Hélène Faille for the initial work on the binaural beamformer. The authors wish to express their appreciation to EERS Global Technologies Inc. (Montréal, Québec, Canada) for providing the custom in-ear devices used in this study.

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TURBULENT ENERGY PREDICTION FOR AN EXTERNAL FLOW AROUND VALEO COOLING FAN BY V^2-F MODELLING AND IMPROVED K-E LOW REYNOLDS MODEL

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Résumé

Le champ de bruit peut être défini comme étant la conséquence des fluctuations de pression générées par les écoulements turbulents proches des parois solides, qui sont régies par des conversions acoustiques basées sur la théorie de Lighthill. Cet article discute des différents résultats de la simulation numérique pour un écoulement externe autour d'un profil d'aile asymétrique (Valeo CD). La simulation numérique consiste à comparer le modèle V^2-f original de Durbin et le modèle k-ε à bas Reynolds. Des modifications ont été introduites dans le modèle k-ε standard, en remplaçant le terme de taux de déformation par la verticité, afin d'améliorer la prédiction d'énergie turbulente du modèle visqueux à faible Reynolds. La comparaison des résultats obtenus a été faite avec des expériences complètes dans une grande soufflerie à l'école centrale de Lyon, et une simulation à grandes échelles (SGE). Le modèle V^2-f a montré une adaptation raisonnable au niveau des zones de séparation et une prédiction satisfaisante d'énergie turbulente près de la paroi, ainsi que le modèle k-ε modifié. Les améliorations sont dues aux fluctuations de vitesse normales v^2 et aux effets anisotropiques modélisés par la fonction de relaxation elliptique proche de la paroi solide.

Mots clefs: Valeo CD, STAR-CD, k-ε– bas Reynolds- V^2 –f, Kato-Launder-SGE.

Abstract

The noise field can be defined as the consequence of pressure fluctuations generated by turbulent flows, close to solid walls, which are governed by acoustics conversions and basing on the Lighthill's theory. This paper is discussing the different results of numerical simulation for an external flow around an asymmetric wing profile (Valeo CD). The Numerical simulation consists of comparing the original Durbin V^2 -f and the k-ε low Reynolds models. Some modifications have been introduced to the k-ε model, by replacing the strain rate term and the vorticitiy, in order to improve the turbulent energy prediction of the low Reynolds viscous models. The comparison of the results obtained has been made with full experiments in large wind tunnel at the central school of Lyon, and LES simulation. The V^2-f model has shown a reasonable adaptation to the separation zones and satisfactory turbulent energy prediction near the wall, comparing to the k-ε modified model. The improvements were due to the normal velocity fluctuations v^2, and the anisotropic effects modelled by the elliptic relaxation function close to the solid wall.

Keywords: Valeo CD, STAR-CD, k-ε–low Reynolds- V^2-f, Kato-Launder-LES.

1 Introduction

The high energetic demands are imposing a wide range of researches in order to develop the aerodynamic performances, for the wind turbines design [1], applied to wind energies sources [2], as well as, the cooling fans systems applied to CPU thermo-regulator [1-2].

Additionally, the far field noise, which is a consequence of the pressure fluctuations, generated in turbulent flows and governed by the Lighthill's acoustic analogy [3-4-5].

The numerical investigation of several viscous models is basing on the turbulent kinetic energy prediction near the solid wall [6-7]. The V^2 -f model has been considered for a long period, as a perfect modeling, among the available low Reynolds viscous models [8-9], taking into account the normal velocity scaling, as well as, the singularity near the wall, however, its weakness appears for the turbulent energy prediction [10-11], which made it ,particularly, limited because of its isotropic relaxation function.

In order to improve the near wall mesh quality, the skewed hexahedral elements have been checked basing on the boundary layer refinement, and the normal distance to the wall y+. The comparison of these models [12-16] has been made in aim to evaluate the turbulent energy prediction at the flow wake zone with the V^2-f modelling. The stability of this model has been checked by different turbulent Intensities at the inlet flow.

The fluctuations of the turbulent boundary layers and wake generated around the profile and their interaction with it, particularly near the trailing-edge region, called self-noise or trailing edge noise [17].

In most cases, the fluctuating field is generated from the stationary RANS solution. Turbulence model is used to obtain a stationary solution of the flow

The modifications introduced to the k-ε low Reynolds model are not very popular though and rarely used with the

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intention of combining the best of both sides implemented to the term of turbulent production between the vorticity and

2 The Durbin V^2-f model equations

The original turbulence model V^2-f developed by the Professor Durbin (NASA 1991) [8-9]. Due to the modifications introduced to the turbulent energy production, this model becomes transient between turbulent viscosity models and second-order modeling. Most important characteristic of this model is the transport equation for the V^2-f component that replaces an equations system for the Reynolds tensor components, and additional equation for the scalar function *f* added to the energy distribution in equation (2), the flow is assuming isotropic close to the wall.

$$\frac{Dk}{Dt} = \frac{\partial k}{\partial t} + U_j \nabla^j k = P_k - \varepsilon + \nabla^j[(\nu + \frac{\nu_t}{\sigma_k})\nabla_j k]$$
$$\frac{D\varepsilon}{Dt} = \frac{\partial \varepsilon}{\partial t} + U_j \nabla^j \varepsilon = \frac{C_{\varepsilon 1} P_k - C_{\varepsilon 2}\varepsilon}{T} + \nabla^j[(\nu + \frac{\nu_t}{\sigma_\varepsilon})\nabla_j \varepsilon] \quad (1)$$

$$\frac{D\overline{v^2}}{Dt} = \frac{\partial \overline{v^2}}{\partial t} + U_j \nabla^j \overline{v^2} = kf - \overline{v^2}\frac{\varepsilon}{k} + \nabla^j[(\nu + \frac{\nu_t}{\sigma_k})\nabla_j \overline{v^2}] \quad (2)$$

$$L^2 \nabla^2 f - f = \frac{1}{T}(C_1 - 1)[\frac{\overline{v^2}}{k} - \frac{2}{3}] - C_2 \frac{P_k}{k} \quad (3)$$

For the homogeneous flow zones ($\nabla^2 f = 0$) (isotropic production), the time and the turbulent length given by:

$$T = \max[\frac{k}{\varepsilon}, 6\sqrt{\frac{\nu}{\varepsilon}}], \text{ and}$$
$$L = C_L \max[\frac{k^{3/2}}{\varepsilon}, C_\eta \frac{\nu^{3/4}}{\varepsilon^{1/4}}] \quad (4)$$

Constants of the model:

$$C_\mu = 0.19,\ k = 1,\ \varepsilon = 1.3$$
$$C_{\varepsilon 2} = 1.9,\ C1 = 1.4,\ CL = 0.3,\ C_\eta = 70$$
$$C_{\varepsilon 1} = 1.4.[1 + 0.045\sqrt{\frac{k}{\overline{v^2}}}] \quad (5)$$

3 Problem solution

The first step is studying an asymmetric airfoil with controlled diffusion "Valeo CD" for low Reynolds number, applied in automotive motorization, and processors cooling by Valeo fans design, corresponding to the experiences carried out in the wind tunnels at Central school of Lyon, which provides the reference of the experimental data basis. The present case corresponds to a pitch angle of 8° and mean velocity inlet of 16 m/s (a Reynolds number of 1.2×10^5 basing on the chord length dimension). The symmetry condition is applied to the top and the bottom of the domain boundaries.

4 Boundary conditions

The set of generated meshes insure the validation method, which release the relationship between the meshes quality and the experimental results, a prior, for asymmetric airfoil simulation [4].

This mesh has been generated by Gambit software in "two dimensions", and exported to the PRO-STAR software in order to control the boundary conditions of the mesh, which is extruded in three dimensions" to run the simulation using the STAR-CD (CCM+) code.

A mesh generated taking in account the geometry coordinates (the chord length C=1), and the numerical workspace, one time of the chord at the inlet flow 1×C (Inlet velocity profile) and two times of the chord at the outlet flow 2×C, 1.5×C in the top and 1.5×C at the bottom,. The boundary conditions represented in Figure 1.

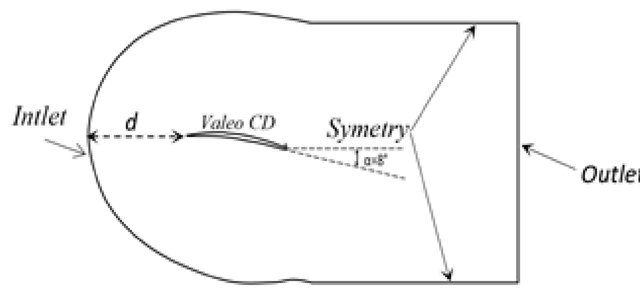

Figure 1: Calculation domain with Boundary conditions

The mesh quality represents the most important stability factor of results. Different meshes sizes have been tested to control the independency of results, in the present simulation a mesh of 86000 cells (Figure 2) has been exploited insuring a normal distance to the wall y^+ lower than 0.35, this mesh is refined too much near the wall in aim to insure a best mesh validation.

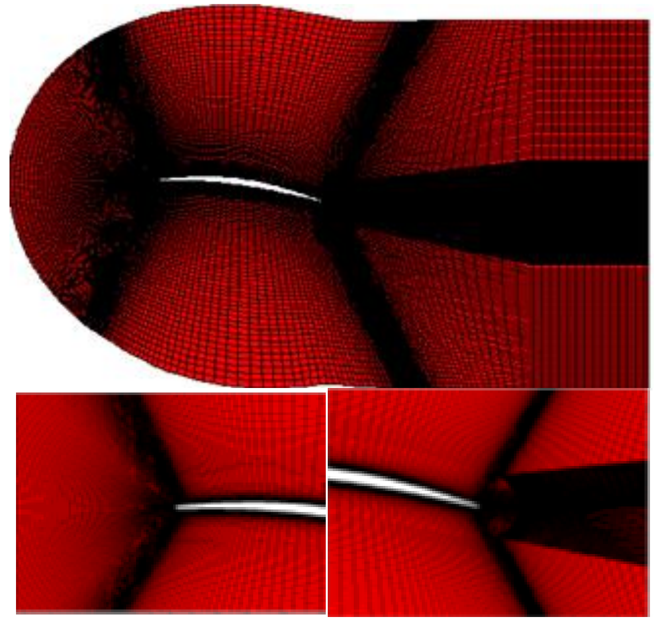

Figure 2: Refined mesh (86000 cells, 0.15<y+<0.35)

5 Results and discussion

The simulation has been achieved by the last version of STAR-CD code, on a PC with two processors (2 CPU) and with a random memory of two Gigabits (2 GB).During the simulation, a mini cluster of 13 processors was helpful to complete the simulation (b21g,UMIST).

The comparison made between different models for the pressure coefficient shows a large recirculation captured by the k-ε model after half of the chord than the other models probably, due to the wrong turbulent energy estimation because of its limited wall function, the difference is obviously observed on the plots of the Figures 3 & 4. As well as, the reasonable agreement of the V^2-f model due to its elliptic singularity function based on the normal velocity fluctuations comparing with the LES model and the experimental results (Ecole Central de Lyon).

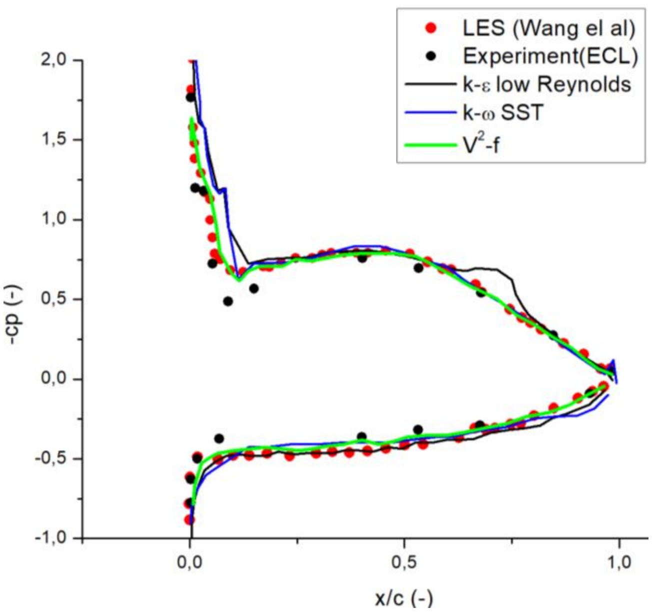

Figure 3: Pressure coefficient at extrados and intrados of the airfoil

5.1 Turbulent energy

Although, the models V^2-f, k-ω SST did not detect any turbulent zone at the trailing edge, but in comparison with the these models and the LES model, the k-ε low Reynolds model indicates a high turbulent energy overestimation, which is an anomalous characteristic of the k-ε low Reynolds model near the separation zones. The plots on the Figure 5 represent a comparison of the kinetic turbulent energy for the different models.

Basing on the profiles shown in Figure 6, the validity of the V^2-f model can be observed comparing with the LES model, as well as, a fast flow acceleration and increase of turbulent energy after the chord half for the k-ε model, which shown an overestimation of turbulent energy K near the trailing edge. The databases generated for the drawing profile of The Large Eddy Simulation (LES) calculated by the average value using a simple program developed in FORTRAN language based on the turbulent energy fluctuation function:

$$K = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \qquad (6)$$

5.2 Prescribe velocity profile and turbulent intensity I in the Inlet flow

To check the probable causes of the turbulent energy overestimation observed on the k-ε low Reynolds model, an arbitrary turbulent intensity (I) has been introduced at the Inlet flow (Figure 6), with two different rates of the prescribe velocity (5%U, and 10%U), using a define function developed in FORTRAN language (bcdefi.f).

The plots of Figure 7 prove that the turbulent intensity has not any effects on the turbulent energy overestimation near the trailing edge zone. Therefore, the turbulent energy excess production near the trailing edge shown by the k-ε model are not due to the turbulent intensity at the Inlet flow.

6 Energy production expression

The production expression for the Low Reynolds k-ε model

$$P_k = \upsilon S_{ij} S_{ij} \qquad (7)$$

The Strain

$$S = \sqrt{2S_{ij}\ S_{ij}} \qquad (8)$$

The strain rate

$$S_{ij} = \frac{1}{2}\left(\frac{du}{dy} + \frac{dv}{dx}\right) \qquad (9)$$

The first modification permits to replace the strain contribution by the multiplication of strain rate and the vorticity expression (LPM).

The vorticity:

$$\Omega_{ij} = \frac{1}{2}\left(\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}\right) \qquad (10)$$

New productionexpression becomes

$$P_k = \upsilon S_{ij} \Omega_{ij} \qquad (11)$$

The second modification permits to take the lowest value between the strain contribution and the multiplication of the strain rate and the vortices, in order to improve the production expression (Limiter Model):

$$P_k = \upsilon \min (S_{ij}S_{ij}, S_{ij}\Omega_{ij}) \qquad (12)$$

Figure 8 shows the turbulent kinetic energy profiles obtained by the first modification LPM and compared to the LES and the standard k-ε models. The results indicate an overestimation of the turbulent kinetic energy far from the profile wall.

The velocity profiles in the Figures 9 &10 show the effect of the linear turbulence production expression. We find that the limiter model provides a better agreement with the LES and the V^2-f model, than the first modifications LPM.

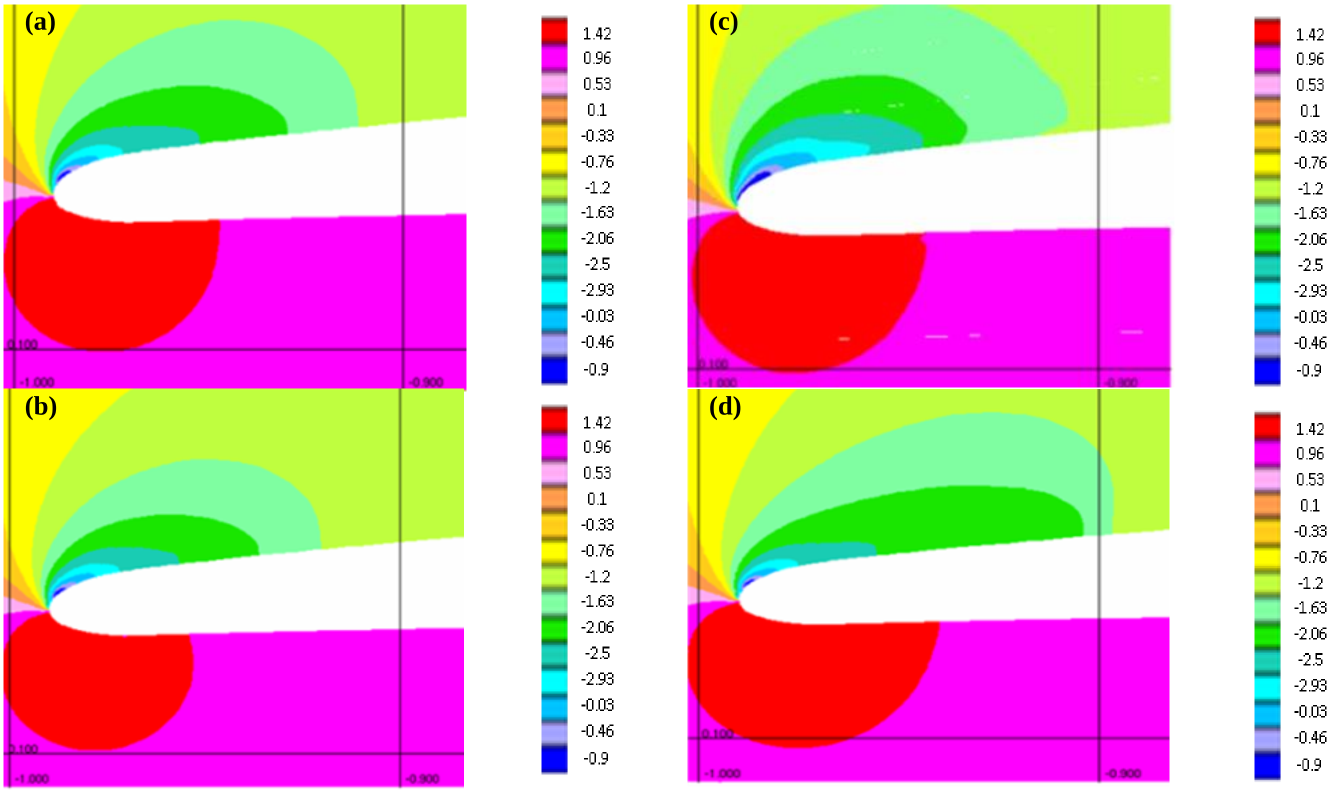

Figure 4: Pressure coefficient for: (a) V^2-f model; (b) k-ω SST model; (c) LES model [7]; (d) k-ε low Reynolds model.

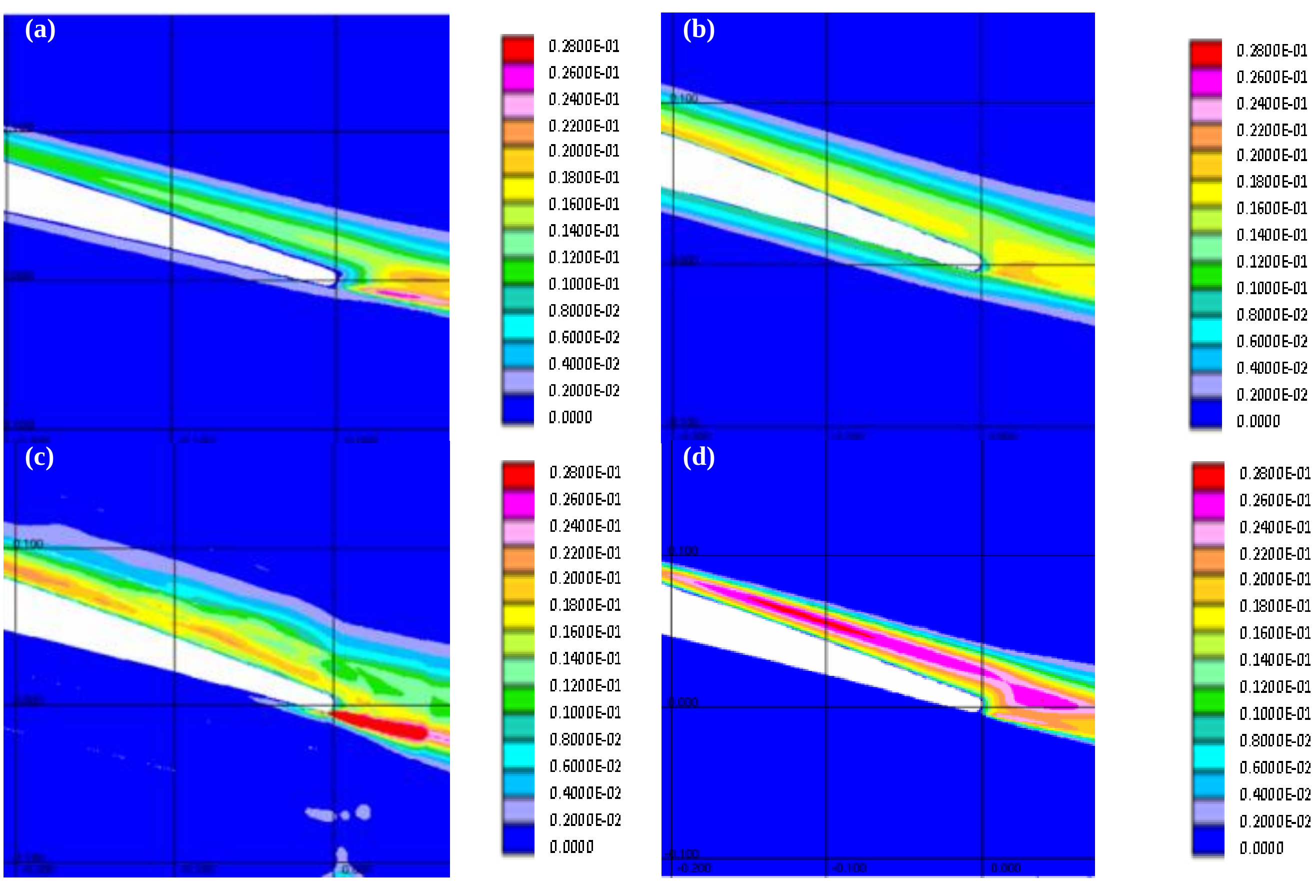

Figure 5: Kinetic turbulent energy at the trailing edge for: (a) V^2 -f model; (b) k-ω SST model; (c) LES model [7]; (d) k-ε low Reynolds model.

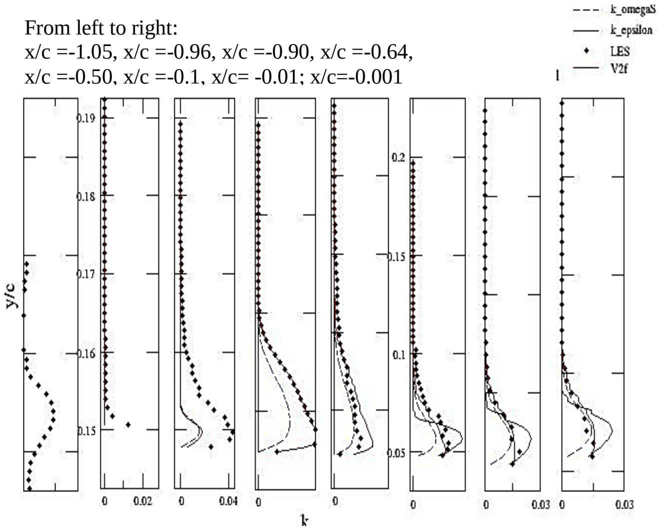

Figure 6: Turbulent energy profiles along the aerofoil chord for: k-Ω SST; k-ε; LES [7] & V²-f model.

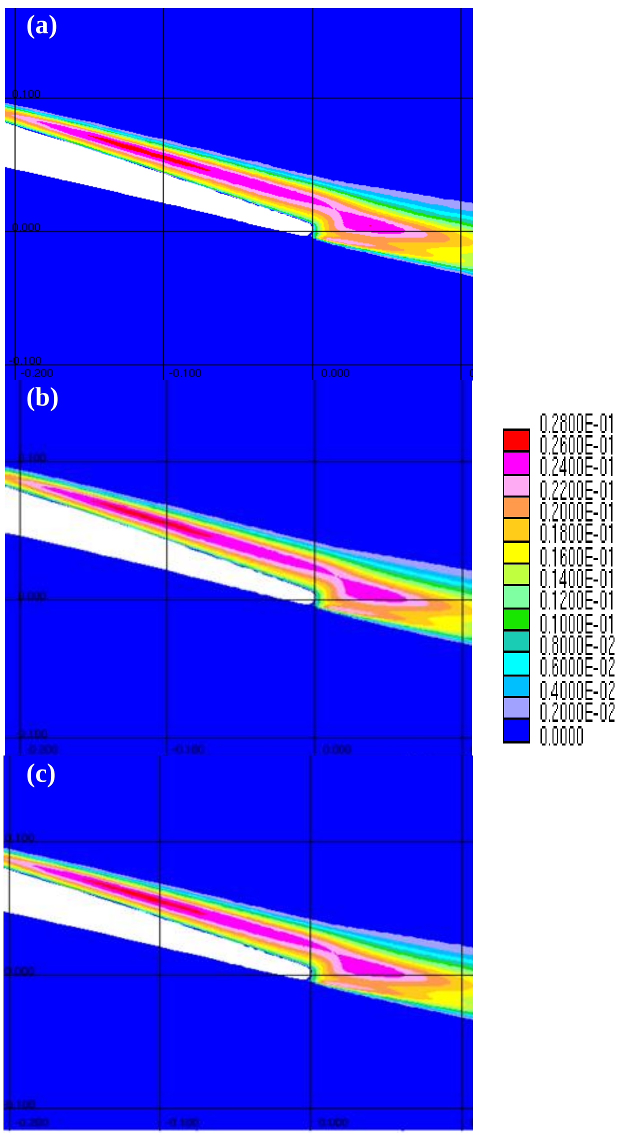

Figure 7: Turbulent energy: (a) without turbulent Intensity I; (b) I=5%U; (c) I=10%U.

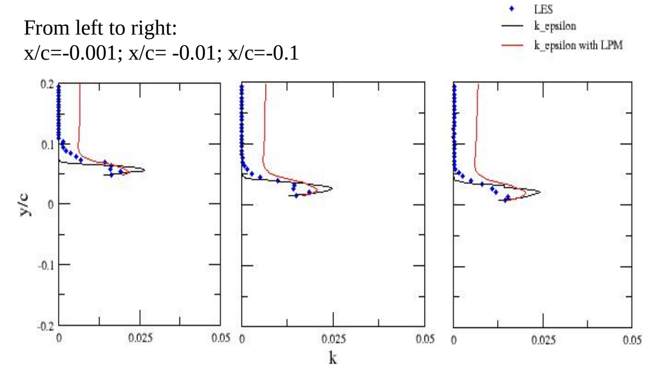

Figure 8: Turbulent kinetic energy profiles with the first modification LPM.

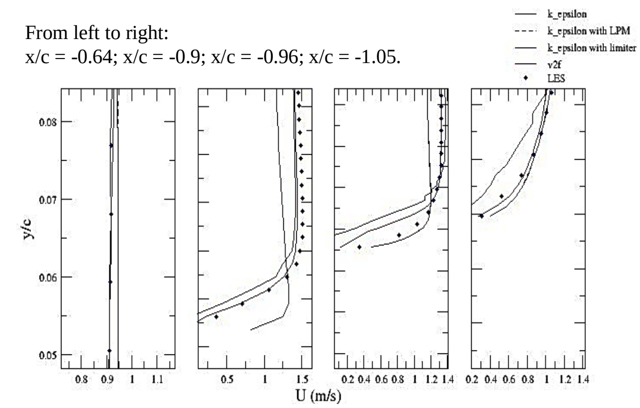

Figure 9: The Velocity profiles for the k-ε model introducing Kato-Launder modifications LPM, and Limiter Model (trealing edge).

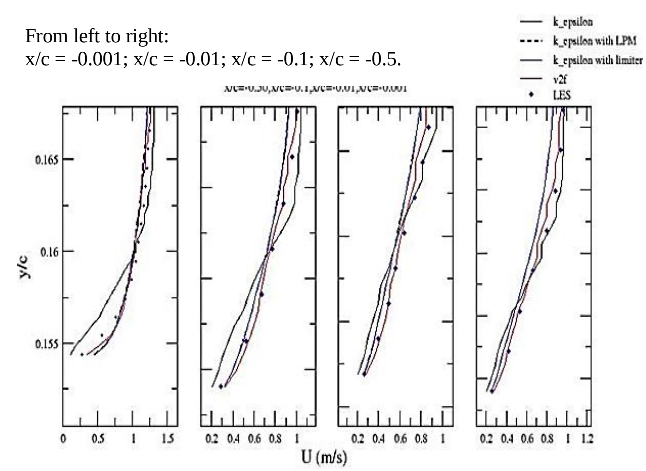

Figure 10: The Velocity profiles for the k-ε model introducing Kato-Launder modifications LPM, and Limiter Model (leading edge)

The results in the figure 11 show that the modified k-epsilon model confirm a better agreement with the experimental data than the standard K-ε low Reynolds model. Hence, the prediction of the turbulent energy is improved near both zones leading and trailing edge. The observed improvements can be explained by the limitation of the turbulent energy production term that introduces the minimum between the vorticity and strain, as well as, the corrected explicit damping function, particularly, near the separation zone (near wall corrections) which is based on a minimum dimensionless distance y+. (About 0.35 in our case).

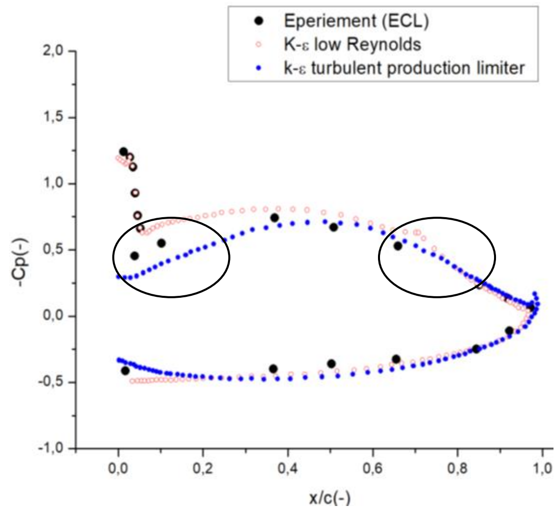

Figure 11: The pressure coefficient distribution obtained by the modified K-ε model with comparison to the standard low Reynolds k- ε model results and experimental data.

7 Conclusion

The model V^2-f represents a future solution basing on its high capacity of prediction for the turbulent energy phenomenon than the available RANS viscous models.

The insufficiency of the k-ε low Reynolds model can be improved by replacing the strain rate by the vorticity in the turbulent energy production term, and correcting the explicit damping function near the separation zone. The comparison between the two modifications proved that the limiter model results are more stable than the first modification LPM.

Although the numerical investigation has been devoted to improve the estimation of the turbulent kinetic energy production, the improvement obtained can be useful to better predict the acoustic far field noise.

Acknowledgments

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ACOUSTIC CORRECTION OF A RENAISSANCE PERIOD HALL

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Résumé

Les salles médiévales et Renaissance sont souvent utilisées pour des événements musicaux ou des conférences. Ces salles ont des plafonds voûtés, tandis que les surfaces sont recouvertes de plâtre et de marbre. L'acoustique de ces lieux n'est pas optimale pour écouter des performances musicales ou des conférences. Pour rendre ces environnements acoustiquement utilisables, une correction acoustique doit être effectuée. Une salle construite à la Renaissance et utilisée pour des manifestations culturelles a été considérée comme une étude de cas. Il ressort des mesures acoustiques, le temps de réverbération est d'environ 4,5 secondes. L'évaluation de la correction acoustique a été réalisée avec un logiciel pour l'acoustique architecturale. Le modèle virtuel a été analysé d'abord dans la configuration initiale, puis avec l'insertion de panneaux insonorisants sur les murs et sous le plafond avec la voûte. Ensuite, la correction acoustique a été réalisée en installant des panneaux insonorisants dans la pièce. Des mesures acoustiques ont été prises avec cette nouvelle configuration, en l'absence du public, et le temps de réverbération aux moyennes fréquences a été réduit à 2,0 secondes, comme indiqué dans le projet de conception.

Mots clefs : Salles Renaissance, acoustique de la salle, tube d'impédance, temps de réverbération, correction acoustique

Abstract

Medieval and Renaissance halls are often used for musical events or conferences. These rooms have vaulted ceilings, while the surfaces are covered with plaster and marble. The acoustics of these places are not optimal for listening to musical performances or conferences. To make these environments acoustically usable, an acoustic correction must be made. A room, built during the Renaissance period used for cultural events, was considered as case study. From the acoustic measurements, it results that at mid-frequencies the reverberation time is about 4.5 seconds. The evaluation of the acoustic correction was carried out with a software for the architectural acoustics. The virtual model was analyzed first in the initial configuration and then with the insertion of sound-absorbing panels on the walls and under the ceiling with the vault. Subsequently, the acoustic correction was performed by installing sound-absorbing panels in the room. Acoustic measurements were taken with this new configuration, in the absence of the audience, and the reverberation time at the mid-frequencies was reduced to 2.0 seconds as presented in the design project.

Keywords: Renaissance halls, room acoustic, impedance tube, reverberation time, acoustic correction

1 Introduction

Ancient buildings, with artistic and historical value, could be used for social, cultural and tourist activity and so, they could be used to increase the development of the region as cultural attractors. Musicals, meetings, conferences could catch the attention of many people. In these historical buildings there are chambers that could be used for different kinds of musicals or conferences. So the rooms built during the Middle Ages and Renaissance, in the logic of improving the historical and artistic heritage, are often used for musical events, exhibitions or conferences.

These types of rooms generally have vaulted ceilings, that were dictated by constructive needs of the time. From an acoustic point of view, monumental rooms are complex places, due to the presence of vaulted or barrel ceilings, niches and vaults, as well as acoustically reflecting surfaces of the walls such as plaster, stucco, along with the presence of marble floors. The acoustics of these places are not suited for listening to musical performances and conferences, since the large dimensions, plastered walls, marble floors and particular geometries cause a long sound tail that negatively affects the listening of the music or understanding of speech.

The audience that attended the events, while appreciating the historical and architectural qualities of the rooms as well as the suggestiveness of the places, is not satisfied with the acoustics due to the presence of excessive reverberation. To make these spaces acoustically usable, an appropriate acoustic correction must be made by inserting sound-absorbing material panels [1, 2]. For conference rooms, where the comprehension of speech is fundamental, a short sound tail is required, i.e. a reverberation time of about 1 second. While for those dedicated to listening to music, a reverberation time of about 2 seconds is required, so that the

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sound reflections can improve the direct components of the sound field and make the listening more pleasant [3 - 6].

This paper presents a case study of a room located inside a monastery, built during the Renaissance period. Following restoration work, which involved re-plastering the walls, restoring the floor with marble tiles, the room was used for conferences and screening films. The room has a width of about 6 metres, a height that varies between 2.5 to 5 metres and a vaulted ceiling about 20 metres long. The volume is about 5,000 m^3. There are large side windows and the back wall, upon which films are projected, was made of plasterboard. Furthermore, there are thirty wooden and fabric chairs arranged in six rows installed. Figure 1 shows the interior of the room at the end of the restoration work. While Figure 2 shows the plan with the most significant geometric dimensions, Figure 3 shows the section. The users of the room complained of poor speech understanding during the lectures and a poor quality of listening to musical performances. Acoustic measurements were taken to evaluate the acoustic characteristics of the room. Analysis of the results showed that at mid-frequencies the reverberation time was about 4.5 seconds and therefore not adequate to the required needs. To obtain optimal listening conditions, it was necessary to reduce the sound tail by inserting panels of sound-absorbing material.

The evaluation of the appropriate acoustic correction was carried out with the help of the "*Odeon*" architectural acoustics software. The virtual model was first analysed in the initial configuration (reflecting walls) and then with the insertion, on the side walls and under the vault, of sound-absorbing panels. In the room afterwards, acoustic correction work was carried out by inserting the sound-absorbing panels on the side walls and under the vault in order to reduce the effects of acoustic focusing due to the particular geometry. The acoustic characteristics were then measured again so as to evaluate the effects of the acoustic correction. The main goal of the acoustic correction is the decreasing of the negative effects of an excessive (sound tail) and to improve the conditions of listening. The hall should be used for meetings and cultural organizations

Figure 1: Interior at the end of restoration work

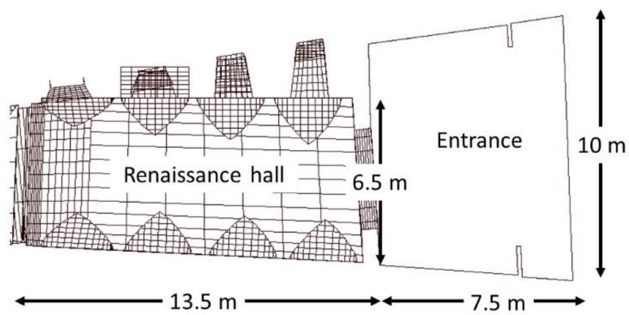

Figure 2: Plan with the most significant geometric dimensions**.**

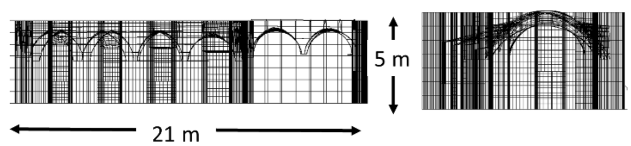

Figure 3: Section with the most significant geometric dimensions

2 Acoustic measurements at the end of the restoration works

In order to analyse the acoustic characteristics of the room, upon conclusion of the restoration works, acoustic measurements were carried out using an impulsive sound source. Acoustic measurements were taken using small firecrackers as the impulsive sound source. The acoustic measurements were carried out in accordance to ISO 3382-1 [7]. The acoustic measurements were taken in the absence of wind and precipitation, with an average temperature of about 20°C and relative humidity of 50%. A BRAHMA microphone was used to record the impulse responses in different receiver points.

The acoustic measurements were taken in empty conditions, without any spectators and there were no noisy activities in proximity and the traffic noise was negligible. During the acoustic measurements the background noise was lower than 30 dBA. The recorded impulse responses were elaborated with the software Dirac 4.0, analysing the acoustic parameters defined in the ISO 3382-1, such as reverberation time (T_{30}), early delay time (EDT), clarity (C_{80}), definition (D_{50}) and sound transmission index for speech intelligibility (STI) [8, 9]. The impulsive sound source was placed at a height of 1.50 metres from the floor, in the position of the speaker (the position in which the speaker sits during the conference), and the sound impulse was detected with a microphone placed at a height of 1.50 meters. The receivers were placed at various points in the hall, in 13 different locations equally distributed. The points where the sound source and the measuring microphone were located are shown in Figure 4.

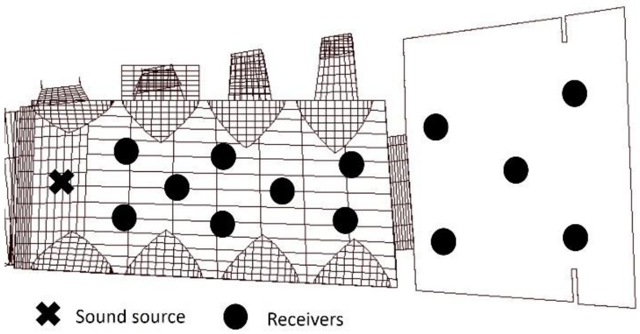

Figure 4: Room with indication of measurement points.

Current architectural acoustics literature shows tables and diagrams in which the optimal acoustic parameters are defined according to the intended use of the room in question. Thus, a room must respect the values of the acoustic parameters shown in Table 1. Figures 5, 6, 7 and 8 show, respectively, the average values and relative standard deviations of the acoustic parameters measured (EDT, T_{30}, C_{80} and D_{50}) at the end of the restoration work.

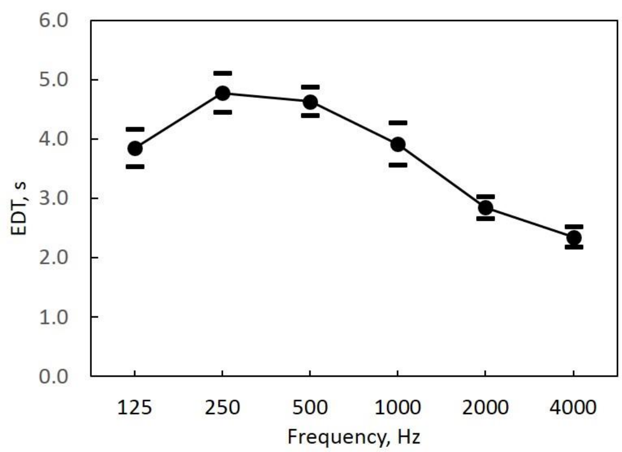

Figure 5: Average measured values of EDT and relative standard deviations.

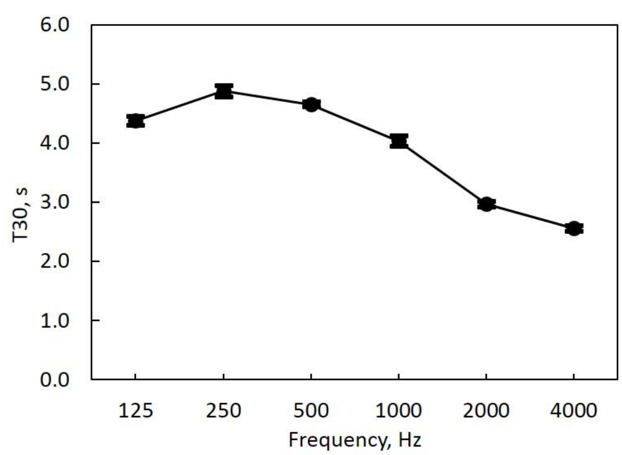

Figure 6: Average measured values of T_{30} and relative standard deviations

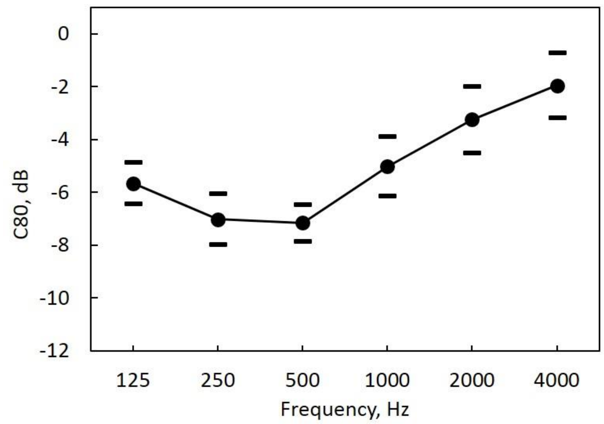

Figure 7: Average measured values of C_{80} and relative standard deviations

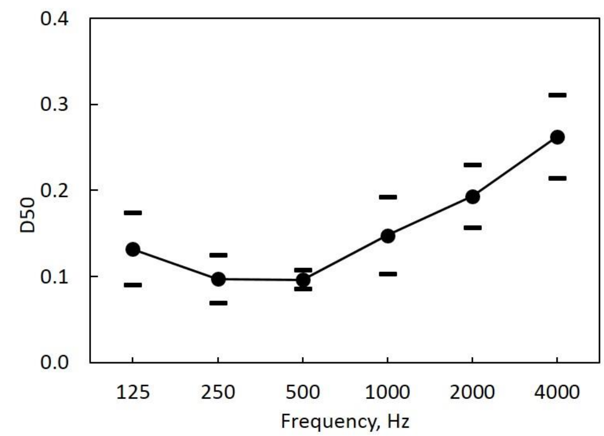

Figure 8: Average measured values of D_{50} and relative standard deviations

The analysis of the measured data showed an excessive reverberation time, at frequencies between 250 Hz and 500 Hz, whose value was about 5.0 seconds, while at the frequency of 1.0 kHz, both the EDT and T_{30} were equal to 4.0 seconds. The reverberation time pattern was a bell, due to the vaulted geometry of the room that focuses the sound in the centre of the room. At the frequency of 125 Hz, the reverberation time decreased respect to that of the successive octave bands (250 Hz and 500 Hz) due to the presence of large glazed surfaces placed laterally to the hall and the back wall made of plasterboard used for film projections. The glazed surfaces and the plasterboard in the low frequency domain behave like extended absorbers. The C_{80} clarity value averaged was about -5.0 dB, while the D_{50} definition averaged value was no greater than 0.3.

A comparison of the average values measured with those of Table 1 showed how the room had not optimal conditions for listening to music or speech. STI is the parameter for the evaluation of the goodness of the speech comprehension in a room, in this condition STI was equal to 0.30 (+/- 0.01). The values of this parameter correspond to a condition of poor intelligibility. In the room there was a poor understanding of speech due to the unsuitable measured acoustic conditions for understanding speech.

Table 1: Optimal acoustic parameter values for the different listening conditions [11].

Parameters	EDT, s	T_{30}, s	C_{80}, dB	D_{50}
Values for musical performances	1.8 < EDT < 2.6	1.6 < T_{30} < 2.2	-2 < C_{80} < 2	< 0.5
Values for speech performances	1.0	0.8 < T_{30} < 1.2	> 2	> 0.5

3 Acoustic properties of the absorbent material

There is no information about the value of the sound absorption coefficient of the material chosen for the acoustic correction. So the authors carried out acoustic measurements to obtain a value of the absorption coefficient which should be used in the numerical model.

The material chosen for the acoustic correction is polyester with a thickness of 4.0 cm. For aesthetic reasons it is covered with an acoustically transparent coloured cloth. There are differences between the absorption coefficients measured with a reverberation chamber or with an impedance tube at normal incidence. But the authors didn't have a reverberation chamber available, so they chose to take the absorption coefficients values using the impedance tube. To assess the material acoustic properties, the absorption coefficient at normal incidence was measured with an impedance tube (tube of Kundt), in accordance with EN ISO 10534-2 [10]. The tube has an inner diameter of 100 mm and length of 560 mm. The distance between the two measurements microphones was 50 mm, with the absorption coefficient measurement that was in the range frequency 200 Hz - 2.0 kHz; while when the distance between the two measurements microphones is 100 mm, the absorption coefficient measurement is in the range frequency 125 Hz - 1.0 kHz. The sound absorption coefficient is obtained from the combination of the transfer functions measured in the two measurement microphones, placed inside the tube. Table 2 shows the average values of the absorption coefficient measured at normal incidence in the frequency range 125 Hz - 4.0 kHz. This average value is obtained from measurements with four different specimens. The value of the sound absorbent coefficient at the frequency of 4.0 kHz is obtained by the extrapolation of the measured data (for the porous materials the values of absorbent coefficient at the frequency of 4.0 kHz is equal to the value measured at 2.0 kHz). Figure 9 shows the impedance tube (tube of Kundt) used for the sound absorption coefficient measurements.

Table 2: Average absorption coefficient measured at normal incidence of the polyester panel

Frequency, Hz	125	250	500	1 k	2 k	4 k
absorption coefficient	0.15	0.40	0.65	0.85	0.90	0.90

Figure 9. Impedance tube (tube of Kundt) used for the sound absorption coefficient measurements

4 Acoustic virtual model

For the purposes of a suitable acoustic correction, the appropriate amount of sound-absorbing material has to be inserted in the room must be evaluated, using the simulation software for architectural acoustics "Odeon" [12 - 14]. This software is based on the principles of geometric acoustics, in particular on a hybrid technique of ray tracing and image sources. The realization of the three-dimensional model is based on flat surfaces that simulate those of each element of the room. After importing the model into the Odeon software, the omnidirectional sound source was inserted and the 13 receiving points were inserted into the room; the values of the sound absorption coefficients of the walls are then assigned. The calculations were performed by fixing set-up parameters: transition order, TO=2; impulse response length = 5.0 seconds; number of late rays = 50,000; impulse response resolution 3.0 ms; max reflection order = 2,000. For the "Odeon" software settings, the scattering coefficient (s) does not depend on the frequency, but rather on the geometrical surface properties [15]. The area where the seats are positioned was simulated as parallelepipeds with a height of 0.8 m, width of 5.0 m and length of 10 m [16]. The area covered by the seats area was equal to 50 m^2, with the assigned value of the absorption coefficient given in [17 - 19] and a value of the scattering coefficient s = 0.5. The first operation is to calibrate the acoustic virtual model; it consists of setting the absorbent coefficient values for all the model surfaces and setting the scattering coefficients for the audience area. The geometric model of the room was calibrated by choosing realistic parameters necessary for the acoustic absorption coefficient in the octave bands in the 125 Hz - 4.0 kHz range, in order to minimize the differences between the measured and calculated mean values of T_{30}. The reverberation time (T_{30}) was chosen as a reference parameter. The calibration consists of changing the absorption coefficient values of the walls so that the reverberation time measured coincides with the simulated one. The calibration was stopped when the difference between the time measured and the time calculated is less than the 5% of all the octave bands calculated between the range 125 Hz – 4.0 kHz. Table

3 shows the absorption coefficient values of the surfaces used for the calibration of the virtual model [20-22].

Table 3: Sound absorption coefficient values of the materials used in the numerical simulation

Frequency, Hz	125	250	500	1 k	2 k	4 k
walls / ceiling	0.03	0.03	0.03	0.03	0.04	0.04
plasterboard	0.25	0.15	0.10	0.09	0.08	0.07
glass	0.20	0.15	0.10	0.10	0.05	0.05

The acoustic measurements carried out, inside the room, after the restoration works and theoretical analysis carried out with the software, showed the presence of an excessive reverberation and non-optimal speech listening conditions. To improve the acoustic performances of the room, it is necessary to reduce the reverberation time by inserting soundproof panels. To improve the acoustics of the room, in the project hypothesis the panels are inserted on the side of the wall in which there are no windows and under the vault to reduce the effects of acoustic focusing, with the absorption coefficient values assigned in the numerical model being reported in Table 2. The theoretical acoustic correction was obtained by inserting in the virtual 34 m^2 surface model of sound-absorbing panels. The numerical results show a reduction in reverberation time and an increase of C_{80} as well as of the STI. After the calibration, the absorption coefficient values of the audience in the room were considered. In fact, the third step of this procedure was to evaluate the effects of the presence of the audience on the acoustic characteristics of the room. In the virtual model, the sound absorption coefficients values of the audience were assigned to the sound coefficients values of box surfaces when the seats were empty. The absorption coefficient values of the audience are reported in current literature. Table 4 shows the audience absorption coefficient used in the virtual model [16, 17, 18]. Figures 10, 11, 12 and 13 show the comparison between the average acoustic parameter values (EDT, T_{30}, C_{80} and D_{50}) obtained through the numerical simulation of the empty room with the acoustic correction and the room when the seats are occupied with the presence of the audience.

Table 4: Sound absorption coefficient values of the audience used in the numerical simulation

Frequency, Hz	125	250	500	1 k	2 k	4 k
absorption coefficient	0.60	0.70	0.80	0.83	0.84	0.85

Figures 10, 11, 12 and 13 do not show the values of the standard deviations because they are the final results of the numerical model elaboration. The values of the acoustic parameters were obtained in an empty room condition, with the presence of the audience there is a reduction in the sound tail and the acoustic parameters improvement.

5 Acoustic measurements after correction interventions

Following the evaluation of the acoustic correction by means of the virtual model, sound-absorbing panels were placed on the walls of the room and under the vault. The absorption coefficients values of the panels were evaluated with the impedance tube. After inserting the sound-absorbing panels, the acoustic measurements in situ were taken again, the sound source and the receivers were put in the same initial positions, both to verify the effectiveness of intervention as provided by the calculated simulation as well as verify the reliability of the predictions implemented by the software for the acoustics architectural “Odeon”. The measurements taken following the similar procedures used for the room before correction and by placing the sound source and measuring microphones in the same points. (as shown in Figure 4). The acoustic measurements were taken in the absence of wind and precipitation, with an average temperature of about 25°C and relative humidity of 50%. During the acoustic measurements the background noise was lower than 30 dBA. Figure 14 shows the room in its current state after the installation of the sound-absorbing panels on the side wall and under the vaults.

Figures 15, 16, 17 and 18 show the average measured values of the acoustic parameters EDT, T_{30}, C_{80}, and D_{50}, together with the intervals of the standard deviation. The measured value of the STI is equal 0.53 (these parameters were measured in an empty room, with the presence of the audience these parameters improve).

6 Results

The acoustic measurements were carried out in an empty room in the absence of the audience. In fact, the presence of the audience allows for a reduction of reverberation time and an increase of the clarity and definition values. The insertion of sound-absorbing panels has made possible to obtain good acoustics of the room. The reverberation time values T30, at the frequencies of 500 Hz and 1.0 kHz, which was estimated by experimental measurements after acoustic correction interventions, are about 2.5 seconds and coincides with the prediction implemented by the architectural acoustics software. While EDT values, at the frequencies of 500 Hz and 1.0 kHz, which were estimated by experimental measurements after the acoustic correction interventions, are about 1.5 seconds and coincides with the prediction implemented by the architectural acoustics software. The analysis of the measured data of EDT and T_{30} show the reduction of these parameters, especially at the frequencies between 250 Hz and 500 Hz. Before the acoustic correction at these frequencies the values of EDT were about 5.0 seconds, and the values of T_{30} were about 4.5 seconds. The sound absorbing panels under the vault have reduced the effects of acoustic focusing, improving the characteristics of the room. The parameter D_{50}, which expresses as a percentage the quantity of the phonemes actually understood, after the inclusion of the sound-absorbing panels, gives values close to 0.5, and also confirms the prediction made by the architectural acoustics software.

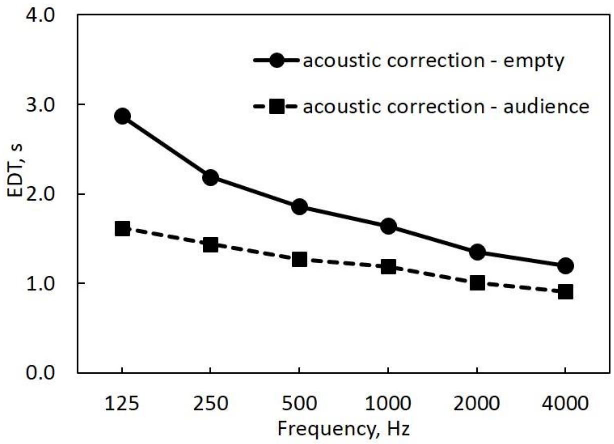

Figure 10: Average calculated values of EDT.

The mean values of C_{80}, in the mid-bands, are included between -1 dB and 1 dB after acoustic correction, and is coherent with the parameters T_{30} and EDT. The value of C_{80} experimentally measured, post opera, confirms the prediction made by the software. For both EDT and T_{30}, by inserting sound-absorbing panels (34 m^2) under the vaults at a distance from the vault of 0.5 m, a significant reduction of these parameters is obtained. The trend is linear decreasing with an increase in frequency. The C_{80} clarity values go from - 5 dB to 0 dB on average. When the acoustic parameters measured showed large standard deviation variations, those values change by changing the position of the receivers.

Similarly, definition goes from an initial value of 0.15 to a value after the acoustical correction of the empty room, to 0.4. Finally, the hall was used for conferences and the public that visits the room gave a positive feedback about the intervention performed.

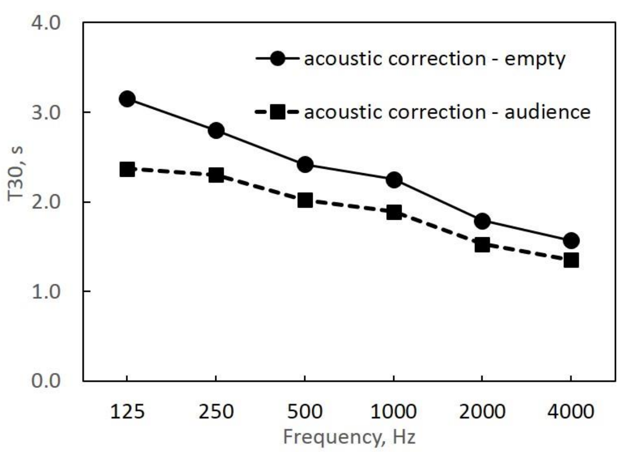

Figure 11: Average calculated values of T_{30}.

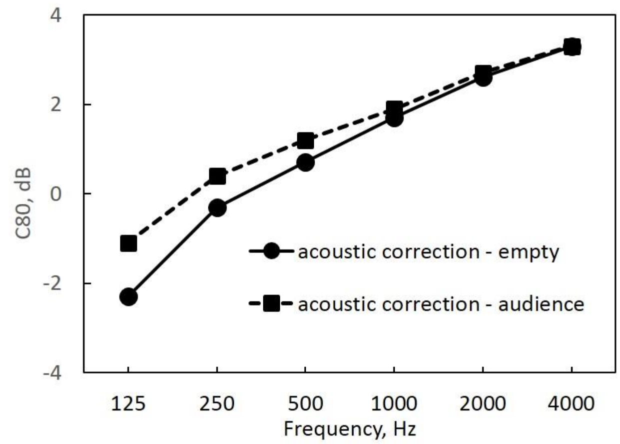

Figure 12: Average calculated values of C_{80}.

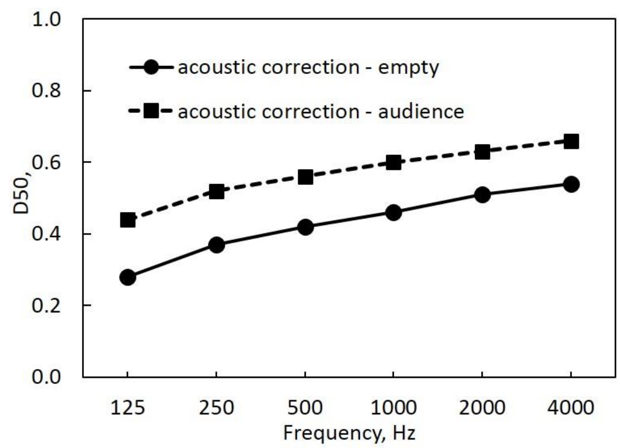

Figure 13: Average calculated values of D_{50}.

Figure 14: Room in its current state after the installation of the sound-absorbing panels on the side wall and under the vaults.

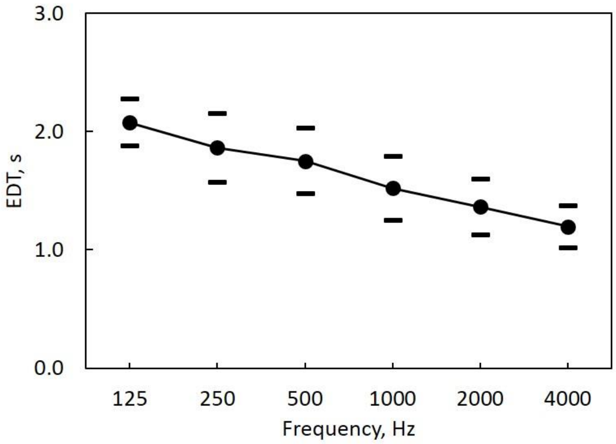

Figure 15: Mean values and relative standard deviations of the measured acoustic parameters of EDT and relative standard deviations.

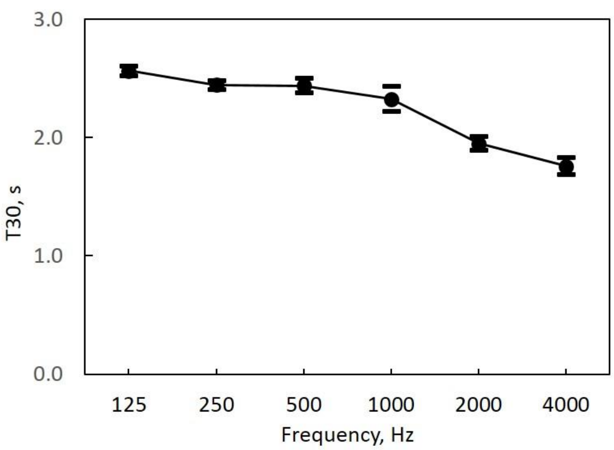

Figure 16: Mean values and relative standard deviations of the measured acoustic parameters of T_{30} and relative standard deviations.

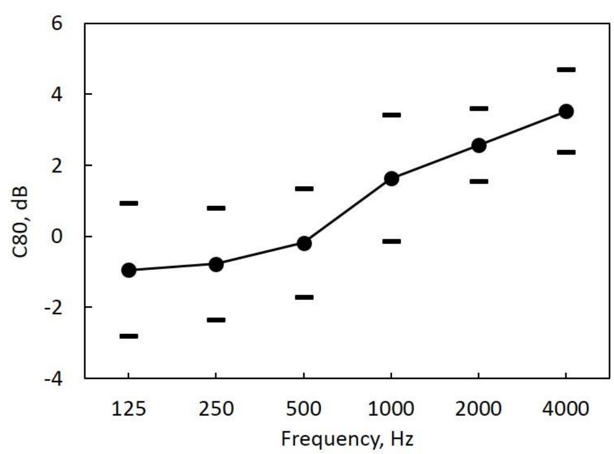

Figure 17: Mean values and relative standard deviations of the measured acoustic parameters of C_{80} and relative standard deviations.

Figure 19 A shows, from a receiver point of view, the progress of the impulse for the hall, before the acoustic correction. It's possible to see that the effects of the acoustic focalization, due to the vaulted ceiling and due to the many sound reflections on the walls, in fact before the reflections, they take much more time to decrease. Figure 19 B shows, from a receiver point of view, the progress of the impulse for the hall, after the acoustic correction. In this configuration the previous reflections tended to decay in a sudden way, due to the acoustic absorption and the effect of acoustic focalization is eased because the soundproofing are collocated under the vaulted ceiling, reducing the unwanted effect

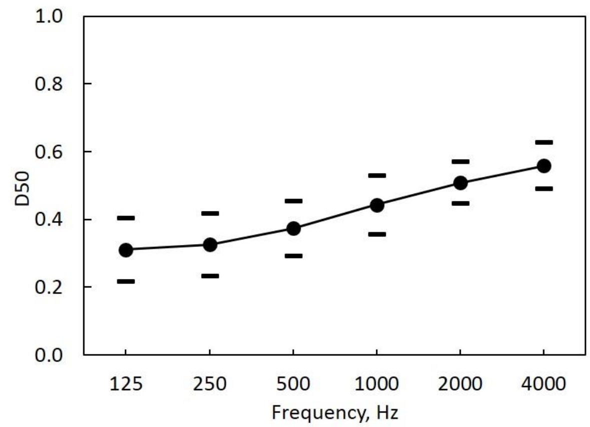

Figure 18: Mean values and relative standard deviations of the measured acoustic parameters of D_{50} and relative standard deviations.

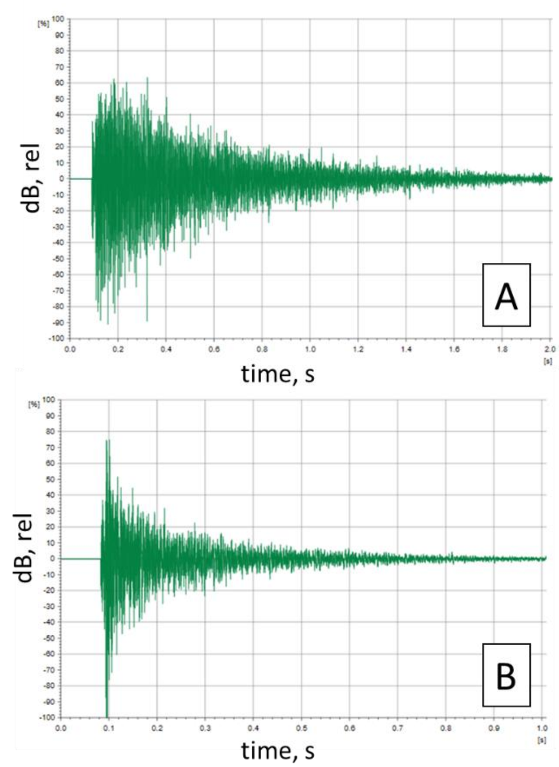

Figure 19: (A) Receiver point, the progress of the impulse for the hall, before the acoustic correction. (B) Receiver point after the acoustic correction

7 Conclusions

This paper discusses the solution for the acoustic correction of a room built during the Renaissance period. The presence of vaulted ceilings and plastered walls caused unsatisfactory acoustics and the audience attending the events was not satisfied due to the excessive sound tail, so it was necessary to carry out appropriate acoustic correction interventions. The hall after the acoustic correction can be used for conferences and film screenings. The acoustic correction was carried out by inserting sound-absorbing panels on the lateral surfaces and under the vaults so as to limit the undesired effects of acoustic focusing. The acoustic measurements carried out in the empty room allowed to verify the initial hypotheses of estimation of the acoustic characteristics of the hall.

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PERCEIVING PROSODIC PROMINENCE VIA UNNATURAL VISUAL INFORMATION IN AVATAR COMMUNICATION

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1 Introduction

Listeners integrate information from simulated faces in multimodal perception [1], but not always in the same way as real faces [2]. This is increasingly relevant with the dramatic increase in avatar communication in virtual spaces [3]. Prosody is especially relevant, because compared to segmental speech sounds, the visual factors indicating prosodic prominence (e.g. eyebrow raises and hand gestures) frequently bear no biomechanical relation to the production of acoustic features of prominence, but are nonetheless highly reliable [4], and avatar virtual communication systems may convey prosodic information through inappropriate means, e.g., by expressing amplitude via oral aperture (louder sound = larger opening).

Given that people are capable of picking up even small visual differences to aid in speech perception when interacting with other humans [5], oral aperture in an avatar might increase the perceived loudness of the stimuli. Furthermore, when the mouth is moving, differences between louder and quieter words may be attenuated by lack of difference in mouth aperture [1]. On the other hand, listener/viewers may disregard this inappropriate visual cue, leaving perceived loudness unaffected.

2 Methods

Ten native English speakers between the ages of 18 and 30 from the University of British Columbia participated in this study for course credit.

The stimuli consisted of videos of a single Facebook Spaces™ avatar (Figure 1) saying a sentence involving two characters and emphasizing one name (e.g. *Lee emailed BRIE.*). The stimuli followed a 2x2x2 Latin square design: Mouth movement (present or absent), emphasized word (first or second character's name), and which character name was rated for loudness (first or second mentioned). The stimuli were counterbalanced for the vowel quality of first character second character's names ([i:], [u:], or [ɑ:]).

To create naturalistic stimuli, the recording experimenter was asked questions that prompted the stimuli sentences with focus on one or the other of the character's names. (e.g. "Who did Lee email?" - "Lee emailed BRIE.",

In the mouth movement condition, lip shapes were simulated by the Facebook Spaces Beta [6] software by enabling the oculus headset microphone. According to a conference talk at F8 2017 [7] the avatar's lips go through visemes based on the acoustic information. Head and body movement were present in both conditions.

Figure 1: Close-up screen capture of Avatar with mouth opened and closed. Arms and torso were visible in the experiment.

Sound was recorded through a lapel microphone and the software Audacity. Auditory stimuli were normalized for amplitude with a script in Praat [8] and then fine-tuned by a research assistant. The externally recorded audio was synced to the in-app audio using Kdenlive [9] and Final Cut Pro X [10] at 30 fps.

Participants sat in a sound attenuated booth in the Interdisciplinary Speech Research Laboratory at the University of British Columbia. Stimuli were presented using OpenSesame 3.2.4 [11] on an iMac 2017, with AKG K240 headphones. The experiment was presented in two blocks. Both blocks consisted of all 36 tokens in pseudo-randomized order. In the first block participants rated the loudness of the first character's name, and in the second block they rated the loudness of the second character's name, each time using a 5-point Likert scale: *1 Not Loud* to *5 Very Loud.* Once a response was collected for one video, the next would be played automatically.

3 Results

The Likert scale data were aggregated [12], and then analyzed with linear mixed effects models in R using the lme4 [13] and lmerTest [14] packages. Crucially, one of the models included mouth-movement as a term (1), and the other did not (2).

(1) Response ~ Accented * Character * Mouth_movement + (1|Subject)
(2) Response ~ Accented * Character + (1|Subject)

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Response referred to the Likert scored loudness, *Accented* to which character name was accented, *Character* to whether the loudness of pronunciation of the first-mentioned or second-mentioned character was rated, *Mouth_movement* referred to whether the avatar's mouth was moving, and *(1|Subject)* includes subject as random intercepts.

There was a two-way interaction of *Accented* and *Character* (t = 9.01, p < .0001). The terms *Character* (t = -12.78, p < .0001) and *Accented* (t = -6.71, p < .0001) were also significant. Accented words were perceived as louder than unaccented words, and character names at the beginning of the sentence were perceived as louder than character names at the end of the sentence (Figure 2).

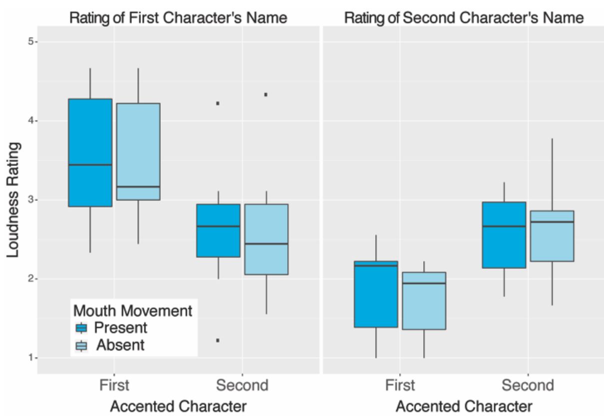

Figure 2: Boxplots demonstrating perceived loudness ratings of first and second characters

Neither *Mouth_movement*, nor any interactions with *Mouth_movement*, were significant (all ts < .53). Adding to the evidence, likelihood ratio test comparing (1) and (2) suggested that (2) is the better model, since there was no significant difference between (1) and (2), and (2) included fewer terms. Taken together, the evidence indicates that *Mouth_movement* played no detectable role in the perception of loudness. An analysis examining *Vowel* also failed to detect any contribution of that term to the model.

4 Discussion and conclusions

This study examined whether the aperture of an avatar's mouth was interpreted as an indicator of loudness. If mouth aperture were taken as an indicator of loudness, then the mouth movement condition would have been perceived as louder than the no mouth movement condition.

The results showed that subjects disregarded mouth aperture when judging the loudness of the words. Not only did they disregard that the mouth was opening more in response to signal amplitude, they even disregarded that for half of the stimuli the mouth didn't open at all.

These results support the finding that speech from avatars is not perceived the same as speech in face-to-face, in-person communication [1]. Mouth movements likely affect speech prosody in other ways than loudness perception, and future work should examine whether mouth aperture has any effect on the general perception of prominence *beyond* loudness, and whether that affects the message level of communication.

Acknowledgments

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CANADIAN ACOUSTICAL ASSOCIATION

Minutes of the Board of Directors Meeting
Monday, May 27, 2019 2:00 PM – 4:30 PM (Eastern Time)
Held by online conference call

1. Call to Order

Meeting called to order at 14:08 EDT.
In attendance: Jeremie Voix, Alberto Behar, Roberto Racca, Umberto Berardi, Dalila Giusti, Mehrzad Salkordeh, Michael Kiefte, Andy Metelka, Bryan Gick, Joana Rocha, Bill Gastmeier, Frank Russo.
Agenda approved: Moved by Jérémie.

2. President's Report (Jérémie)

International congress on sound and vibration (ICSV26) held in Montreal July 8-11; will provide free booth for CAA-ACA and coverage in IJAV publication. Umberto gave some details on how CAA would participate: journal editor, copyeditor and one more member of staff would run the booth. Umberto has prepared flyers and a poster to promote the Canadian Acoustics journal. Would have a laptop for people to enroll in the CAA if desired. Canadian Acoustics bookmarks also being prepared; they could potentially be placed in all delegates bags if printed in 900 copies.

Request for special membership for local chapters. Question whether to proceed. Dalila expressed doubts about the value of the CAA providing financial support for chapters; rather having them self-sufficient in their fundraising. Or could build an add-on fee for membership in a chapter as part of the CAA membership fee. It was felt that CAA should support the creation of these local chapters (initial lumpsum, help for room rental, etc.) but that CAA limits its financial involvment too. Jeremie will draft an outline framework as part of a response to Toronto local chapter.
Lifetime or multi-year membership questions. No resolution after some discussion; will be on the backburner until further notice

Thanks from Jérémie to board members for support in nominating him for the ICA early career award. Will receive the honour at ICA2019 in Aachen (Germany) and will present CAA.

Jérémie informed the board that CAA is supporting the ICA application to transfer its office in Spain in preparation for upcoming conference.

Opportunity to display CAA information at upcoming Canada Wide science fair in Edmonton and future ones for a small sponsorship ($500) for a display. Question whether we should go for this on an ongoing basis. Concern from Dalila that our current Science Fair award is the only one to carry an admin fee, equal to 100% of the acutual award. Issue taken under reserve. Jérémie will investigate the added visibility that this display would provide CAA and query about the admin fee.

Jérémie has been soliciting early 2019 the CAA directors for a "Membership Task Force" to better understand sustaining subscribers expectations and how the Association could support them better. Finalizing a survey with Andy; a few Board members including Roberto, Mehrzad, Alberto and Bill offered to assist in its drafting.

Jérémie suggested a process for recognizing long serving members of the Association. Frank suggested introducing a fellowship level. Must be commensurate to the small size of the Association; can't have too many recognitions relative to the membership. Frank suggested he write an outline of how the fellowship system would work and share it with Jeremie for discussion at next Board meeting.

3. Social media outreach (Frank)

Social media has been very dormant; Frank needs support because he cannot dedicate enough time to it. Would like some social media savvy people to either feed him information or do the actual posting (with supervision from someone the Board can trust).

4. Awards Report (Joana)

First year for her in this role; welcomes any comments. Received information from all the individual awards coordinators about nominations. There are some mismatches between coordinators' area of expertise and the awards they coordinate. Umberto feels that way about his role on the Hétu prize; Jeremie suggested it should be handled by Alberto who agreed to take up the role (Umberto will send him three applications). Question to Dalila about whether every prize has been sent to the winners for last year; Dalila confirmed that all prizes have been disbursed. Joana noted suggestion from Bryan to have a (preformatted) letter from a student's supervisor as a requisite to apply for an award, to yield legitimacy to the application. Joana also pointed out that some awards often receive no applications; they may have to be better advertised. Jeremie says that the effort should be on the shoulders of the individual award coordinators who have the connections in their fields of expertise; suggested to improve the networking with them by beat the drum a couple weeks before the deadline. Jeremie also pointed out a suggestion made by Joana at some point to encourage award winners to contribute a short article for the Journal. This could be done through a mention in the award rules and fine prints in the application form. This form needs updates anyway, as the logo is probably 20 years old.

5. Past and Upcoming Meetings

AWC/ASA-2018: Victoria, BC (Roberto)

Total attendance was 1357 (including 211 Canadians and 359 students) with 1290 presentations in 121 sessions. These numbers were considerably above expectations for fall meetings (usually 900-1000 attendees). The conference made about $22k profit out of a total budget of $550k (not a big profit, but the first ASA conference in recent years not to lose money). From a CAA standpoint, however, Roberto's subjective impression corroborated by some feedback from relevant parties is that the joint conference somewhat alienated the normal AWC delegates base both on an individual delegate level (less flexibility with submissions, program changes etc.) and on a corporate level (no possibility of sponsorship or exhibiting). Generally, a dedicated CAA meeting has a much greater potential for cementing the Association and raising awareness about its activities as well as promoting membership / support.

AWC 2019: Edmonton (Benjamin Tucker) [Online Guest]

PayPal problems are potentially hampering registrations currently (Dalila offered alternative ways especially for exhibitors and sponsors to contribute), but otherwise everything is on track. Abstract deadline on 14 June. The three plenary speakers have been confirmed. One of them works on the acoustics of indigenous languages; another on music composition.

AWC 2020: Sherbrooke (Philippe-Aubert Gauthier)

Concerns about little known location, but it is an excellent site and the organizers are very well connected. Likely to be held at a country resort with good transportation from the airport, rather than in the downtown core. To be held 7-9 October; Some Directors expressed concerned that weather will already be turning wintery. Jeremie promised good weather.

AWC 2021: St-John's (Benjamin Zendel & Len Zedel)

Frank and Jeremie have been active in assisting the organizers. Explored various options and agreed that it should be held downtown for best attendance. Choice of hotel has fallen on the Sheraton; a deposit will have to be paid soon (Dalila will coordinate). Usual issues of dealing with a large chain hotel (A/V monopoly and the like). Dates 29 September – 1 October.

Conference manual - update (Frank)

Jeremie has merged the most recent draft from Frank with the existing 2001 guide and circulated it already to Sherbrooke convenors for AWC2020. Jeremie will keep it updated until further notice.

6. Treasurer's Report (Dalida)

CAA made 47K at the Guelph conference and ~26K interest on investments; finances in good shape. About 370K invested in various GIC instruments; TD is doing a good job managing. Taxes have been filed; HST refund incoming. Mehrzad voiced his concern that the Association is not providing valuable services to its members; some of the money should be spent in perks to exhibitors such as free entrances to the conference.

Dalila moved to approve; Jeremie seconded; carried unanimously.

7. Secretary's Report (Roberto)

The current tally of Association members and Canadian Acoustics subscribers is summarized in the table below, which shows by comparison the numbers reported at the two prior Board meetings.

Category	Paid-up 2019 (as of 26 May 2019)	Paid-up 2018 (as of 4 Nov 2018)	Paid-up 2018 (as of 3 May 2018)
Regular member	152	168 (18 new AWC17)	152
Emeritus	1	1	1
Student	17	26 (3 new AWC17)	20
Sustaining subscriber	17	19	20
Indirect subscribers			
- Canada	5	6	3
- USA	3	3	1
- International	3	2	2
Direct subscribers	3	4	3
Total	**201**	**229**	**202**

The overall numbers have dropped back to the levels of one year ago after a temporary surge from automatic enrolment of non-member registrants at the 2017 AWC (a practice now discontinued). Roberto noted the need not only to provide support and tangible benefits to existing and new members but also to canvass former members for input on what would make the Association more relevant to them; this was discussed among the Board and led to the agreement to draft and circulate a survey as part of a drive to revitalize the membership base by improving the Association's value to its members. Roberto also advised that some recent difficulties with the online payment system for memberships and subscriptions, due to a policy revision by PayPal which required a complex re-accreditation process, may have prevented several renewals which hopefully will be attempted again.

On other business, progress is still being made in collaboration with the Journal's editorial staff to establish more timely protocols for responding to notifications and requests from both regular and indirect subscribers, and to transfer over to the Journal's production team some circulation related tasks for better efficiency. Communications between the membership / outside parties and the Secretary remain frequent and constructive; where applicable, they are relayed in a timely manner to the Board and the executive officers for discussion and formal action.

8. Editor's Report (Umberto)

March issue has been produced and sent; took much work but was a good product with enhanced international content. Was supposed t be the audiology issue but that was moved to the June issue as content is now ready (6 papers overall; copyediting nearly finished).

September issue will be the typical conference issue.

After July conference in Montreal, will gather articles for December issue.

Oliver Valentin is retiring as copy editor and a new one is incoming for the AWC September issue

At least three editors short in specialty areas; physical acoustics & ultrasound, bioacoustics, and underwater acoustics; temporary vacancy in architectural acoustics but Umberto can fill in until regular editor recovers from sick leave. We need solid names for the three missing areas, willing to serve for at least five years (usually no more than a couple of articles a year).

9. Varia

Michael suggested considering very low membership and registration fees for students, like the ASA does. An investment in the future. Umberto supported the idea of essentially sponsoring student memberships from the funds of the Association.

Mehrzad suggested using extra funds in the Association to provide value to the corporate / sustaining subscribers, like sponsoring events that benefit industry or providing free advertising. Also, the content of conferences and journal must include more generally usable information.

Dalila recommended that we survey our membership at all levels (as already mentioned by Jeremie) to find out what value they see in the association and how we can better meet their goals.

10. Next meeting : Oct. 8th, 2019 @4pm(MDT) in Edmonton (AB)

Jeremie suggested that we have a pre-meeting focused on the results of the "Membership Task Force" hopefully reviewing the results of the survey for our investigation into membership. Will confirm a start time (likely 2:30pm) with AWC2019 convenors.

11. Motion to Adjourn

Moved by Dalila and seconded by Roberto. Adjourned at 16:40 EDT.


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ACOUSTICS WEEK IN CANADA 2019 – Edmonton AB

October 9-11, 2019

Sutton Place Hotel Edmonton

Welcome to Edmonton!

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

Plenary Lectures/Technical Sessions

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

Plenary Speakers

Hildegard Westerkamp (Soundscape Composition and Acoustic Ecology)
Sonya Bird (Speech Acoustics and Indigenous Languages)
Michelle Vigeant (Acoustics & Architectural Engineering)

Exhibition & Sponsorship

There will be an exhibition area for acoustical equipment, products, and services on Thursday October 10. If you or your company is interested in exhibiting, or if you would be interested in sponsoring a conference social event, technical session, coffee

breaks, or student prizes, please contact the **Exhibition Coordinators.** The conference offers an excellent opportunity to showcase your company and products or services.

Student Participation

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

Paper Submissions

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

Contacts/Organizing Committee

Conference Chair	Benjamin V. Tucker, University of Alberta (benjamin.tucker@ualberta.ca)
Treasurer:	Corjan Buma, University of Alberta/ACI (meanu@ualberta.ca)
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Sutton Place Hotel Edmonton

Bienvenue à Edmonton!

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

Séances plénières et sessions scientifiques

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

Scéance plénières

Hildegard Westerkamp (Composition de paysages sonores et écologie acoustique)
Sonya Bird (Acoustique de la parole et langues autochtones)
Michelle Vigeant (Acoustique et ingénierie architecturale)

Expositions et commandites

Il y aura un espace d'exposition pour l'équipement en acoustique, les produits et les services le jeudi 10 octobre. Si vous ou votre entreprise êtes intéressé à exposer, ou si vous êtes intéressé à commanditer un événement social du congrès, une session

scientifique, des café pauses, ou des prix d'étudiants, veuillez contacter **le coordonnateur de l'exposition.** Le congrès offre une excellente occasion de présenter votre entreprise et vos produits ou services.

Participation des étudiants

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

Soumissions

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

Contacts / Comité d'organisation

Présidents:	Benjamin V. Tucker, Université de l'Alberta (benjamin.tucker@ualberta.ca)
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Prix étudiants et subventions:	Mary Ingraham, University of Alberta (maryi@ualberta.ca)

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

7-11 july 2019
ICSV26
MONTRÉAL
26th International Congress on Sound & Vibration
The annual congress of the International Institute of Acoustics and Vibration (IIAV)

WELCOME TO ISCV26, MONTRÉAL, QC, CANADA

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

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

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

THE CONGRESS VENUE: HOTEL BONAVENTURE

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

CONGRESS SECRETARIAT ICSV26

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

KEY DATES

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

ORGANISED BY

International Institute of Acoustics and Vibration

In cooperation with

CANADIAN ACOUSTICAL ASSOCIATION
ASSOCIATION CANADIENNE D'ACOUSTIQUE

Jointly with

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CANADIAN ACOUSTICS ANNOUNCEMENTS - ANNONCES TÉLÉGRAPHIQUES DE L’ACOUSTIQUE CANADIENNE

Looking for a job in Acoustics?

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

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

August 5th 2015

ICSV26 to be held in Montreal, July 2019

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

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

October 12th 2017

International Symposium on Room Acoustics - ISRA2019

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

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

February 15th 2019

Acoustics Week in Canada 2019

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

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

April 1st 2019

Acoustics Week in Canada 2020

AWC 2020 will be held October 7 – 9, 2020 in Sherbrooke (Québec) with Prof. Philippe-Aubert Gauthier as General

Chair. https://awc.caa-aca.ca/index.php/AWC/AWC20 -

May 3rd 2019

Acoustics Week in Canada 2021

AWC 2021 will be held in St-John's (Newfoundland) with Profs. Benjamin Zendel and Len Zedel as co-chairs. https://awc.caa-aca.ca/index.php/AWC/AWC21

May 3rd 2019

2020: International Year of Sound

The International Year of Sound (IYS 2020) is a global initiative to highlight the importance of sound in all aspects of life on earth and will lead towards an understanding of sound-related issues at the national and international level.

- Inspired by the achievements of La Semaine du Son (The Week of Sound), and following naturally as an important contribution to UNESCO Resolution 39 C/49 25 September 2017 on "The Importance of Sound in Today's World: Promoting Best Practices", the International Commission for Acoustics (ICA) is mobilizing its Member Societies and International Affiliates to promote best practices in sound during the year of 2020 to create an International Year of Sound (IYS 2020). - - For more info, visit http://sound2020.org/ -

May 3rd 2019

ASTC Workshop by the National Research Council Canada

The National Research Council Canada will be hosting a workshop to give an overview of new tools to calculate the ASTC.

This workshop will be held during the 2019 Acoustics Week in Canada meeting in Edmonton, Alberta on October 9-11, 2019. - More info available from https://awc.caa-aca.ca/public/conferences/2/AWC19/ASTC_workshop_flyer.pdf -

June 11th 2019

À la recherche d'un emploi en acoustique ?

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

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

August 5th 2015

International Symposium on Room Acoustics (ISRA 2019)

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

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

February 15th 2019

Semaine canadienne de l’acoustique 2019

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

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

April 1st 2019

To: ICA Member Societies
and International Affiliates

Dear Colleagues,

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

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

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

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

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

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

With my best regards

Michael Taroudakis
President of the ICA

INTERNATIONAL YEAR OF SOUND 2020

National/International Coordinators

Education and Outreach on Sound for Society and the World

Culture – Creativity – Nature – Health – Science – Technology

Development – Education – History

Outcome of the UNESCO Charter of Sound

MISSION

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

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

ACTIVITIES/EVENTS IYS 2020

These will fall into three main categories:

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

LIAISON AND STEERING COMMITTEES

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

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

STRUCTURE FOR ICA MEMBER ORGANISATIONS ACTIVITIES/EVENTS

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

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

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

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

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

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

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

TYPES OF ICA MEMBER ORGANISATIONS ACTIVITIES/EVENTS

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

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

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

Activities related to the annual meeting or conference.

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

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

Activities related to education.

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

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

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

Activities addressed to the general public

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

TYPES of ICA ORGANIZED AND CENTRALLY FUNDED EVENTS:

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

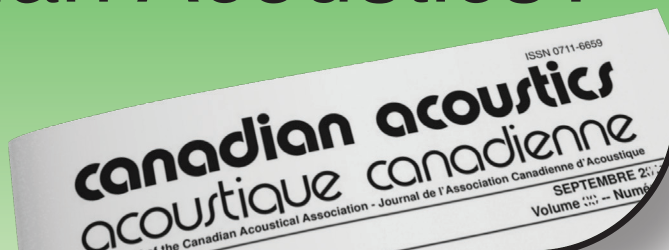
- Design of promotional material (posters and leaflets) to be distributed electronically to ICA members and International Organizations. The ICA members will include this material in their web-sites. After printing, these leaflets will be available for distribution to all the events related to the IYS.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

MAJOR INTERNATIONL CONFERENCES ASSOCIATED WITH THE IYS 2020

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

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

Why publish in Canadian Acoustics?



Because, it is...

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

Pourquoi publier dans Acoustique canadienne ?

Parce que, c'est...

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

Canadian Acoustical Association
Association canadienne d'acoustique

Application for Membership

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

Subscriptions to *Canadian Acoustics* *or* Sustaining Subscriptions

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

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

Address for subscription / membership correspondence:

Name / Organization ______________________________

Address ______________________________

City/Province ______________ Postal Code __________ Country ______________

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Areas of Interest: (Please mark 3 maximum)

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

For student membership, please also provide:

__________ __________ ______________________________

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

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

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[ ] $135 including International mailing

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(4 issues/yr)

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

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

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

Formulaire d'adhésion

L'adhésion à l'ACA est ouverte à tous ceux qui s'intéressent à l'acoustique. La cotisation annuelle est de 120.00$ pour les membres individuels, et de 50.00$ pour les étudiants. Tous les membres reçoivent ***l'Acoustique Canadienne***, la revue de l'association.

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

Les abonnements pour la revue ***Acoustique Canadienne*** sont disponibles pour les compagnies et autres établissements au coût annuel de 120.00$. Des compagnies et établissements préfèrent souvent la cotisation de membre bienfaiteur, de 475.00$ par année, pour assister financièrement l'ACA. La liste des membres bienfaiteurs est publiée dans chaque issue de la revue ***Acoustique Canadienne***..

Notez que tous les paiements électroniques sont acceptés en ligne http://jcaa.caa-aca.ca

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Cocher vos champs d'intérêt: (maximum 3)

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

Prière de remplir pour les étudiants et étudiantes:

__________ __________ __________ __________

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

Cocher la case appropriée:
[ ] Membre individuel 120.00 $
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Merci de noter que le moyen de paiement privilégie est le paiement par carte crédit en ligne à *http://jcaa.caa-aca.ca*

Pour les individus ou les organisations qui préféreraient payer par chèque, l'inscription se fait en ligne à *http://jcaa.caa-aca.ca* puis le chèque peut être envoyé à :

Secrétaire exécutif, Association canadienne d'acoustique :
Dr. Roberto Racca
c/o JASCO Applied Sciences
2305–4464 Markham Street
Victoria, BC V8Z 7X8 Canada

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The Canadian Acoustical Association gratefully acknowledges the financial assistance of the Sustaining Subscribers listed below. Their annual donations (of $475 or more) enable the journal to be distributed to all at a reasonable cost.
L'Association Canadienne d'Acoustique tient à témoigner sa reconnaissance à l'égard de ses Abonnés de Soutien en publiant ci-dessous leur nom et leur adresse. En amortissants les coûts de publication et de distribution, les dons annuels (de 475$ et plus) rendent le journal accessible à tous les membres.

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