Measurement of Occupational Sound Exposure from Communication Headsets

by

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Abstract

Increased use of communication headsets found in various workplaces raises concerns regarding exposure to potentially hazardous noise levels. Current national and international standards specify a wide range of simple and specialized methods for the measurement of sound exposure under communication headsets. However, to date, quantitative data comparing the degree of agreement between the different measurement methods or their relative performance are lacking, and it is not known if occupational health and safety (OHS) or hearing loss prevention (HLP) stakeholders have the necessary training and equipment to integrate them in their daily practice.

A three-step study addressing several knowledge gaps on this topic is presented in this thesis. First, a questionnaire survey distributed to OHS and HLP stakeholders has revealed that knowledge of specialized measurement techniques and access to the necessary equipment varies significantly depending on the training of the different professionals. There is therefore reason to specify several methods in measurement standards to meet the specific needs and expertise of the different stakeholders involved. Second, a series of experiments conducted with single and multiple expert participants indicated that the Type 1 artificial ear is not suited for sound exposure measurement with communication headsets, while Type 2 and Type 3.3 artificial ears are in good agreement with the acoustic manikin technique specified in the International standard ISO 11904-2. Finally, laboratory experiments were conducted to test the indirect calculation method proposed in the Canadian standard CSA Z107.56. Results revealed that the calculation method is suitable to identify possible situations of exposure over the regulatory limit (e.g. 85 dBA), but refinements are proposed to improve measurement accuracy.

Overall, this thesis provides new knowledge to guide selection of the most suitable methods for the assessment of communication headset exposure taking into account expertise, access to equipment, and field logistic constraints. Results also have direct implications for future revisions of existing measurement standards. Finally, this work could be the basis for detailed guidelines on noise exposure measurements under communication headsets to better inform OHS and HLP professionals and ultimately prevent occupational noise-induced hearing loss.

To my parents, Albert and Bernadette,
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List of Acronyms

AFD Anchorage Fire Department
ANR Active Noise Reduction
ANSI American National Standards Institute
ASA Acoustical Society of America
AS/NZS Australian/New Zealand Standards

B&K Brüel & Kjaer
BN Background Noise

CCOHS Canadian Centre for Occupational Health and Safety
CSA Canadian Standards Association

DRDC Defence Research and Development Canada

EN European Standards
ETSI EG European Telecommunications Standards Institute (Guide)

F-MIRE Field Microphone in a Real Ear

HATS Head and Torso Simulator
HCP Hearing Conservation Program
HINT Hearing-in-Noise Test
HLP Hearing Loss Prevention
HLPB Hearing Loss Prevention Branch
HLPP Hearing Loss Prevention Program
HPD Hearing Protection Devices

IEC International Electrotechnical Commission

IEC/TS International Electrotechnical Commission (Technical Specifications)
ISO International Organization for Standardization
ITU-T International Telecommunication Union - Telecommunications Sector

KEMAR Knowles Electronic Manikin for Acoustic Research

LAeq A-weighted, Equivalent Sound Level
LoA Limits of Agreement
LZeq Z-weighted, Equivalent Sound Level

MIRE Microphone in a Real Ear

N-IHL Noise-Induced Hearing Loss
NIOSH National Institute for Occupational Safety and Health
NR Noise Reduction
NRR Noise Reduction Rating

OHS Occupational Health and Safety
OSHA Occupational Safety and Health Administration

SNR Signal-to-Noise Ratio

Chapter 1

Introduction

1.1 Statement of problem and motivation

Hearing problems can have an effect on a person's emotional, physical, and social well-being. Among the various causes of hearing impairment, noise-induced hearing loss (N-IHL) is a widespread concern and a population health issue. Noise in the workplace is responsible for 16-24% of adult-onset hearing loss worldwide [10] and is the second most prevalent self-reported work-related injury [9]. In fact, N-IHL remains one of the most significant work-related health burdens, causing problems not only for the individuals involved, but also for their co-workers and families. In the United States, approximately 22 million workers are exposed to potentially hazardous noise levels [13] and occupational noise-induced hearing loss affects 10 million workers [10]. In the European Union, 7.2% of workers report work-related hearing problems [11].

While noise is present with most work activities, the World Health Organization identifies some occupations at risk for N-IHL such as those in manufacturing, transportation, mining, construction, agriculture, and the military, among others [3]. Some workplaces, most importantly those where dangerous types of material, impact processes, or commercial jets are present, are associated with particularly high levels of noise [3]. In addition to these factors, the increased use of wired and wireless communication headsets is raising concerns regarding exposure to potentially hazardous noise levels [12]. Communication headsets can be commonly found in various workplace settings for example call centers, retail stores, fast food outlets, airport ground and control tower operations, industrial and construction sites, military sites, and law enforcement agencies [5]. In all cases, while their use in occupational settings varies, workers are subject to noise exposure from both the audio signals from the headset and the noise from their surrounding environment. These factors pose challenges when carrying-out measurements of noise exposure.

Several national and international standards propose procedures for noise exposure measurements in occupational settings with the use of a sound level meter or noise dosimeter (ANSI/ASA S12.19 [1], CSA Z107.56 [4], ISO 9612 [8]). These methods are applicable when sound sources are far from the ears of the workers but are not suitable when sound sources are close to, or occlude, the ears such as with the use of headsets. The International Organization for Standardization describes two specialized methods for the measurement of noise from sources close to the ears: the Microphone in a Real Ear (MIRE) (ISO 11904-1 [6]) and the acoustic manikin (ISO 11904-2 [7]) techniques. In order to assess exposure and enable comparison with occupational noise limits, in-ear measurements collected with these methods must be converted to the sound field with third-octave calculations. Some national standards (CSA Z107.56 [4], AS/NZS 1269.1 [2]) specify the use of general-purpose artificial ears with single number corrections to convert measurements to the equivalent diffuse field. Finally, the Canadian standard [4] also specifies an indirect calculation method as a simpler alternative requiring only a sound level meter or noise dosimeter, and computational steps that consider the external background noise, the noise reduction of the device, and the effective listening level set by the user.

Each method presents advantages and disadvantages regarding their use for the measurement of noise under communication headset. However, to date, there is no quantitative data available to compare the degree of measurement agreement between the different methods. In addition, while the use of these different measurement methods requires various levels of technical expertise, it is not known if occupational health and safety (OHS) or hearing loss prevention (HLP) stakeholders have the necessary training and equipment to integrate them in their daily practice. All these factors are important to guide the selection of the most suitable method for a given situation.

1.2 Research objectives

The overall goal of this doctoral thesis is to increase understanding about the measurement methods that can be used by OHS and HLP stakeholders to assess noise exposure under communication headsets in the workplace, and to evaluate, compare, and refine these various tools. More specifically, this thesis will address three research gaps related to noise measurements under communication headsets. The first is to document the awareness of OHS and HLP professionals of the issue of communication headset noise exposure, their knowledge of the different measurement tools available, and their access to basic and specialized equipment. Secondly, this thesis aims to compare different artificial ears proposed in national standards for noise measurement under communication headsets (CSA Z107.56 [4], AS/NZS 1269.1 [2]) against international standards methods such as the acoustic manikin technique (ISO 11904-2 [7]). Thirdly, the alternative calculation method proposed in the Canadian standard (CSA Z107.56 [4]) will be further investigated to better understand the influence of the background noise, the headset type and the attenuation on the effective listening level of the communication speech signal set by the user in a workplace setting.

Findings from this thesis could provide knowledge to routinely integrate the measurement of noise exposure under communication headsets in current hearing loss prevention frameworks. Collected data from this study could also warrant further refinement of existing standards. Finally, this work could help elaborate guidelines on noise exposure measurements under communication headsets, including recommendations for safe use of these devices in the workplace. Overall, this could bring forth an upstream approach towards preventing N-IHL by educating and informing OHS and HLP professionals, consequently benefiting both the employer and the employee and maintaining good hearing health of workers at risk.

1.3 Methodology and approach

In order to address the above-mentioned objectives, a multi-step study was undertaken:

- A survey was conducted using a questionnaire created and distributed to stakeholders in OHS and HLP in Canada to gain a better understanding of professionals' awareness on measurement methods for noise exposure under headsets as well as their access to the basic and specialized measurement tools.
- Pilot in-laboratory measurements were carried-out with a single participant, expert in the field of interest, to compare the equivalent diffuse-field level between direct methods for measurement of headset noise exposure, and to evaluate the effect of different fitting methods on acoustic measurements.
- In-laboratory acoustic measurements were conducted with multiple participants with technical and/or clinical expertise in the field of interest to compare the direct methods for measurement of headset noise exposure in terms of measurement repeatability for each test setup, measurement agreement between the different test setups, and use of single number corrections or third-octave band procedures to convert in-ear sound levels to the diffuse field.
- In-laboratory experiments were carried-out with participants to evaluate the impact of various headset and background noise characteristics on user preferred in-headset speech listening level. This was to help refine the simple indirect calculation method which is designed to provide an estimate of noise exposure.

1.4 Thesis outline and contributions

This thesis is by article and is comprised of a review of the literature followed by a collection of four articles, and a concluding chapter.

Chapter 2 provides an overview of hearing loss in the workplace and hearing loss prevention programs followed by a review of the literature on communication headsets in the workplace and measurement methods for noise exposure under these devices. The source of the second part of this chapter is a proceedings paper from a conference of the *International Commission on the Biological Effects of Noise*.

Chapter 3 presents the results from the questionnaire distributed to OHS and HLP stakeholders in Canada to document their awareness of noise exposure from communication headsets in the workplace and their access to basic and specialized measurement tools. This chapter, the first article of this thesis, arises from a publication in the quarterly journal *Canadian Acoustics*.

Chapter 4, the second article of this thesis, is a pilot study which compares acoustic measurements under communication headsets taken with different setups described in national and international standards. The source of this work is a proceedings paper from the *International Congress on Acoustics* and is published in the *Proceedings of Meetings on Acoustics*. Subsequently, Chapter 5 describes the continuation of this work where more elaborate experiments were conducted with different measurement setups. This chapter, the third article of this thesis, is a manuscript published in the interdisciplinary journal *Noise and Health*.

Chapter 6 is the fourth and last article of this thesis. This study investigates the relationship of preferred listening level with headset type, noise type and noise level. This work will be the basis for an upcoming submission in a peer reviewed journal.

Finally, a global summary of the research findings, contributions, limitations, future work, and concluding remarks is provided in Chapter 7, followed by a statement of contribution of the authors and collaborators in Chapter 8.

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Chapter 2

Review of Literature

This chapter starts by providing a description of noise-induced hearing loss (N-IHL) and its prevalence in the workplace. Subsequently, a summary of the different components of hearing loss prevention programs (HLPP) is presented, including related national/international standards and current challenges. Finally, the last section of this chapter forms a proceedings paper that was presented at a conference of the *International Commission on the Biological Effects of Noise* [56] and reviews studies pertaining to noise exposure assessments from communication headsets in occupational settings followed by standardization efforts on measurement methods and field procedures in this area.

2.1 Hearing loss in the workplace

Hearing loss is the temporary or permanent, partial or total inability to hear. N-IHL is characterized by a gradual, typically binaural, reduction of hearing sensitivity due to noise, normally first observed in the higher frequencies [10, 62, 76]. Such loss can be temporary if the exposure is moderate, but repeated exposure to intense noise gradually leads to permanent sensory damage [10, 15]. Before hearing loss becomes permanent, temporary loss occurs [70]. Regular exposure to less intense sounds can accumulate unnoticed over a long time period, and lead to irreversible damage to the inner ear [10, 11]. Various physiological, psychological, and emotional issues are associated with this chronic health condition [62, 76]. For example, tinnitus and difficulty understanding speech or communicating are commonly observed [61, 76]. Moreover, hypertension, decreased vision, cardiovascular disorders, and sleeping disorders, are documented consequences [61, 62, 80].

With the increase of occupational and recreational noise exposure in the general living environment in both developed and developing regions, noise-induced hearing loss is considered an important social and population health problem of the 21st century that affects all ages [3, 18, 61]. According to a report by the World Health Organization [19], noise is usually defined as occupational or environmental at the community, residential, or domestic level. Several sources indicate that exposure to noise is a stressor that affects most people [66, 77]. While preventable with the use of noise control measures and proper protection, N-IHL is the second most common type of sensorineural hearing loss after deterioration due to age [62, 66].

Noise in the workplace is an important risk factor for hearing loss and consequently N-IHL is identified as a significant occupational health problem worldwide [19]. Such a loss is often the result of a noisy workplace, the second most prevalent self-reported work-related injury [3, 15, 58], and tends to occur within the first five to ten years of exposure [70]. Occupational N-IHL has a prevalence of approximately 7% in Western countries, 21% in developing countries, and is responsible for an overall average of 16-24% of adult-onset hearing loss internationally [58]. According to the U.S. National Health and Nutrition Examination Survey, 22 million American workers are exposed to potentially hazardous noise levels on the job [72]. N-IHL is the most common occupational disease in the U.S. [57] involving at least 11 million workers [36, 57]. Similarly, 7.2% of workers in the European Union report work-related hearing problems [60]. Unfortunately, similar numbers are still not available for Canada [27].

In a cross-sectional study conducted to estimate the prevalence of hearing loss among industries in the U.S., the adjusted prevalence ratios were high in mining, wood product manufacturing, and construction of buildings [52]. N-IHL is also common in the military where some trades such as infantry, artillery, and flight engineering are most at risk [1]. Occupational noise is a risk factor different from environmental noise since it is the respon-

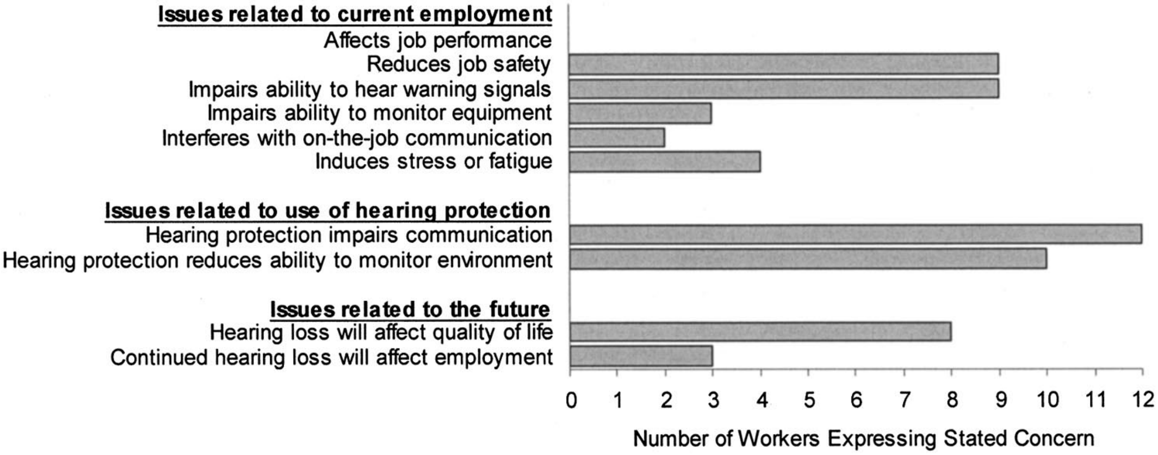

Figure 2.1: *Difficulties and concerns expressed by noise-exposed, hearing-impaired workers and frequency of their expression during the focus group sessions (n = 31) [55].*

sibility of both the employers and the workers [19, 21]. Employers are expected to provide proper training and the tools needed to protect their employees. Workers are expected to avoid exposing themselves to hazardous noises, to use hearing protection when necessary, and to stay informed by participating in hearing loss prevention training [21]. Unfortunately, occupational N-IHL is often overlooked and can become a health problem affecting an employee's safety and performance at work [67]. The consequences of impaired communication in the workplace due to hearing loss include social isolation, anxiety, irritability, decreased ability to monitor the environment, increased injuries, decreased self-esteem, and lost productivity [2, 19, 62, 70]. These difficulties and concerns were highlighted in a study conducted by Morata and colleagues [55] where a focus group of workers from the manufacturing, mining and construction industries with self-reported hearing loss were interviewed (Figure 2.1). Abel [2] obtained similar results in a study on hearing loss in the military environment. Also, from a socio-economic standpoint N-IHL leads to a financial burden resulting from costs associated with diagnosis, treatment (e.g., hearing aids), workers' compensation, and rehabilitation [19, 70].

Finally, a report prepared for New Zealand's Accident Compensation Corporation by members of the University of Auckland states that noise exposure and N-IHL rates are not equally distributed across the general working population [75]. While various interventions and frameworks may be implemented to address and prevent N-IHL in the workplace, inequality may exist between groups that have access to, or are knowledgeable about these preventative measures. The following section presents an overview of hearing loss prevention programs.

2.2 Hearing loss prevention programs

2.2.1 Elements of hearing loss prevention programs

When high risk noise levels are identified, mandatory Hearing Loss Prevention Programs (HLPP), also often called Hearing Conservation Programs (HCP), are implemented and followed by health and safety officers, based on a framework that focuses on safety and noise protection in the workplace [27, 81]. These programs are designed with an upstream approach to maintaining good hearing health in at-risk populations [71, 75] and are the most effective way to control noise exposure and protect workers' hearing [74]. The series of elements of a comprehensive HLPP aimed at quantifying noise hazards and controlling risks to hearing for workers are schematized in Figure 2.2. Many national and international standards detail procedures and methods related to these different components. The framework ensures control of the various factors leading to noise exposure in the workplace, including [10, 27, 33, 74]:

- Hazard identification and noise measurement: to identify the person at risk
- Engineering and administrative noise controls measures: to remove the hazard as much as possible or to redeploy staffing to minimize noise exposure
- Personal hearing protection: to prevent loss when noise cannot be reduced
- Audiometric monitoring: to ensure that prevention measures are adequate to maintain good hearing health for each exposed worker, or to refer for compensation or clinical services
- Training and motivation: to encourage workers to engage in behaviour to protect their hearing
- Program evaluation and record keeping: to identify weakness, failures, and successes, in order to bring forth improvements

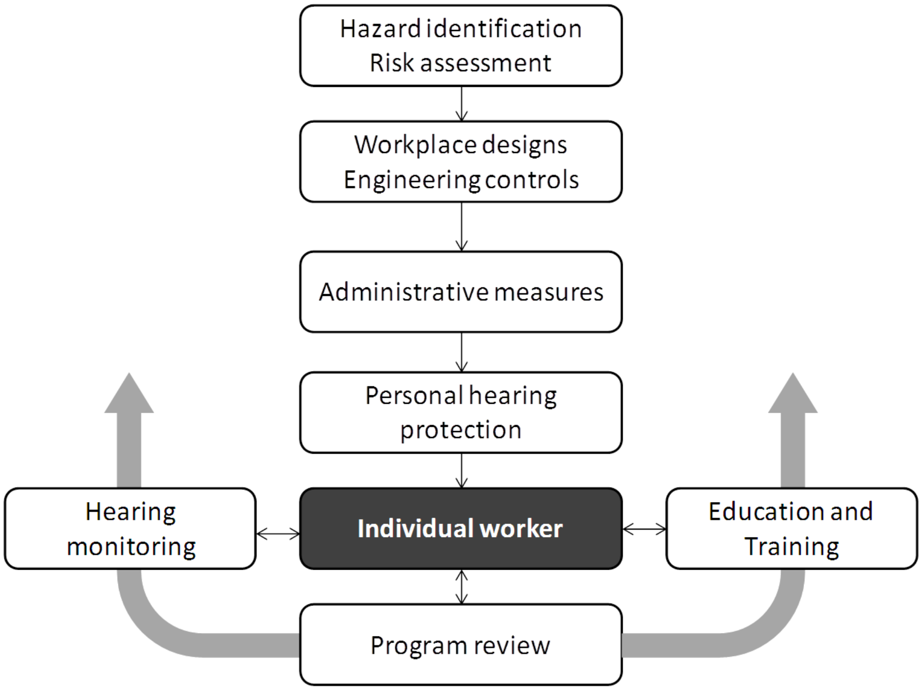

Figure 2.2: *Main elements of a hearing loss prevention program [31].*

A specific example illustrating this hierarchical schematization is provided by the Hearing Loss Prevention Branch at the National Institute for Occupational Safety and Health (NIOSH) where a program to reduce N-IHL in the mining industry was developed based on the elements of HLPP (Figure 2.3).

HLPPs are effective in reducing overall incidence of hearing loss, as long as noise is especially controlled at the source [27]. Additional benefits of properly implemented HLPP are experienced by both employees and management, in terms of better workplace communication, safety, and efficiency for example [70]. Recently, Alice Suter and colleagues [70, 73, 74] thoroughly described the state of HLPP as a whole and at each element of the program. Much of the information in the following sections is based on their work, in particular on the U.S. National Research Agenda for the Prevention of Occupational Hearing Loss [73, 74].

Hazard identification and noise measurements

Hazard identification and noise measurements are the first and essential steps to a HLPP in order to have an accurate picture of the noise risks in a given occupational setting.

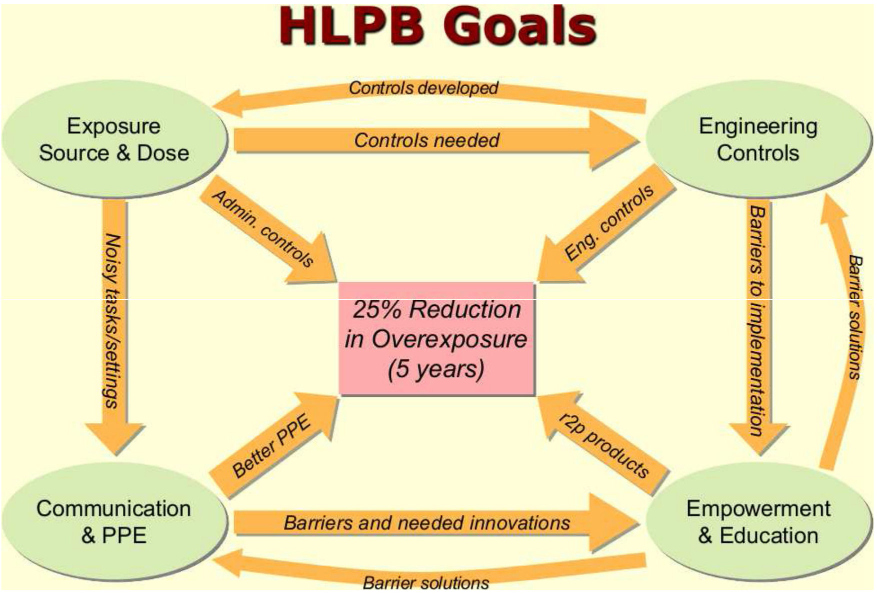

Figure 2.3: *The Hearing Loss Prevention Branch (HLPB) goals at the National Institute for Occupational Safety and Health (NIOSH) Pittsburgh Research Laboratory. This framework illustrates the different programmatic areas that need to be addressed to reduce and prevent hearing loss in the mining industry: noise dose/source relationships, availability of effective noise controls, worker empowerment and education, communication issues and personal protective equipment [53].*

This is necessary to identify the workers at risk, determine the hazardous sources of noise, prioritize control efforts, apply interventions, select appropriate hearing protection devices (HPD), evaluate the success of the noise control measures or interventions, and compare the exposure longitudinally. An inspection is undertaken with workers and health and safety representatives to identify hazardous noise sources and work activities. Subsequently, a quantitative assessment is conducted to measure the sound pressure levels using typically a sound level meter or noise dosimeter. Based on assessments of the risk of N-IHL, most regulatory authorities have suggested an 8 hour noise exposure limit of 85 dBA (see [16] for limits in Canadian jurisdictions).

ISO 9612 [48] describes an engineering method to help users perform the assessment of the noise exposure of workers. The standard specifies three measurement strategies (task-based measurement, job-based measurement, and full day measurement) and provides information on selecting the best measurement strategy for a particular situation.

Resulting measurements conducted according to this standard provide information to define priorities for noise control measures. Similarly, at a national level, ANSI/ASA S12.19 [4] and AS/NZS 1269.1 [6] describe methods that can be used to measure noise exposure of a worker in the United States and Australia/New Zealand respectively. In Canada, procedures for the measurement of occupational noise exposure are defined in CSA Z107.56 [22] as part of the series of standards for acoustics and noise control.

Once hazards have been identified and noise measurements have been conducted, engineering and administration noise control measures are sought were needed.

Engineering and administrative noise control measures

The first and best solution to reducing noise exposure in the workplace is to eliminate or reduce the noise at both the collective and the individual level. Engineering controls that are usually technically and economically feasible have an important role by reducing noise at the collective level [74]. Steps towards the long-term reduction of noise risks include a Buy Quiet policy targeting manufacturers who supply low noise equipment, for example, and revisions to already existing work processes to reduce noise or substitute with quieter alternatives. Another solution to reducing a given worker's noise exposure is through administrative measures for noise areas. Some examples include the use of signage, restricting the number of personnel, rotating personnel, and adjusting schedules [31].

Several international standards detail procedures related to noise control measures. ISO 4871 [45] provides information on the noise declaration that a manufacturer must include on the noise output while the machine is in use. This standard also references the ISO 3740 [43] and ISO 7574 [46] protocols for measurement of noise emission and statistical methods for determining noise emission values of machinery, respectively. There are also various guidelines on different aspects of noise control such as the design and strategies for low noise work places (ISO 11690 [37]), noise control for silencers (ISO 14163 [40]), noise control design procedures for an open plant (ISO 15664 [41]), noise control by enclosures and cabins, and noise control in offices and workrooms (ISO 15667 [42]). At a national level, AS/NZS 1269.2 [7] provides guidance on the management of noise control in occupational settings in Australia and New Zealand. In Canada, CSA Z107.58 [23] describes noise emission declarations for machinery and equipment, and promotes the manufacturing of quieter machinery and a quieter workplace.

Personal hearing protection

At the individual level, HPDs reduce noise when other control measures are insufficient and have been exhausted. Three main factors influence the efficiency of HPDs in reducing noise exposure: the attenuation of the device, the proper fit of the device, and the time the device is worn. Hearing protectors must be selected carefully and should take into account the attenuation needed, the constraints of the task, the auditory demands, the auditory state of the worker, and user preferences. As an alternative to conventional passive devices, advanced hearing protection devices with equal protection and enhancement of auditory performance (e.g., communication, localization) are increasingly common.

International and national standards can provide information on the selection, use, maintenance of hearing protectors and measurement of noise attenuation or residual noise under these devices. Namely, the ISO 4869 [44] series of standards address hearing protectors in terms of measurement of sound attenuation, estimation of A-weighted sound pressure level, and measurement of insertion loss. ANSI/ASA S12.6 [5] proposes methods for measuring the real-ear attenuation of hearing protectors and EN 458 [12] provides guidelines and recommendations on selecting them. The Canadian standard CSA Z94.2 [25] presents information on performance, selection, care, and use of HPDs.

Audiometric monitoring, education, training, and program review

Hearing monitoring is the regular testing of a worker's hearing acuity by pure-tone audiometry performed in a booth by a trained technician. Recommendations on best practice suggest conducting an audiogram at the end of a work shift to identify temporary threshold shifts in hearing levels [21, 79]. While most regulatory authorities have adopted an 8 hour exposure limit around 85 dBA in the workplace (see Canadian Centre for Occupational Health and Safety (CCOHS) 2014 for limits in Canadian jurisdictions [16]) this regulation does not necessarily guarantee that a given worker will not incur hearing loss from the noise exposure because of variations in hearing loss susceptibility between individuals and noise measurement uncertainty. Therefore, hearing monitoring programs are most valuable in providing feedback on the success of HLPP at the individual level and can provide important information to make the necessary adjustments when hearing loss is observed. This monitoring is particularly essential in cases of extreme exposure such as with military workers. At the international level, the ISO 8253-1 [47] defines audiometric test methods. At the national level, CSA Z107.6 [24] describes pure tone air conduction threshold audiometry testing for occupational applications.

Education and training are also important in a HLPP and should be incorporated at every stage. Knowledge, theory and skills should be translated. Workers should be informed periodically on possible effects of noise exposure, the purpose of each element of the HLPP, the selection, fit, care and use of hearing protectors, the meaning of warning signs, and the importance of audiometric evaluations. Proper understanding will consequently minimize risks associated with hazardous noise. Distribution of this information should be framed for each particular audience.

Finally, periodic program evaluations are important to review the various components of the HLPP and its overall effectiveness. In Canada, CSA Z1007-16 defines the management of a HLPP and its components [21].

2.2.2 Challenges

Several logistical and technical challenges present themselves at the different levels of the HLPP framework as reported, based on both evidence and observations, by Alice Suter and colleagues [70, 73, 74]. Understanding the gaps and challenges within HLPP and their consequences is essential to addressing the problems and improving the framework.

Hearing loss prevention programs

With regard to hazard identification and noise measurement, several barriers present themselves. Variations in noise exposure measurements for a given worker, called measurement uncertainty, can reach several decibels as a result of daily working conditions such as the worker's mobility or rotation, change in production volume, differences on time spent at various tasks on different days, non-routine or non-scheduled tasks, and routine tasks conducted infrequently. All these factors affect the daily noise exposure and should be reduced or ideally eliminated to improve accuracy. A second source of measurement uncertainty can be due to the instrumentation used. New measurement methods are being developed, such as for example in-ear dosimetry under hearing protectors [13, 74]; however they have not yet been standardized and each method comes with its own sources of error. Also, appropriate methods or exposure limit criteria have not been fully established yet for situations with extended work shifts or environments where different types of noises are present. Impulse, blast and impact noises are a particularly important issue for researchers in N-IHL because of the difficulties associated with measuring these complex noises in the workplace. Finally, ototoxicity appears as a challenge since the evaluation of chemicals and their toxicity needs to be refined, especially combined with noise exposure. Also, comprehensive programs for workers exposed to ototoxic agents and vibrations are lacking.

Similarly, problems emerge at the noise control level of the HLPP. In North America, a major hurdle to the use of engineering noise control is the lack of regulatory requirements. Another common issue is the misconception that noise control is too difficult or expensive, or in some cases not necessary where HPDs are available. In part, this could be due to the lack of dissemination of noise control tools and information, and of clear, correct, comprehensible noise emission information for equipment. Consequently, the range of solutions is larger than what is actually implemented. Additionally, gaps exist in control technology and the availability of quieter tools and machines need to be addressed. Lastly, the shortage of acoustical engineers partially due to the lack of training programs, and engineers having little knowledge in noise control, can be an obstacle to attaining the noise control needed in the industry.

While HPDs provide additional protection at the individual level, challenges present themselves related to their use in noisy environments. The noise reduction provided by HPDs can vary considerably across workers since there is little control over the fit of the protector on each individual or on the proportion of time it is worn. Additionally, while many different noise-reduction ratings (NRR) have been proposed, they do not necessarily correlate with real-world performance [30]. In terms of communication, hearing protectors may affect the hearing of important sounds from the work environment (e.g., speech, warning sounds, machine sounds) in some situations. For example, the use of HPDs increases the already diminished ability to hear warning sounds and signals in workers suffering from hearing loss [2, 55]. As a result, such workers may remove their HPDs to communicate, thereby exposing themselves to hazardous noise levels. Finally, the use of hearing aids poses another set of difficulties when combined with HPDs.

Although audiometric testing does not provide a comprehensive understanding of auditory performance in the workplace, regular hearing tests are invaluable to monitor the hearing status of a worker. However, certain logistical challenges present themselves related to scheduling these audiometric assessments and to non-optimal testing conditions where extraneous noise during a test can affect the audiometric results for example. Also, since N-IHL can take many years to develop, audiometric monitoring often serves to document hearing shifts after they have taken place. Therefore, while these tests are an essential component of a hearing loss prevention framework, the focus should be on engineering noise control [70].

Communication headsets and their integration in a HLPP

By and large, HLPPs have not yet been adapted to workers who use communication headsets in occupational settings, especially at the noise measurement and education levels. In order to apply a hearing loss prevention framework to protect workers from noise exposure due to the use of communication headsets, certain elements must be considered. An individual who wears such a device is exposed to the noise coming from the headset as well as the noise from the surrounding environment, with aural communication as a focal requirement for task execution. In some settings, the noise may be very loud (e.g., construction sites) causing the worker to increase headset volume in order to understand the signal [32]. In other settings, the surrounding noise may be less significant (e.g., call centers), but the worker could still be exposed to a high headset volume. Therefore, in addition to the surrounding noise over which the worker has little or no control, the individual's behaviour in setting the volume level is a direct factor underlying noise exposure with communication headsets. Also, in these situations, the noise source is close to the ear and specialized measurement methods beyond the typical standardized methods specified in international standard ISO 9612 [48] (or equivalent national standards) are required. Lastly, workers in occupational settings that are not typically considered high risk (e.g., retail outlets) may not be followed by a health and safety officer. It then becomes the responsibility of the workplace manager to enforce regulations in order to protect the employees. These managers must be trained to understand their role, and the employees must be made aware of best practices in the use of headsets. Both should therefore have access to the proper information and documentation. An investigation on the measurement of noise under communication headsets is warranted as a first step towards addressing barriers to HLPP pertaining to the use of these devices in the workplace.

2.3 Communication headsets in the workplace

2.3.1 Field assessments of signals under headsets

Assessments of noise exposure from headsets are complex and must consider several elements such as the contributions from the background noise and the audio communication signal at or in the ear, as well as the transformation from in-ear sound measurements to the sound field. Questions on suitable measurement procedures and analysis methods to assess exposure levels from headsets date back well over thirty years.

Early studies

In the late 1970s, it was observed that several radio operators at marine and aircraft traffic stations in Canada received compensation for noise-induced hearing loss. This prompted a series of studies conducted for Transport Canada [8, 9]. Noise exposure measurements and audiometric assessments were made for radio operators using different types of headsets at three stations on the east and west coasts. Different noise recording methods were used including a miniature microphone at the entrance of the ear canal for circum-aural and supra-aural headsets, and/or a 2 cm^3 coupler for insert headsets attached to a dosimeter. To compensate for the acoustical effects of the head and pinna and allow comparisons to the applicable regulatory limit, measured levels were either corrected using a single number of 8 to 10 dB [8] or through a frequency-dependent equalization network [9]. In a final study, Forshaw et al. [29] estimated mean exposure levels ranging from 79 to 82 dBA during normal radio operations. However, because of occasional narrow-band peaks and artifacts in signal transmission strength due to atmospheric conditions, daily exposure was estimated to be about 90 dBA in some cases.

From 1985 to 1995, a Knowles Manikin for Acoustic Research (KEMAR), modified at the University of Toronto for increased sound isolation and the provision of artificial skin lining inside and around the ear, was used to assess headset noise exposure under contracts carried out for Labour Canada. Measurements covered nine different work sites and various intra-aural, supra-aural, and circum-aural devices [26, 50]. All measurements were conducted with two identical communication headsets; one worn by the worker to fulfill daily tasks and another placed on the manikin positioned near the worker in the same noise environment (Figure 2.4). A splitter was used to duplicate the electric signal to the headsets. Manikin sound levels were transformed to diffuse sound field equivalent levels using either a third-octave band calculation [50] or a filter module connected directly to the recording equipment [26]. Noise exposure levels of workers in quiet office settings (e.g., telephone operators, air traffic controllers) ranged from 64 to 81 dBA, which were below the limits set by Canadian provincial and federal authorities. In moderately noisy environments (e.g. telephone cable maintenance operators), noise exposure was between

Figure 2.4: *Examples of manikin headsets sound measurements in the field [26, 50].*

70 and 84 dBA. Finally, workers in noisy settings (e.g. airport ground crew) were exposed to 76 to 95 dBA, which in some cases exceeded noise exposure limits. Analysis of the complete data indicated a correlation between the sound field equivalent levels and the background noise around the users. The highest exposure was found in a headset that was modified by an airport mechanical shop.

Military

A few studies on noise exposure from headsets used by military personnel are found in the literature. While some work has been done with pilots on noisy flight decks [34] and naval radio operators in the United Kingdom [35], the evaluation of communication headsets for military applications has been an active field of research at Defense Research and Development Canada (DRDC) in Toronto. Crabtree [20] used miniature microphones and real-ear procedures to measure at-ear sound levels arising from the use of circum-aural communication headsets by pilots and support crew during long-range military flights. Some of the devices provided passive-only attenuation of the background noise while others had integrated active noise reduction technology (ANR). Measurements were taken when the communication channel of the headset was ON and OFF. Over all headsets and crew member positions, at-ear sound levels varied from 76 to 97 dBA when the communication channel was ON, and from 63 to 82 dBA when the communication channel was OFF, clearly highlighting the contribution of the communication signal to the overall exposure. ANR technology was found to be capable of reducing the risks to hearing by providing a better, quieter, listening environment for users, enabling them to reduce the volume level of the communication signal. This observation was found especially when the crew members had experience with the headset. With one particular ANR device, crew members were able to reduce at-ear sound levels by more than 11 dB on average.

Call and communication centers

Several studies focused on noise exposure from communication headsets worn in office settings by call center agents and telephone operators. Background noise present in offices is typically caused by human activity (e.g., phone calls), office equipment (e.g., computers), building indoor installations (e.g., ventilation system), and outdoor noise (e.g., traffic) and can be annoying and harmful to the workers [49]. The noise exposure of these workers can also include high level intermittent squeals in the communication network.

Chiusano and colleagues [17] studied a group of 37 workers at a U.S. Department of Defense facility who wore a headset continuously throughout their work shift. Noise exposure was assessed in real ears where the subminiature microphone tip was placed at the entrance of the ear canal. Equivalent continuous sound levels, not converted to free field, ranged from 80 to 104 dBA with maximum peak values ranging from 119 to 149 dB SPL. Based on these results, the authors proposed recommendations to develop a noise hazard awareness training program to meet the needs of these workers. Patel and Broughton [63] assessed the noise exposure of call center operators through measurements of background noise levels, at-ear noise levels generated by the headsets, and information on typical working patterns of 150 operators at 15 call centers in the United Kingdom. At-ear measurements were taken using the KEMAR manikin and converted to the sound field according to the transfer function described by Rice and colleagues [68]. Daily noise exposure varied from 67 to 84 dBA. Likewise, Peretti and colleagues [64] reported measurements at a tape-recording division of a newspaper, at a telephone central office of a government organization, and at a bank call center using the Brüel & Kjaer head and torso simulator (HATS). Diffuse-field related equivalent continuous sound levels were between 50 and 87 dBA. In a similar study by the French National Research and Safety Institute, Planeau [65] used the Brüel & Kjaer Type 4152 artificial ear to measure noise levels in 24 call centers across a range of industry sectors. Participants also answered a questionnaire on their preferred volume setting.

Twenty-seven percent of operators who responded to the questionnaire and participated in the study were exposed daily to more than 85 dBA. A 5 dB uncertainty was estimated due to the headset position on the artificial ear and the variability of the transfer function.

More recently, Smagowska [69] reported noise levels at call center workstations. Measurements were carried out with a miniature microphone placed at the entrance of the external ear canal according to ISO 11904-1 [38]. Daily noise exposure ranged from 62 to 87 dBA and results showed that background noise at call center workstations can be an annoying factor contributing to hearing loss in some cases. Trompette and Chatillon [78] measured headset sound levels in 117 operators in 21 call centers in France. A CORTEX manikin fitted with a Type 3.3 artificial ear and pinna was used to conduct measurements. Headset diffuse-field equivalent levels ranged from 60 to 90 dBA in background noise ranging from 50 to 62 dBA. While there were complaints reported by the operators regarding background noise, the study did not show a correlation between headset sound levels and background noise; however, this may be due to several factors including the narrow range of background noise levels [32].

Other studies

Williams and Presbury [82] conducted a study on the noise exposure of radio announcers. These workers must monitor their own voice for quality control while simultaneously receiving an audio signal from program producers in their headphones. Measurements were obtained by placing an identical headset, connected in parallel to the one in use, on a Brüel & Kjaer Type 4152 artificial ear attached to a sound level meter. An 8 dB single number correction factor derived by Macrae [51] and specified in AS/NZS 1269.1 [6] was used to convert at-ear levels to the sound field. Noise levels varied across individual announcers and some announcers were exposed to levels that represent a potential risk to their hearing.

Lastly, a report was released by the National Institute for Occupational Safety and Health (NIOSH) in response to a request for a health hazard evaluation at the Anchorage Fire Department (AFD) in Alaska [14]. Concerns on the feedback noise and squeals from communication headsets were expressed by dispatchers. In a laboratory setting, recordings of feedback noise such as spikes and squeals from headsets were played back into a KEMAR manikin. Results showed that daily exposure of dispatchers at the AFD facility did not exceed the NIOSH regulations and were not considered hazardous. The study concluded that by reducing background noise, dispatchers would be able to reduce headset volumes, reducing the risk for high level squeals from the headset and therefore minimizing the risks of prolonged and repeated exposure to peak sound levels.

2.3.2 Review of measurement methods

As surveyed above, several measurement and analysis methods were developed over the years to measure noise exposure from communication headsets. The following section presents the challenges and issues that emerge when attempting to take measurements of noise sources under occluded ears as well as the course that has led to existing measurement standards.

Measurement challenges

Several issues related to field logistics, measurement tools, and data transformation arise when conducting measurements of noise exposure under headsets. Firstly, workers wearing communication headsets are exposed to the external background noise around them and the internal audio communication signals from their device, and both may contribute to the total noise exposure (Figure 2.5). However, these two sources are not independent. Users naturally adjust the volume setting of their headset to ensure proper reception of the speech or audio signal above the noise entering the device. Secondly, sound from the headset is produced at or in the ears, and the acousto-mechanical properties of the head, pinna, and ear canal must be considered. Typical noise measurement procedures using sound level meters and dosimeters become unsuitable, and in-ear recording techniques are required. Thirdly, in order to achieve a valid assessment, measurements must be carried out in a safe manner while workers are conducting their normal duties. Finally, the in-ear data collected must be converted to sound field equivalent levels to enable comparison with occupational noise limits.

Figure 2.5: *Interdependent factors: Residual noise and communication signal related to external noise [26, 50].*

Standardization efforts

Several national and international standards, such as ANSI/ASA S12.19-1996 R2011 [4], CSA Z107.56-13 [22], and ISO 9612:2009 [48], describe procedures for the measurement of occupational noise exposure. These standards focus on exposure measurements from sound sources at a certain distance from the body. Procedures described in these standards require that the noise measuring microphone be kept away from the ear, and attached on the shoulder or fixed on a tripod near the position of the worker. Consequently, they are unsuitable for the measurement of noise exposure under headsets where sound sources are purposely very close to the ear. Specialized equipment and techniques are required for direct measurements under occluded ears and sound transformation procedures are needed to compare results to regulatory limits which refer to the sound field at the position of the worker.

Early studies of exposure from communication headsets used a wide diversity of measurement methodologies and procedures to transform at-ear measurements to the sound field. Barron and Associates [8, 9] were one of the first to use the Microphone in a Real Ear (MIRE) technique for this application. The equipment consisted of a miniature microphone placed at the entrance of the ear canal and an electrical filter that restored the signal to the equivalent diffuse sound field. The MIRE technique provides the most direct estimate of the worker's sound exposure and is believed to possess the best face validity [6]. However, the method is invasive and can restrict head and body movements of the worker, and so it may be difficult to implement in a real workplace for a sustained period of time. Also, special expertise is required to position the miniature or probe microphone accurately and safely in the ear canal of workers and without sound leakage. The University of Toronto studies [26, 50], on the other hand, exemplify an early use of an acoustic manikin for measurements under headsets. The method requires two headset units with identical signal output, one headset worn by the worker and the other placed on the manikin positioned near the worker in the same background noise. Manikin measurements are then transformed to the equivalent diffuse sound field using post-hoc third-octave band level corrections [50] or through a compensation filter in the measurement chain [26]. The worker is free from the measurement apparatus with this method, but the field logistics and manikin handling can be cumbersome in practice, and also the equipment is not widely available.

In parallel, laboratory studies on the head-related transfer functions of the human ear led to the specification of third-octave band procedures for the conversion of MIRE and manikin measurements to the free or diffuse sound field arising from sources close to the ear; both methods described by the International Organization for Standardization. ISO 11904-1 [38] applies to MIRE measurements obtained using miniature or probe microphones inserted in the real ear of subjects. ISO 11904-2 [39] applies to sound level measurements using a standardized acoustic manikin with embedded ear simulator and associated microphone. It is important to note, however, that both standards focus on sound data transformations procedures. Recently, the Canadian standard CSA Z107.56 [22] put additional emphasis on the field logistics while conducting headset sound measurements in the workplace. Likewise, document ETSI EG 202 518 V1.2.1 [28] by the European Telecommunications Standards Institute provides detailed guidance on conducting noise exposure measurements for users of handset or headset terminal equipment.

Van Moorhem and colleagues [54] also devised an indirect procedure for measuring noise exposure of individuals who wear communication headsets. Firstly, the electrical-to-acoustic transfer function of the headset is determined with a KEMAR manikin in a laboratory setting and, together with the diffuse-field correction of the manikin, a correction filter is derived. Then, field measurements are conducted where the electrical signal to the headset is recorded and processed through the correction filter to obtain the sound field related exposure. This system eliminates the need for the use of a probe microphone placed in the worker's ear or use of a manikin in the field, but the method assumes linear transmission through the headset. A version of this technique is included in the Occupational Safety and Health Administration (OSHA) Technical Manual (Section III, Chapter 5, Section III, Appendix F) [59] and the Australian/New Zealand standard AS/NZS 1269.1 [6]. This indirect method has also been proposed in the guide ETSI EG 202 518 V1.2.1 [28] when large scale monitoring of call center agents is needed.

Other researchers, like Macrae [51], looked at formalizing simpler procedures and field equipment to complement real-ear and manikin methods. For supra-aural and circum-aural headphones, the use of a general-purpose artificial ear was proposed in conjunction with a single number correction of 8 dB to convert measurements to equivalent diffuse-field levels. For insert earphones, an occluded ear simulator was proposed with a single number correction of 5 dB. These provisions are included in the Australian/New Zealand standard AS/NZS 1269.1 [6]. In terms of the artificial ear procedure, it is less expensive, more practical, and more accessible [51]. However, the validity of these simpler procedures for sound measurements under headsets is uncertain, and the degree of agreement with more established real-ear and manikin methods is largely unknown [32].

Finally, in response to the many technical and logistical challenges that present themselves when making direct measurements under communication headsets in occupational settings, the Canadian standard CSA Z107.56 [22] recently introduced a simple method based on the principle that the exposure can be estimated from the external background noise level (BN) and the noise reduction of the device (NR) on the basis of the relationship between the listening volume set by the user and the residual noise under the headset (Figure 2.5). This method only requires the use of a sound level meter or noise dosimeter and computation steps based on an equation summing up sound levels from two sources: the residual noise under the headset and the communication signal. To estimate the latter, a listening signal-to-noise ratio (SNR) of 15 dB above the residual noise is assumed based on an analysis of previous field studies [32]. While this method does not provide a direct measurement under the headset, it can be useful in the early stage of an assessment or for screening purposes.

2.4 Summary

This chapter presented N-IHL in the workplace, described HLPPs at each level of the framework, and reviewed literature on communication headsets in occupational settings and related noise measurement methods. The use of these headsets presents various challenges with respect to the HLPP framework (Figure 2.2), in particular at the noise measurement and education levels. Exposure to sound under headphones and headsets has long been known as a complicated issue. Over the years, different measurement methods have been used to assess noise exposure under these devices worn in various workplace environments. A review of previous studies indicates that noise exposure often depends on the external background noise and could exceed regulatory limits in some cases. While several methods are proposed in national and international standards, few studies have used more than one method to conduct measurements. Therefore, the compatibility and test-retest reliability of the various measurement methods have yet to be explored. Furthermore, both frequency-dependent transformations (third-octave, compensation filter) and single number corrections have been used to convert measurements to sound field equivalent levels, but the increase in measurement uncertainty associated with the latter simpler procedure has not been established. Finally, knowledge of stakeholders in hearing loss prevention and occupational health and safety on the various measurement tools and methods for communication headsets remain unknown as well as access to the necessary equipment by these specialists. In order to provide proper training and guidelines to educate these stakeholders, such information in necessary. These gaps warrant further investigation of the problem of communication headset use in the workplace and related noise measurements under these devices.

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Chapter 3

Questionnaire to Stakeholders

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Keywords: communication headsets, measurements, acoustic manikin, artificial ears

Ethics certificate: H03-12-09

Some of the findings of this article were presented at a professional development course [5] and were included in a poster presentation [9]. This chapter has been the subject of a journal publication:

- Nassrallah, F., Giguère, C., & Dajani, H. R. (2014). Communication headsets in the workplace: Accessibility to noise exposure measurement in Canada. *Canadian Acoustics*, *42(4)*, 15-21.

Abstract

Use of communication headsets and other wearable listening devices can contribute to increased noise exposure at the workplace as users are subjected to both the audio signal from the headset and the surrounding external noise. Two specialized methods are described in ISO 11904 for direct measurement of sound exposure from communication headsets: the Microphone in a Real Ear and the acoustic manikin. Other standards also propose the use of simpler artificial-ear procedures or an indirect calculation method (AS/NZS 1269.1, CSA Z107.56). However, there is currently little information related to the use of all these methods by researchers, audiologists, occupational hygienists, and other relevant professionals. A questionnaire was distributed to stakeholders in occupational health and safety and hearing loss prevention in Canada to document their awareness of the problem, their knowledge of the different measurement tools, and their access to this equipment. Results illustrate that knowledge of specialized measurement techniques and access to the necessary equipment varies significantly depending on the type of training of the different professionals. This survey therefore validates the need to propose several methods in measurement standards to assess noise exposure from communication headset to serve the needs of the different groups of professionals.

3.1 Introduction

Noise-induced hearing loss is often the result of a noisy workplace and is the second most prevalent self-reported work-related injury [11, 12]. Twenty-two million Americans are subjected to hazardous noise levels in their workplace [15]. It has also been estimated that three million Americans can be exposed to high levels of noise due to their use of headsets on the job [13]. Similar figures are currently not available for the Canadian population. Nevertheless, in the past decade, there has been an increase in the use of wired and wireless headsets in various occupational settings worldwide, e.g. in call centres, retail stores and fast food outlets, airport ground and control tower operations, industrial and construction sites, military sites, law-enforcement agencies, etc [6, 10]. Some workers wear noise-reducing headsets or advanced technologies, as exemplified by airline pilots or military personnel, to attenuate the very noisy background and enhance the communication signal. Others, such as call center operators, use hands-free communication headsets or low attenuation devices in an environment where background noise is not as significant.

Several factors ranging from field logistics to data transformation arise when conducting measurements of noise exposure from headsets [2, 6, 10]. Firstly, workers wearing communication headsets are simultaneously exposed to two sound sources both contributing to the total exposure level: the surrounding workplace noise passing through the headset and the internal audio signals from the device. Secondly, since sound from the headset is produced at or in the ears, the acousto-mechanical properties of the head, pinna, and ear canal must be considered. Thirdly, in order to achieve a valid assessment, measurements must be carried out in a safe manner while workers are conducting their normal duties. Lastly, after the data is collected, in-ear measurements must be converted to the sound field to enable comparison with occupational noise limits.

As a result of the above factors, and in contrast to general noise measurements surveys conducted with a sound level meter or dosimeter, specialized equipment and techniques are required for occluded-ear sound measurements from communication headsets. Over the last forty years, several studies have focused on noise assessments from communication headsets in various occupational settings using a range of measurement methods [10]. Results from these field studies indicated that noise exposure was often dependent on external background noise and in some cases exceeded regulatory limits.

A range of noise exposure assessment methods, varying widely in complexity and required expertise, have been proposed by different standardization bodies [2, 6, 10]. The International Organization for Standardization describes two techniques for noise measurements under occluded ears: the Microphone in a Real Ear or MIRE (ISO 11904-1) and the acoustic manikin (ISO 11904-2) [7, 8]. Alternative methods using ear simulators and artificial ear procedures have also been standardized (AS/NZS 1269.1, CSA Z107.56) [1, 4]. All these techniques are specified in the recently revised CSA Z107.56 standard [4]. In addition, this Canadian standard also specifies an indirect calculation method requiring only a sound level meter or noise dosimeter, and necessitating much less expertise.

Stakeholders in occupational health and safety (OHS) and related professionals in hearing loss prevention (HLP) face the constraint of having little access to resources to conduct noise exposure measurements from communication headsets. It is not known if these stakeholders and professionals have access to specialized equipment or if simpler techniques using a sound level meter or noise dosimeter could fill a gap in measurement accessibility.

The goal of this paper is to report on a survey of OHS and HLP professionals in Canada in order to document their awareness on the issue of communication headset noise exposure, their knowledge on the different measurement tools available, and their access to basic and specialized equipment. Stakeholders that may have encountered situations where communication headsets were worn include audiologists, occupational hygienists, health and safety consultants, acoustical consultants, health workers, and other relevant individuals responsible for health and safety in their workplace. Survey results could guide future revisions of noise exposure measurement standards and suggest guidelines on the best practices to adopt according to available resources and the specific training of the various stakeholders.

3.2 Methods

3.2.1 Questionnaire development

A bilingual questionnaire was created focusing on several issues including the level of awareness on the methods of noise exposure assessment with communication headsets, and the access to measurement equipment among OHS and HLP stakeholders in Canada. The English version of the questionnaire was carefully reviewed by three experts in noise in the workplace: two professors in Audiology and Speech-Language Pathology and one professor in Electrical Engineering. The French version of the questionnaire was also reviewed by three experts in the field: two audiologists and one professor in Audiology and Speech-Language Pathology. Both versions were adapted accordingly and comments were integrated to define the final questions. The questionnaire was finalized following a review by a researcher in acoustics and noise.

A total of twenty-five multiple choice, checkbox, and open text box questions were prepared and entered in an online-based platform, FluidSurveys, to create a four-part bilingual questionnaire entitled *Communication Headsets; Use and Noise Measurement in the Workplace / Casques de communication; L'utilisation en milieu de travail et la mesure d'exposition au bruit associée.* The content of the first part, *General Information*, was designed to gather demographic information about the experience, training, and workplace of the respondents. The second section of the questionnaire, *Noise Measurement in the Workplace*, captured their level of awareness on hearing loss prevention and use of communication headsets in the workplace, their knowledge on measurement techniques as well as their access to measurement equipment. The third section of the questionnaire, *Experience in Noise Measurement under Communication Headsets in the Workplace*, was only answered by individuals who confirmed having taken communication headset measurements at least once during their career. The fourth part of the questionnaire surveyed respondents on their opinions regarding the *Availability of Information on Communication Headset Usage in the Workplace.* Table 3.1 provides the complete list of questions.

3.2.2 Questionnaire distribution

The questionnaire was delivered to the widest possible array of OHS and HLP stakeholders in Canada covering researchers, practitioners, consultants, and regulators during a seven month period, from May 2013 to November 2013. Associations, professional groups, and other organizations involved in workplace health and safety, hearing loss prevention, and/or occupational noise measurements were targeted. The questionnaire was distributed by the following means: requests through email to a network of the researchers' contacts, hard copies handed-in at professional events, direct requests to members of associations, and invitations through third-party distribution lists via email and/or electronic news bulletins. Table 3.2 provides the complete list of professional groups, associations and organizations contacted, as well as the events attended, and the respective means of distribution of the questionnaire.

Table 3.1: *Complete list of items presented in the questionnaire.*

General information / Renseignements généraux	
Professional training (college/university degree(s), ...).	Open text box
Health and safety training specific to noise exposure, if any.	Open text box
Current workplace (specify if it is in the public or private sector).	Open text box
Current position title.	Open text box
Number of years of experience in health and safety in the workplace.	Open text box
Number of years of experience in health and safety specific to noise exposure in the workplace.	Open text box
Role with regard to health and safety in the workplace.	Multiple choice
Noise measurement in the workplace / Mesure du bruit dans le milieu de travail	
How would you judge your level of awareness on noise measurement and hearing loss prevention in the workplace?	Multiple choice
Do you have access to basic equipment (e.g., sound level meter, dosimeter) to measure noise levels in the workplace?	Multiple choice
Select all the equipment that applies and specify the type/manufacturer/model.	Checkboxes
How would you judge your level of awareness on the problem of noise exposure from the use of communication headsets in the workplace?	Multiple choice
How would you judge your level of awareness on the techniques of noise measurement under headphones and communication headsets, more specifically using an acoustic manikin, a microphone in a real ear, or artificial ears?	Multiple choice
Do you have access to specialized equipment (e.g., acoustic manikin, artificial ear, microphone in a real ear) to measure noise levels of sound sources close to the ear (e.g., communication headsets, earphones, hearing aids, etc)?	Multiple choice
Select all the equipment that applies and specify the type/manufacturer/model.	Checkboxes
Have you ever done interventions (e.g., measurements, discussions, proper headset selection) with regard to the use of communication headset in the workplace?	Multiple choice
During your interventions, have you taken measurements of noise exposure under communication headsets?	Multiple choice
Experience in noise measurement under communication headsets in the workplace / *Expérience de mesure du bruit sous les casques de communication en milieu de travail*	
Please select all the workplace environments where you have taken noise exposure measurements from communication headsets.	Checkboxes
In total throughout your career, for approximately how many workers have you taken noise exposure measurements under communication headsets?	Multiple choice
Under which types of communication headset configuration have you taken measurements?	Checkboxes
Under which types of earphones on the communication headsets have you taken measurements?	Checkboxes
Did the communication headsets have the following elements? (Three elements listed in questionnaire)	Multiple choice
What equipment have you used to measure noise exposure under communication headsets?	Checkboxes
Did you correct the measured values to be representative of the worker's exposure? (Three types of corrections listed in questionnaire)	Multiple choice
Did the results obtained from the noise exposure measurements demonstrate that an intervention programme should be put in place in this/these workplace(s)? (Four types of interventions listed in questionnaire)	Multiple choice
Please provide additional information on your experience measuring noise under communication headsets in the workplace.	Open text box
Availability of information on communication headset usage in the workplace / *Accès à l'information sur les casques de communication en milieu de travail*	
Do you see value in increasing the spread of information on communication headsets, noise measurement methods under these devices, and the safe use of these devices, to individuals in the field of health and safety in the workplace?	Open text box
What do you think would be the best way to spread this information to individuals in the field of health and safety? (e.g., workshops, information sheets, etc.).	Open text box Open text box

Table 3.2: *Associations, professional groups and organizations contacted, events attended, and means of distribution of the questionnaire.*

Association/group/event	Distribution method of questionnaire
Academics from different universities	Email to a network of contacts
Canadian Association of Speech-Language Pathologists and Audiologists	Email to members through a third party via a monthly issue of an electronic newsletter
Canadian Audiology Association (CAA)	Email to members through a third party
Canadian Center for Occupational Health and Safety (CCOHS)	Email to a distribution list
Canadian Hearing Report	Email to a distribution list through a third party via a monthly issue of an eletronic newsletter. Also posted on social media
Canadian Registration Board of Occupational Hygienists (CRBOH)	Email to contacts
Occupational Hygiene Association of Ontario (OHAO)	Email to members through a third party via a monthly electronic news bulletin
Occupational Hygiene Association of Ontario (OHAO) professional development course attendants	Distribution to event participants
Occupational hygienists in the province of Quebec	Email to contacts through a third party
Ordre des orthophonistes et audiologistes du Québec (OOAQ)	Email to members through a third party via a monthly info-letter
Ordre des orthophonistes et audiologistes du Québec (OOAQ) Colloquium on Hearing Loss in the Workplace	Distribution to event participants
Standardization/Technical committee members	Email to a netword of contacts
Sustaining subscribers of the Canadian Acoustical Association	Email to contacts

Distribution of the questionnaire was approved by the Office of Research Ethics and Integrity at the University of Ottawa. Within the FluidSurveys platform, the identity of the respondents of the questionnaire is anonymous. Due to third party distribution, the total number of OHS and HLP stakeholders reached is unknown. From 2009 to 2011, there were approximately 2600 audiologists and speech-language pathologists on record according to Service Canada [14]. Also, based on a Cross Canada Survey conducted in 2010, there were 1760 reported occupational hygienists [3]. The proportion of these professionals active in HLP is however not documented.

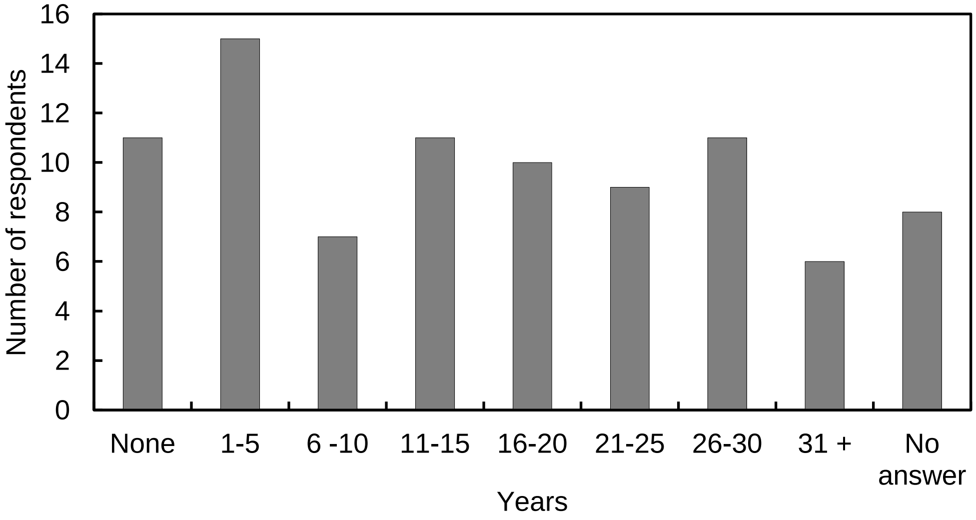

Figure 3.1: *Distribution of the number of years of experience of respondents in health and safety in the workplace (n = 88).*

3.3 Results

In all, 93 questionnaires were completed and received. Five questionnaires were removed due to missing information or because they were deemed from an ineligible source (e.g., outside of the country). A total of 88 questionnaires were considered in the data analysis.

3.3.1 General information

The respondents' experience in workplace health and safety was distributed nearly uniformly from no experience to over 31 years in the field (Figure 3.1). Different levels of responsibility were noted across respondents as they were asked to define their role with regard to health and safety (Table 3.3) within their respective workplaces (Table 3.4).

In terms of health and safety training specific to noise exposure, some respondents attested having taken a course in noise and hearing protection, safe exposure to noise, hearing conservation, noise measurements, or industrial noise reduction as part of their educational degree. Others attributed their specific training or knowledge on noise exposure to their work experience or collaborations. Approximately 10% of respondents noted having no formal training in this area.

Table 3.3: *Role of respondents with regard to OHS in the workplace (n = 88).*

Role	Respondents
Health and safety consultant	9
Acoustical consultant	8
Responsible for health and safety in my workplace	22
Health worker - Public health sector	21
Health worker - Provincial workplace compensation board	5
Professor or researcher	10
Health worker in private sector	3
Combination of two or more of the roles above	3
Other/Unspecified	6
No answer	1

Based on the diversity of respondents' professional training, current workplace (Table 3.4), number of years of experience in health and safety in the workplace (Figure 3.1), and role with regard to health and safety in their workplace (Table 3.3), respondents were grouped into four distinct types for subsequent analyses: *Researchers* (n = 14), *Audiologists* (n = 32), *Occupational Hygienists* (n = 18), and *Others* (n = 24). Individuals in the *Researchers* category were of various educational levels (nine doctoral degrees, two master's degrees, one medical doctor, and two bachelor's degrees) and conducted research in academia or governmental settings in acoustics, noise control, health and safety, or related fields. *Audiologists* were defined as individuals with formal university training in Audiology and who were active practitioners. Of these respondents, thirty-one had a master's degree in Audiology and one had a master's degree in Speech-Language Pathology. The *Occupational Hygienists* category included individuals who had a background in health and safety management and control in the workplace, or related fields. Of these respondents, ten held a master's degree, two held a bachelor's degree, and six held a college diploma. The *Others* category was comprised of individuals involved in standardization bodies related to OHS and/or were acoustical consultants. Respondents in this heterogeneous group had attained various levels of education (one doctoral degree, four master's degrees, four bachelor's degrees, ten college diplomas, three with no postsecondary education).

Table 3.4: *Current workplace of respondents (n = 88).*

Sector	Workplace	Respondents
Public	University	9
	Workplace health and safety	7
	Transportation/utilities	9
	Health care/clinical	13
	Other/unspecified	28
Private	Health care/clinical	9
	Company/manufacturer/plant	13

3.3.2 Noise measurement in the workplace

In the second part of the questionnaire, respondents were asked to provide information on their level of awareness on hearing loss prevention, on the problem of noise exposure from headsets, and on the techniques of noise measurement from headsets. Group results are presented in Figure 3.2.

Across groups, respondents generally assessed their level of awareness on noise measurement and hearing loss prevention in the workplace mainly from good to excellent (Figure 3.2). When asked more specifically about their level of awareness on the problem of noise exposure from the use of communication headsets, respondents reported having mostly little awareness on the topic (Figure 3.2). Regarding the specific techniques of noise measurement from communication headsets (e.g., acoustic manikin, microphone in a real ear, artificial ears), the level of awareness varied widely between groups (Figure 3.2). *Researchers* indicated that they had little to excellent awareness; *Audiologists* mostly little or good awareness; *Occupational Hygienists* and *Others* little or no awareness.

Access to basic equipment for the measurement of noise levels in the workplace and to specialized equipment for the measurement of sound sources close to the ears differed across categories of respondents (Table 3.5). At least one basic noise measurement tool (i.e., sound level meter and/or noise dosimeter) was accessible to all *Researchers*, all *Occupational Hygienists*, a third of the *Audiologists*, and half of the individuals in the *Others* group. Access to specialized equipment was not as common. Most *Researchers* (11/14) had access to an acoustic manikin, a type of artificial ear, and/or a MIRE system. About half of the

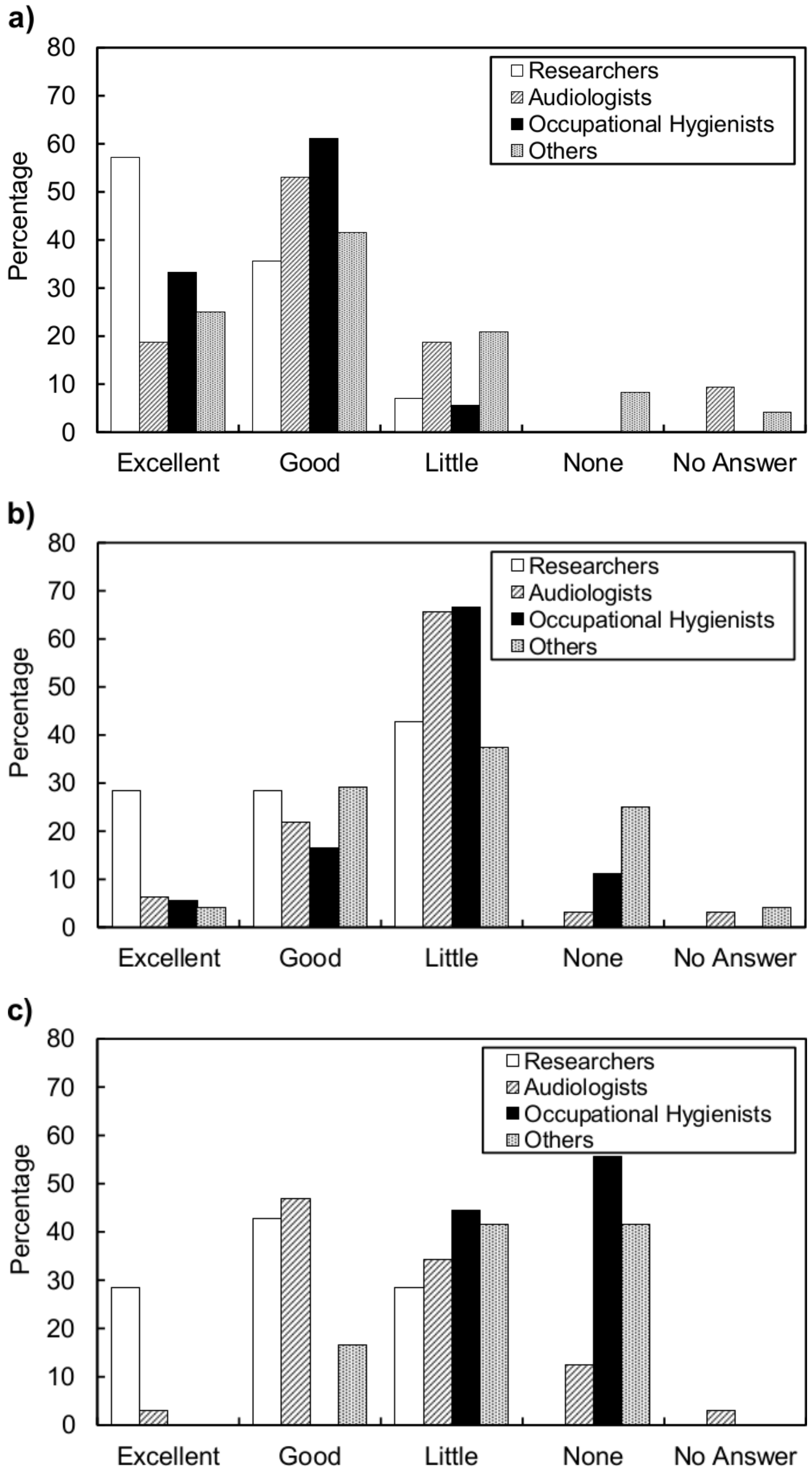

Figure 3.2: *Level of awareness on: a) noise measurement and hearing loss prevention in the workplace; b) the problem of noise exposure from the use of communication headsets in the workplace; and c) the techniques of noise measurement from headphones and communication headsets, more specifically using an acoustic manikin, a microphone in a real ear, or artificial ears.*

Table 3.5: *Access to basic (e.g., sound level meter, dosimeter) and specialized (e.g., acoustic manikin, microphone in a real ear, artificial ears) noise measurement equipment. Note: One audiologist did not answer the question on specialized equipment.*

Categories	Basic equipment		Specialized equipment	
	Yes	No	Yes	No
Researchers	14	0	11	3
Audiologists	11	21	14	17
Occupational hygienists	18	0	0	18
Others	12	12	3	21

Audiologists (14/31) had access to an acoustic manikin, a type of artificial ear or more predominantly to a MIRE system such as found in hearing aid electro-acoustic analysers (e.g., Verifit, Fonix, Affinity, OTOPro). Few individuals in *Others* (3/24) had access to an acoustic manikin, a type of artificial ear, or a MIRE system. None of the 18 *Occupational Hygienists* had access to any of these specialized measurement tools.

3.3.3 Noise measurement from communication headsets in the workplace

Respondents were asked about their experience carrying out interventions related to the use of communication headsets in the workplace (i.e., measurements, discussions on safe use of headsets, selection of headsets). Of the 88 respondents, 50 had never been involved in such situations. Among the remaining 38 individuals, only three respondents (two *Researchers*, one *Audiologist*) had carried out noise measurements from communication headsets in the workplace at least once during their career. These three cases specified having collected such measurements for a range of 1 to 35 workers in specific settings including call centers, airports, and/or in a clinical setting. The two *Researchers* respondents attested to the need for noise reduction interventions for some of the workplaces where they had conducted their measurements. They emphasized the importance of conducting such noise evaluations.

3.3.4 Information on communication headset usage in the workplace

In the last part of the questionnaire, respondents were asked about their views for spreading knowledge on noise measurement methods suitable for communication headsets in the workplace. Most respondents (96%) agreed that there is value in spreading information on this topic. Respondents commented on the lack of information and resources available to relevant OHS stakeholders on this problem. In particular, they indicated that there is a lack of information provided to, or discussed with, the workers.

Respondents indicated that there is a misconception of the risks involved in the use of communication headsets in occupational settings. Factors such as headset attenuation, signal to noise ratio, and daily duration of the signal in the headset, for example, are reported not being considered.

In order to increase the spread of knowledge on the problem of communication headsets in the workplace and related noise measurements, respondents suggested various methods of information diffusion. Firstly, one respondent mentioned that the standardization and regulation bodies could help diffuse the information. Secondly, several respondents indicated that stakeholders in OHS could be reached through such methods as formal group settings (e.g., conferences), written documents (e.g., information, brochures, articles in magazines and journals, websites), online media (e.g., webinars, videos), and professional development courses or active workshops. In addition, the benefit of including formal or online training and certification exams on the topic was noted. Thirdly, a few respondents mentioned that manufacturers and distributors could include more information on the safe use of communication headsets (e.g., with regard to signal to noise ratio) with their products.

3.4 Discussion

Due to complicated field logistics, specialized measurement tools, and complex data transformation steps, measurement of sound under headphones and headsets is a challenging task. In anticipation of the measurement difficulties and the wide range of expertise of potential users of the measurement tools, CSA Z107.56 [4] defined several methodologies for noise measurements from communication headsets. At the time of publication of the revision of the standard in August 2013, little information was known about the prospective users of the different measurement methods. The present study, carried out from May 2013 to November 2013, documents the level of expertise of OHS and HLP stakeholders in Canada for making noise measurements with headsets, and the accessibility of basic and specialized equipment by these potential users of the standard. More specifically, this work allows gaining more insight into the different needs and technical expertise among relevant stakeholders in the field of health and safety or hearing loss prevention in Canada.

Results from the questionnaire indicated that knowledge on the techniques of noise measurement with communication headsets and access to specialized equipment varies significantly according to the different types of stakeholders in OHS and HLP (i.e., *Researchers, Audiologist, Occupational Hygienists, Others*). While most *Researchers* have access to some form of specialized equipment (e.g., acoustic manikin, artificial ear, MIRE, and/or F-MIRE), other specialized tools are more accessible to *Audiologists* (e.g., hearing aid analysers). In contrast, *Occupational Hygienists* did not report having access to any specialized measurement tool (Table 3.5). Still, this group of professionals may be required by their task description to take noise measurements in occupational settings including the assessment of noise from communication headsets. However, given their good overall awareness of issues pertaining to noise measurement and hearing loss prevention (Figure 3.2), and their access to basic measurement equipment such as a noise dosimeter or sound level meter (Table 3.5), an alternative measurement method is warranted for these professionals. To fill this need, CSA Z107.56 proposes a simple calculation method that requires the use of a sound level meter or noise dosimeter and computation steps based on an equation that considers the external background noise level, the noise reduction of the device, and the relationship between the listening volume set by the user and the residual noise under the headset [4]. On the other hand, *Audiologists* and *Researchers* may find specialized measurement methods to be more suitable for their needs. Given the heterogeneous characteristics of the participants in the *Others* category (primarily individuals involved in standardization bodies related to OHS and acoustical consultants), it is difficult to anticipate their preferred measurement method. However, only 13% of them reported having access to specialized equipment and the CSA Z107.56 [4] calculation method may also be warranted for this group.

The results of this survey therefore validate the need to propose several direct specialized methods and indirect calculation procedures for communication headset noise exposure assessments, tailored to different groups of professionals and taking into account their respective role, expertise, and access to equipment.

3.5 Conclusion

In general, there is a wide range of expertise regarding noise measurement from communication headsets. Furthermore, access to basic and specialized equipment varies across the different types of professionals in Canada. Despite the diversity of training across OHS and HLP stakeholders that can be involved in communication headset interventions, there is certain homogeneity within groups of professionals. This validates the need to develop guidelines and training material specific to each group of stakeholders. Further research is also needed regarding the compatibility of the different measurement methods, which is largely un-documented.

3.6 Acknowledgements

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Chapter 4

Comparison of Direct Measurement Methods - Pilot Study

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Ethics certificate: H04-10-08

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Abstract

Specialized equipment and techniques are required to carry out sound measurements under occluded ears for the purpose of assessing the noise exposure from communication headsets. Standard ISO 11904 describes two procedures: 1) the Microphone in a Real Ear (MIRE) and 2) the acoustic manikin technique using an occluded ear simulator IEC 60318-4. Methods using simpler artificial ears, such as IEC 60318-1, have also been proposed in national occupational noise measurement standards. Such fixtures are more practical to use and more easily accessible. However, they have not been designed specifically for noise measurements under communication headsets and there is little comparative data to the manikin technique, which is considered the gold standard for simulated in-situ acoustic measurements. Fit-refit measurements were obtained under laboratory conditions with four measurement setups (artificial ear Type 1, Type 2, Type 3.3, and acoustic manikin), three communication headset types (circum-aural, supra-aural, intra-aural) and six different communication signals. Data were transformed into equivalent-diffuse sound levels using third-octave procedures as well as single number corrections. Overall, results across measurement setups are in good agreement, except for the Type 1 artificial ear, but single number corrections reduce measurement accuracy.

4.1 Introduction

According to the U.S. National Health and Nutrition Examination Survey, 10 million workers suffer from occupational noise-induced hearing loss, the second most prevalent self-reported work-related injury [3, 17]. Among other factors, the increased use of wired and wireless communication devices is raising concerns regarding exposure to potentially hazardous noise levels [19]. Communication headsets are commonly found in workplace settings such as, call centers, retail stores, fast food outlets, airport ground and control tower operations, industrial and construction sites, military sites, etc. [7]. They can be worn, for example, to attenuate a noisy background while enhancing the received communication signal, or to enable hands free communication in a less noisy environment [21]. While their use in occupational settings varies, in all cases the worker is exposed to the surrounding workplace noise as well as to the audio communication signals from the headset.

Given the increased use of these devices in the last decade, proper measurement tools and methods are required to assess noise exposure from communication headsets usage in the workplace. However, several challenges arise when carrying out an assessment of noise exposure under headsets. Firstly, when a device is occluding the ear, measurements become dependent on the acousto-mechanical properties of the head, pinna, and ear canal [5], and in-ear recording techniques are required [7]. Secondly, since the assessment of noise exposure specified in occupational standards is based on free field measurements, in-ear measurements must be converted to the free field in order to enable a comparison with legislated exposure limits [5, 7]. Thirdly, both the audio signals generated by the headset and the external background noise passing through the headset contribute to the total noise exposure and must be taken into account. Finally, the worker must be able to operate normally during the field recording period to achieve a valid assessment under realistic working conditions. In response to these challenges, specialized equipment and techniques are required to carry out direct sound measurements under communication headsets [7].

Most standards for the measurement of noise exposure in the workplace are applicable for sources far from the ear (CSA Z107.56 [4], ANSI/ASA S12.19 [1], ISO 9612 [13]), but ISO 11904 [11, 12] describes two methods for measurement of noise for sources close to the ears.

Firstly, ISO 11904-1 [11] defines a Microphone in a Real Ear (MIRE) method where acoustic measurements are realized by using miniature or probe microphones inserted in the ear of workers and then converted to equivalent free-field or diffuse-field levels. This method provides a most direct estimate of noise exposure and likely has the best face validity [2]. However, its invasive nature could restrict body movements and it could be resisted by the workers.

Secondly, ISO 11904-2 [12] defines sounds measurements taken with an acoustic manikin comprising an embedded ear simulator (Figure 4.1). The manikin's proportions are based on human averages, allowing a simulation of the acousto-mechanical properties of the

Figure 4.1: *Devices used to measure noise levels under communication headsets. a) KEMAR acoustic manikin - G.R.A.S., 45BA - (Permission to reproduce this image was granted from G.R.A.S.), b) Type 1 artificial ear - Brüel & Kjaer, 4153 - (Copyright ©Brüel & Kjaer), c) Type 2 artificial ear - G.R.A.S., RA0045 - (Permission to reproduce this image was granted from G.R.A.S.), and d) Type 3.3 artificial ear - G.R.A.S., 43AG - (Permission to reproduce this image was granted from G.R.A.S.).*

torso, head, pinna, and ear canal. For sound exposure measurements in the field, both the worker and the manikin, placed in close proximity, must wear a matched pair of the same headset [5, 7]. Alternatively, the electrical signal feeding the worker's headset can be recorded in the field and played back on the manikin in a laboratory setting or filtered by the electrical-to-acoustical transfer function of the headset [2, 18]. With either setup, the worker can carry out tasks normally while the noise levels are being recorded. Manikin sound pressure levels are typically analyzed in one-third octave bands and converted to the free or diffuse field using one-third octave band conversion factors [12]. The resulting free or diffuse-field related sound level is reported in dBA where it can be compared to the legislated limit. Single number corrections applied to A-weighted manikin measurements have also been proposed [2, 16].

The manikin method can be cumbersome and the instrumentation required is not widely available. To simplify the measurement and analysis procedures, the Australian/New Zealand Standard AS/NZS 1269.1 [2] specifies the use of a general-purpose artificial ear (IEC 60318-1 [9], a Type 1 artificial ear under ITU-T P.57 [14]) for headphones and of an ear simulator (IEC 60318-4 [10], a Type 2 artificial ear under ITU-T P.57 [14]) for insert earphones, in conjunction with single number corrections [16]. While these provisions offer a more practical alternative to using a manikin and carrying out one-third octave band sound field conversions, the impact of these simplifications is largely unknown. Use of the

Type 3.3 artificial ear (ITU-T P.57 [14]) is another alternative to carry out communication headset sound measurements (Figure 4.1) [7].

Little is known about the degree of agreement between the various test measurement setups and sound field conversion procedures that have been proposed to conduct noise measurements under communication headsets. The goal of this study is to examine 1) if the different measurement setups produce the same equivalent diffuse-field level, 2) if the fitting method affects measurements, and 3) if single number and one-third octave band sound field conversion methods are in agreement.

4.2 Methods

4.2.1 Participants

A participant experienced in the fitting of earphones, hearing protectors and headsets on real ears, manikins, and artificial ear test measurement setups, was asked to perform 12 test-retests sound measurements with four headsets on four test setups.

4.2.2 Audio signals

A sound file was prepared consisting of the concatenation of four speech-like signals and two background noise-like signals, each signal separated by three seconds of silence. The four speech-like signals exemplify the acoustical characteristics of voice signals typically transmitted over communication channels. The two noise signals are examples of background noises that can be picked up and transmitted over noisy communication channels. The spectrum of each signal is presented in Figure 4.2. The different signals were as follows:

- ICRA 1: Continuous speech spectrum noise [6]
- ICRA 5: Modulated speech spectrum noise [6]
- IEC 60268-1: Speech-music programme-simulated noise [8]
- Hearing-In-Noise Test (HINT) sentences [20]

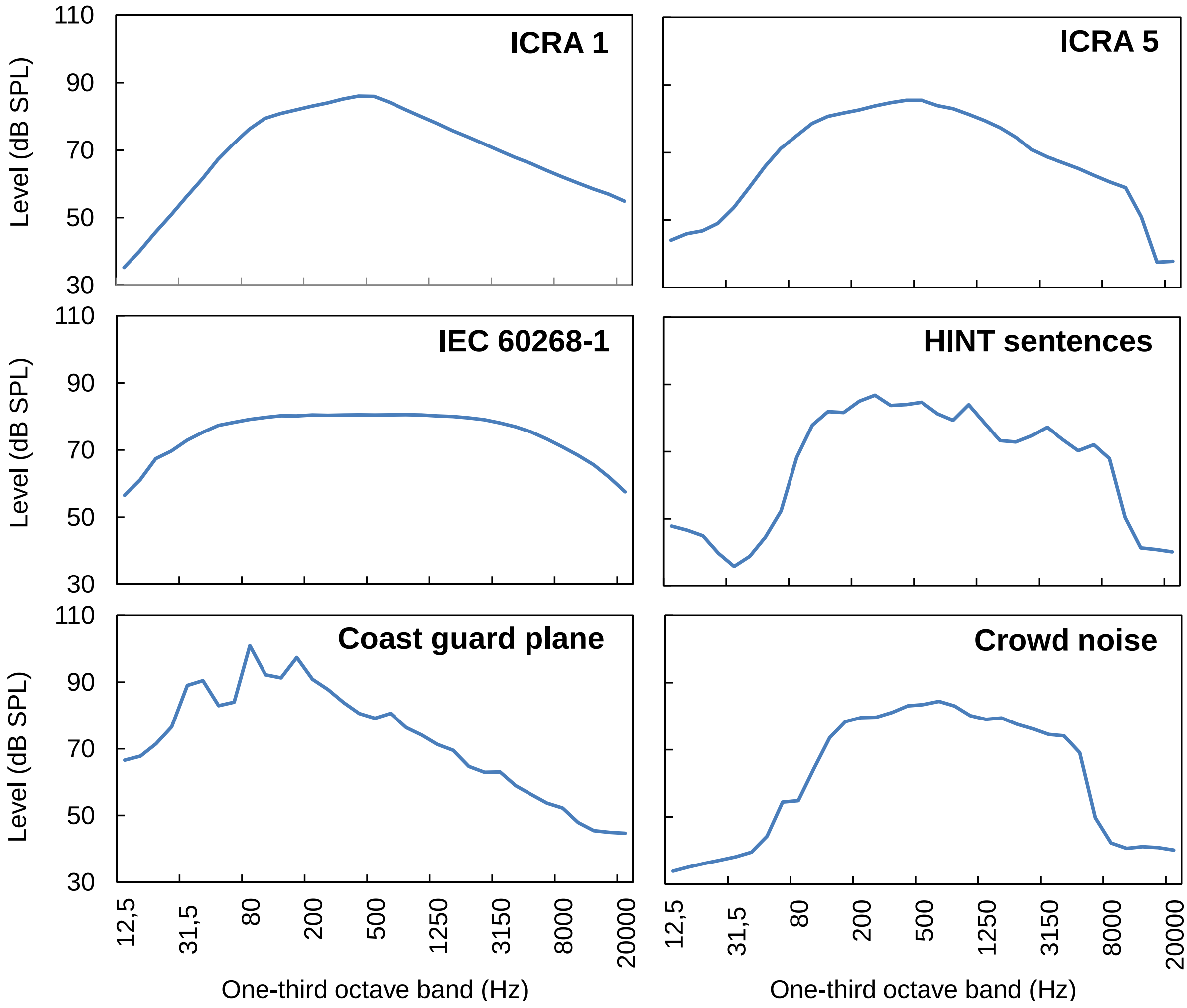

Figure 4.2: One-third octave band spectra for the six audio signals used in the study.

- Coast guard plane [15]
- Crowd noise [15]

Each signal was 30 seconds but only the first 10 seconds were used for analysis. The six signals were equalized to the same A-weighted level on the sound file.

4.2.3 Headsets

Four different headsets used in a wide range of occupation settings and applications were chosen for this experiment. The David Clark 40642G-01 circum-aural headset is designed

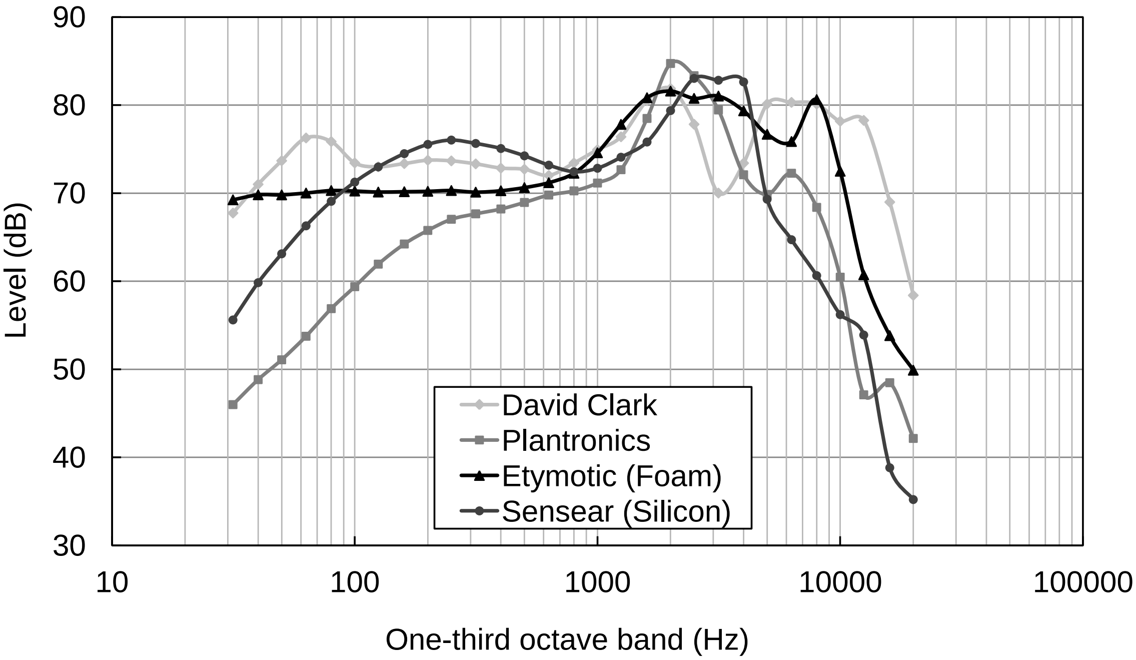

Figure 4.3: *Frequency response of the headsets measured on the KEMAR acoustic manikin.*

for high noise environments. The Plantronics HW261N supra-aural device is a telephone headset typically found in call centers. The Etymotic MC2 intral-aural headset works with tablets or smart phones. Finally, the Sensear Smart Plug SP1 with intral-aural foam or silicon ear tips is designed for high noise environments such as industrial, commercial, military, etc. The frequency response of these headsets, measured on the acoustic manikin using a pink noise audio signal, is within 5 dB in the range of 500-2500 Hz, but differences are more pronounced at higher and lower frequencies (Figure 4.3).

4.2.4 Procedure

All experiments were conducted under identical conditions in a laboratory setting in the Hearing Research Laboratory at the University of Ottawa. The experiment was approved by the Office of Research Ethics and Integrity of the university. In a soundproof room, the participant was asked to position the headsets on the test measurement setups (acoustic manikin, Type 3.3 artificial ear, Type 2 artificial ear, or Type 1 artificial ear). Measurements were taken for 12 fits of each headset-measurement setup combination (Table 4.1).

Table 4.1: *Combination of measurement setups and headsets tested with number of fitting methods for each case.*

Headset	Acoustic manikin	Artificial ear Type 3.3	Artificial ear Type 1	Artificial ear Type 2
David Clark 40642G-01	1	1	1	
Plantronics HW261N	1	2	3	
Etymotic MC2 - Foam ear tips	1	1		1
Sensear Smart Plug - Foam ear tips	1			
Sensear Smart Plug - Silicon ear tips	1	1		1

Headsets could be fitted in different ways on some measurement setups (Type 3.3 artificial ear and Type 1 artificial ear). To explore this effect, different fitting methods were investigated for one headset (Plantronics HW261N) as shown in Table 4.2.

Once the headset was placed on the test setup, a recording of the six audio signals was sent to the headset by means of an iPod touch player connected to an amplifier (Yamaha AV Receiver RX-A820). The volume of the amplifier was kept constant in all conditions (audio signal, measurement setup) for a given headset. The volume was adjusted to achieve an in-ear level of about 90 dBA (about 85 dBA after diffuse field conversion) to simulate loud noise sources that workers may encounter in the workplace. The sound generated by the headset was picked up by the microphone in the selected test measurement setup, which was calibrated according to manufacturer's instructions. The acoustical signal was recorded and analyzed using a sound level meter (B&K 2250).

From the data collected with the sound level meter, LZeq values were extracted in one-third octave bands for each audio signal and headset-measurement setup combination. Data were then A-weighted and transformed to equivalent diffuse-field levels using the one-third octave correction factors specified in ISO 11904-2 [12] or the single number correction factors specified in AS/NZS 1269.1 [2].

Table 4.2: *Description of various methods used for fitting the Plantronics HW261N supra-aural headset on the Type 3.3 artificial ear and the Type 1 artificial ear.*

Measurement setup	Fitting methods	Description
Type 3.3 artificial ear	Fitting A1	The earphone is placed on the artificial pinna and held by the spring-loaded arm of the test fixture with a force of approximately 4.9 N (0.5 kg).
	Fitting A2	The test earphone is placed on the artificial pinna. The other earphone is placed under a table. A wooden block is added under the table to ensure that the distance between both earphones is the same as the width of the head of the acoustic manikin (152 mm) to provide an equivalent headband force.
Type 1 artificial ear	Fitting B1	The earphone is placed on the artificial ear (with the conical adaptor) and held by the spring-loaded arm of the test fixture with a force of approximately 4.9 N (0.5 kg).
	Fitting B2	The test earphone is placed on the artificial ear (with the flat mounting plate). The other earphone is placed under a table. A wooden block is added under the table to ensure that the distance between both earphones is the same as the width of the head of the acoustic manikin (152 mm) to provide an equivalent headband force.
	Fitting B3	The test earphone is placed on the artificial ear (with the conical adaptor). The other earphone is placed under a table. A wooden block is added under the table to ensure that the distance between both earphones is the same as the width of the head of the acoustic manikin (152 mm) to provide an equivalent headband force.

4.3 Results

4.3.1 Conversion to diffuse field levels across headsets and noises

The average difference between the KEMAR measured levels and the equivalent diffuse-field levels obtained using the one-third octave conversion procedure (ISO 11904-2 [12]) is displayed in Table 4.3 for each headset and audio signal. Across headsets, the difference ranged from 1.3 dBA (Sensear, Coast guard plane) to 11.1 dBA (Plantronics, IEC 60268-1). The differences across noises were greater with the Plantronics headset (from 5.3 dBA-11.1 dBA) and lower with the Sensear device (from 1.3 dBA-7.8 dBA). The mean diffuse-field conversion difference varied across headsets from 4.8 dBA (David Clark) to 8.7 dBA (Plantronics) and across signals from 2.6 dBA (Coast guard plane) to 8.8 dBA (IEC 60268-1).

Table 4.3: *Difference (dBA) between the KEMAR measurement levels and the diffuse field levels obtained with 12 fits/refits from 4 headsets and 6 audio signals.*

Audio signal	David Clark	Plantronics	Etymotic foam tips	Sensear silicon tips	Range	Mean
ICRA 1	4.5	8.2	5.5	3.5	3.5 - 8.2	5.4
ICRA 5	4.7	8.3	5.6	3.6	3.6 - 8.3	5.5
IEC 60268-1	7.6	11.1	8.8	7.8	7.6 - 11.1	8.8
HINT sentences	4.4	9.2	6.1	4.0	4.0 - 9.2	5.9
Coast guard plane	1.6	5.3	2.3	1.3	1.3 - 5.3	2.6
Crowd	6.3	9.9	7.4	5.8	5.8 - 9.9	7.3
Range	1.6 - 7.6	5.3 - 11.1	2.3 - 8.8	1.3 - 7.8		
Mean	4.8	8.7	5.9	4.3		

Similar results were obtained with the Type 2 and Type 3.3 measurement setups. The largest difference in measured levels and equivalent diffuse-field levels remained between the IEC 60268-1 signal and the coast guard plane signal across different headsets. The AS/NZS 1269.1 [2] specifies a 5 dB single-number correction for the diffuse-field conversion in the case of the acoustic manikin and the Type 2 artificial ear. However, results in Table 4.3, carried out with the one-third octave procedure specified in ISO 11904-2 [12], illustrate that the difference between manikin measured levels and equivalent diffuse-field levels varies depending on the headset and audio signal. This is due to the different frequency responses of the headsets and spectral characteristics of the audio signals used.

4.3.2 Comparison of diffuse field levels across measurement setups

Type 2 and Type 3.3 artificial ears compared to manikin

Figure 4.4 illustrates the diffuse-field corrected levels and standard deviations obtained with the ICRA 1 signal for 12 fits/refits with four different headsets on several measurement setups. The levels were all converted based on the one-third octave band conversion factors from ISO 11904-2 [12]. For three headsets (David Clark, Etymotic, Sensear), the manikin setup yielded slightly higher diffuse-field levels than those derived from the Type 3.3 and Type 2 artificial ear setups. The maximum difference (1.8 dBA) was for the Etymotic

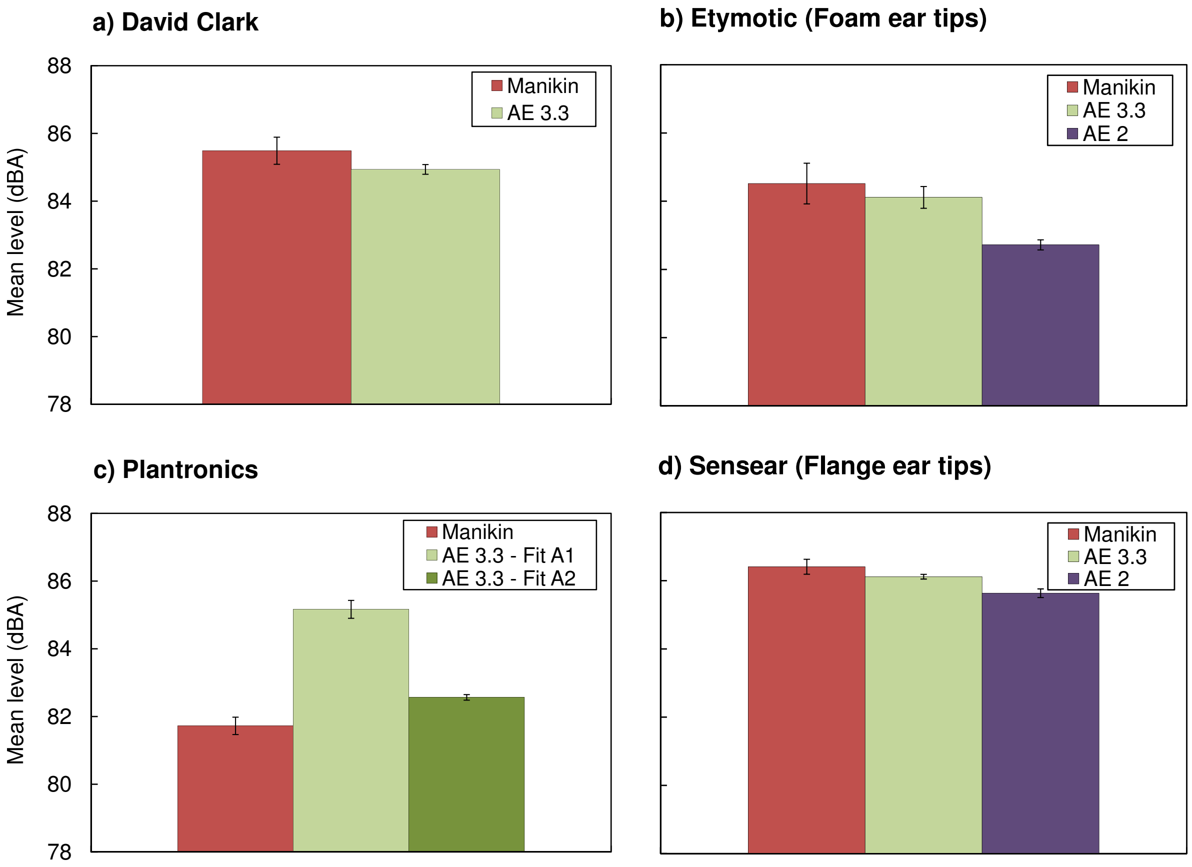

Figure 4.4: *Diffuse-field corrected levels of the ICRA 1 audio signal using one-third octave band conversion factors for 12 fit/refits for four headsets on selected measurement setups. a) David Clark headset on the manikin and Type 3.3 artificial ear (AE 3.3). b) Etymotic headset with foam ear tips on the manikin, Type 3.3 artificial ear (AE 3.3) and Type 2 artificial ear (AE 2). c) Plantronics headset on the manikin and Type 3.3 artificial ear (AE 3.3) with fitting methods A1 and A2. d) Sensear Smart Plug headset on the manikin, Type 3.3 artificial ear (AE 3.3) and Type 2 artificial ear (AE 2).*

MC2. Since the occluding ear simulator is the same in all three measurement setups (IEC 60318-4 [10]), differences are likely due to the different external ear and pinna simulation (or lack thereof) across the three setups, which could affect fitting of the headsets.

Figure 4.4c illustrates the difference in diffuse-field corrected levels obtained with the manikin and the two fitting methods of the Plantronics headset on the Type 3.3 artificial ear. The fitting with a 4.9 N force on the earphone (A1) yielded a higher level (85.2 dBA) than the other fitting (A2) where the headband was stretched to a typical head size

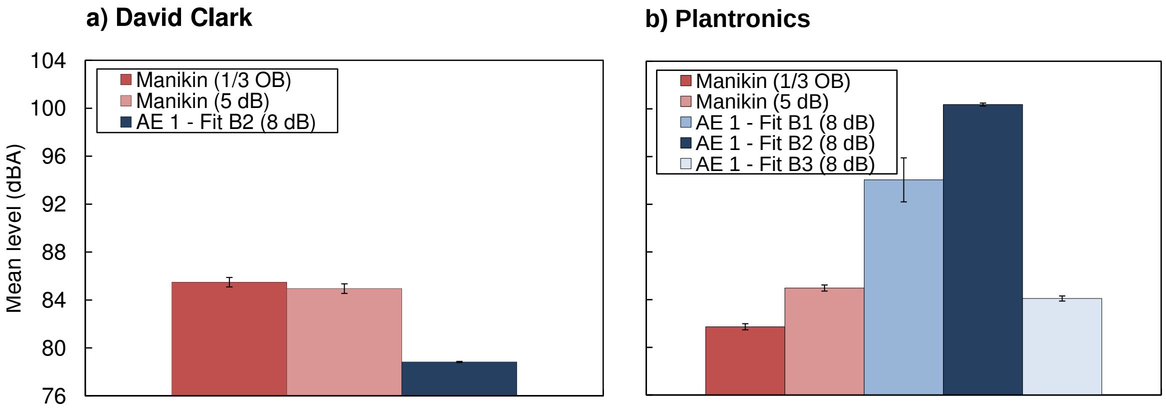

Figure 4.5: *Diffuse-field corrected levels of the ICRA audio signal for 12 fit/refits for two headsets on selected measurement setups and conversion methods. Manikin with one-third octave band (OB) conversion (dark red), manikin with 5 dB correction (light red), and Type 1 artificial ear (AE 1) with 8 dB correction (dark blue). a) David Clark headset. b) Plantronics headset - three fitting methods were used with the Type 1 artificial ear and are identified with a different shade of blue.*

(82.6 dBA). Fitting A1 provided a much tighter fit than A2. Results illustrate the effect of headband force when supra-aural headsets are fitted on test setups using an artificial pinna. Fitting A2 yielded results that were the closest to the manikin setup (a difference of 0.8 dBA), as expected, since the headband force would be very similar in both cases.

Type 1 artificial ear compared to manikin

Diffuse-field converted levels from the Manikin and the Type 1 artificial ear are compared in Figure 4.5 for the ICRA 1 signal. Manikin measurements were converted with the one-third octave band conversion factors from ISO 11904-2 [12] and the 5 dB single number correction from AS/NZS 1269.1 [2]. Measurements with the Type 1 artificial ear were converted with the 8 dB single number correction from AS/NZS 1269.1 [2].

Manikin results are similar with both conversion methods for the David Clark headset (difference of 0.5 dBA), but differed significantly for the Plantronics headset (difference of 3.1 dBA), paralleling the differences listed in Table 4.3 for the ICRA 1 signal.

Results with the Type 1 artificial ear differed markedly from the manikin results, particularly when compared to the gold standard ISO 11904-2 procedure [12]; by 6.7 dBA for the David Clark, and by 2.4 dBA to 18.6 dBA for the Plantronics over the three different fitting methods. Of the three methods, levels obtained with fitting B3 were the closest match to the results with the manikin. With this fitting, the conical ring adapter of the test fixture is used, instead of the flat mounting plate, and the headband force of the Plantronics headset is very similar to that produced when fitted on the manikin. Attempts were made to improve the correspondence between manikin and Type 1 artificial ear results, using one-third octave corrections for both the Type 1 (as per Macrae 1995 [16]) and the manikin (ISO 11904-2 [12]) setups, but a better match could not be achieved.

4.4 Conclusion

While standard ISO 11904-2 [12] describes an acoustic manikin measurement setup and one-third octave diffuse-field sound conversion procedures to assess noise exposure under communication headsets, simpler measurement setups and conversion procedures have also been proposed and described [7]. In this study, measurements on four test setups (manikin and Type 3.3, Type 2 and Type 1 artificial ears) were carried out in conjunction with one-third octave band and single number conversion procedures. Data were collected for six different audio signals for 12 fit/refits of circum-aural, supra-aural and intra-aural communication headsets.

Results showed that the difference between manikin measured levels and the equivalent diffuse-field levels is highly dependent on the frequency response of the headset and the spectrum of audio signal transmitted (overall range 1.3-11.1 dB). Due to these factors, single number corrections are not always in good agreement with one-third octave band conversions.

The fitting method also largely affected measurements with the supra-aural headset. The diffuse-field level obtained increased significantly with the force applied to the test earphone. For the Type 3.3 artificial ear and the Type 1 artificial ear (with conical adapter), a fitting method simulating the natural headband force from an average human head yielded levels that more closely matched those with the acoustic manikin.

While the results with the acoustic manikin, the Type 3.3 artificial ear and the Type 2 artificial ear were in broad agreement (differences within about 2 dBA for same fitting force), results with the Type 1 artificial ear provided a poorer match highly dependent on the fitting method.

The results reported in this study are from a single subject who fitted all headsets onto the measurement test setups. Further research is needed to investigate between-subject variability with the different measurement setups and headset types.

4.5 Acknowledgements

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Chapter 5

Comparison of Direct Measurement Methods - Full Study

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Keywords: acoustic manikin, acoustical standards, artificial ears, communication headsets, noise exposure

Ethics certificate: H04-10-08

Some of the findings of this article were presented in a poster format at a conference [34]. This chapter has been the subject of a journal publication:

- Nassrallah, F. G., Giguère, C., Dajani, H. R., & Ellaham, N. N. (2016). Comparison of direct measurement methods for headset noise exposure in the workplace. *Noise & Health, 18(81)*, 62-77.

Abstract

The measurement of noise exposure from communication headsets poses a methodological challenge. Although several standards describe methods for general noise measurements in occupational settings, these are not directly applicable to noise assessments under communication headsets. For measurements under occluded ears, specialized methods have been specified by the International Standards Organization (ISO 11904) such as the microphone in a real ear and manikin techniques. Simpler methods have also been proposed in some national standards such as the use of general purpose artificial ears and simulators in conjunction with single number corrections to convert measurements to the equivalent diffuse field. However, little is known about the measurement agreement between these various methods and the acoustic manikin technique. Twelve experts in the field positioned circumaural, supra-aural and insert communication headsets on four different measurement setups (Type 1, Type 2, Type 3.3 artificial ears, and acoustic manikin). Fit-refit measurements of four audio communication signals were taken under quiet laboratory conditions. Data were transformed into equivalent diffuse-field sound levels using third-octave procedures. Results indicate that the Type 1 artificial ear is not suited for the measurement of sound exposure under communication headsets, while Type 2 and Type 3.3 artificial ears are in good agreement with the acoustic manikin technique. Single number corrections were found to introduce a large measurement uncertainty, making the use of the third-octave transformation preferable.

5.1 Introduction

Noise in the workplace is responsible for 16-24% of adult-onset hearing loss worldwide [39] and is the second most prevalent self-reported work-related injury [38]. In the United States, 22 million workers are exposed to potentially damaging noise levels [47] and occupational noise-induced hearing loss affects 10 million workers [39]. In the European Union, 7.2% of workers report work-related hearing problems [41]. Among various factors, the increased use of wired and wireless communication headsets is raising concerns regarding exposure to potentially hazardous noise levels [43]. Communication headsets are commonly found in workplace settings such as call centers, retail stores, fast food outlets, airport ground and control tower operations, industrial and construction sites, and military sites [17, 37]. They can be used, for example, to enhance the received communication signal in adverse noise [14] or to enable hands free communication in less noisy environments [50]. While their use in occupational settings varies, in all cases the worker is exposed to the surrounding workplace noise as well as to the audio communication signals from the headset. Users typically adjust the volume setting of their communication headset to overcome the masking effects of the background noise entering the device in order to ensure proper reception of the audio signal such as speech. Depending on the situation, communication signals may occur continuously or intermittently; when present, they have been found to be a significant source of noise exposure [17].

Given the increased use of communication headsets in the last decade, proper measurement tools and methods are required to assess noise exposure from these devices in the workplace. However, several methodological challenges arise when carrying out noise measurements with communication headsets. First, when a device is occluding the ear, measurements become dependent on the acousto-mechanical properties of the head, pinna, and ear canal [14] and in-ear recording techniques are typically required [17]. Second, both the audio signals generated by the headset and the external background noise passing through the headset contribute to the total noise exposure and must be accounted for. Third, the worker must be able to operate normally during the field recording period to achieve a valid assessment under realistic working conditions. Finally, since the assessment of noise exposure specified in occupational standards is based on free or diffuse sound field measurements, in-ear measurements must be converted to equivalent sound field exposure levels to enable a comparison with the regulatory exposure limit, for example, 85 dBA [14, 17].

Despite these challenges, several methods have been proposed and used in the past forty years to assess noise exposure from the use of communication headsets in various workplaces [17, 37]. Field studies have been conducted to evaluate noise exposure of radio operators [6, 7, 16], military personnel [12], call and communication center operators [11, 42–44, 46, 48] as well as workers in others occupations [10, 14, 31, 50]. Results from these studies indicate that noise exposure from communication headsets often depends on the external background noise and could exceed regulatory limits in some workplaces or situations, especially in noisy environments [37].

Several national and international standards (e.g., ANSI/ASA S12.19 [2], ISO 9612 [28]) describe methods for noise measurements in occupational settings using sound level meters and noise dosimeters. These standards assume that noise sources are not in close proximity to the ears; as such, they are not directly applicable for measurement of noise under communication headsets. Consequently, ISO 11904 [25, 26] describes two specialized methods for the measurement of noise for sources close to the ears. The first method described in ISO 11904-1 [25] defines a microphone in a real ear (MIRE) method where acoustic measurements are performed using miniature or probe microphones inserted in the ears of workers and then converted to equivalent free-field or diffuse-field sound levels. This method provides a most direct estimate of noise exposure and likely has the best face validity [5]. The second method described in ISO 11904-2 [26] defines sound measurements taken with an acoustic manikin comprising an embedded ear simulator and microphone. The manikin's construction allows a simulation of the acousto-mechanical properties of the torso, head, pinna, and ear canal for an average adult. With either method, the in-ear unweighted sound pressure levels are analyzed in third-octave bands and converted to the free or diffuse sound field, then A-weighted using third-octave band attenuation factors [25, 26]. The resulting A-weighted free or diffuse-field related sound exposure level can then be compared to the regulatory limit. Of note, the manikin transfer function specified in ISO 11904-2 [26] used to convert to free-field or diffuse-field related sound levels is corrected to yield the same results as the MIRE technique in ISO 11904-1 [25], a mean value for a human population.

Special considerations must be given to field logistics since workers using headsets must be able to carry out their tasks normally while the measurements are being taken. Use of the MIRE technique can restrict head and body movements in some situations and as such it may be resisted by the workers when sustained for a long period of time. With the manikin technique, the issue is that the worker can no longer continue to communicate when the headset is placed on the manikin. ISO 11904-2 [26] does not provide procedures to overcome this challenge. Several approaches have been devised such as duplicating the electrical signal to the headset and using two matched headsets, one worn by the worker and the other fitted on the manikin placed in close proximity to the worker [14, 17]. Another approach is to record the electrical signal feeding the worker's headset in the field and either playing it back on the manikin in a laboratory setting or filtering the signal through the electrical-to-eardrum transfer function of the manikin [5, 40]. Still, the manikin method is considered to be quite cumbersome to use in the field, and the instrumentation is not widely available.

In an effort to simplify the manikin measurements and analysis procedures, the Australian/New Zealand Standard AS/NZS 1269-1 [5] specifies the use of a general-purpose artificial ear (IEC 60318-1 [19], a Type 1 artificial ear under ITU-T P.57 [29]) for headphones and the use of an ear simulator (IEC 60318-4 [21], a Type 2 artificial ear under ITU-T P.57 [29]) for insert earphones. Single number corrections that can be applied directly to the A-weighted measurements are also proposed for each artificial ear as well as for the manikin technique [5, 13]. In addition, use of the Type 3.3 artificial ear (ITU-T P.57 [29]), a device combining a pinna simulator, the IEC 60318-4 [21] ear simulator and a cheek-plate, offers another alternative to carrying out communication headset sound measurements [17]. The recent revision of Canadian standard CSA Z107.56 [13], specifies all these alternative methods and emphasizes field logistics while conducting headset sound measurements in the workplace. Since these methods are less expensive and less cumbersome to use, they are attractive when a compact setup is needed. However, while these alternative methods and provisions offer more practical and accessible options compared to using an acoustic manikin and/or carrying out third-octave band sound field conversions, as specified in ISO 11904-2 [26], their effectiveness has yet to be determined. Furthermore, procedures for fitting supra-aural earphones and circum-aural ear cups of various shapes and models on artificial ears have not been formalized and studied in the context of communication headset measurements.

Given the array of techniques proposed for noise exposure assessments under communication headsets, a recent study was conducted to evaluate accessibility of these different measurement methods to relevant stakeholders [35]. A survey was distributed to occupational health and safety professionals and hearing loss prevention professionals in Canada. Results indicated that there is a wide range of expertise regarding noise measurement from communication headsets and that access to basic or specialized equipment varies greatly across the different types of professionals. Consequently, there is a need for different direct and indirect measurement methods tailored to different groups of professionals while considering their respective roles, expertise, and access to equipment. However, few studies have used more than one method to conduct measurements, and little is known on the degree of agreement between the various test measurement setups.

A pilot study (Chapter 4) was conducted to examine if results from different measurement setups, headset fitting methods, and conversion factors to relate measurements to the diffuse field were in agreement [36]. One expert positioned various types of headsets on four measurement setups (ISO 11904-2 [26] manikin technique, and ITU-T P.57 [29] Type 3.3, Type 2 and Type 1 artificial ears) while acoustic measurements were collected for six different audio signals from 12 fit/refits of various types of communication headsets. Results indicated that while the acoustic manikin and Type 3.3 and Type 2 artificial ears were in agreement, compatibility of the Type 1 artificial ear depended on the fitting method which largely affected results. In addition, the difference between manikin measured levels and the equivalent diffuse-field levels was somewhat dependent on the headset and the noise type, which implied greater measurement uncertainty when using a single number conversion compared to using standardized ISO third-octave band correction factors.

This present work expanded on the pilot study using multiple participants to compare the different measurement setups in order to provide a more comprehensive account of the different sources of measurement variability, including both within-subject and between-subject variability for various types of audio signals and communication headsets. The main goals were to investigate (1) the measurement repeatability for each individual setup, (2) the measurement agreement between the different test setups, and (3) the increased measurement uncertainty associated with using single number corrections instead of third-octave band procedures to convert in-ear sound levels to the diffuse field.

5.2 Methods

5.2.1 Participants

Twelve individuals (6 males, 6 females), with technical and/or clinical expertise in the field interest, participated in this study. Participants were asked to complete a questionnaire focusing on their professional expertise and employment history as well as on their experience fitting hearing devices and using sound measurement equipment (Appendix C). The participants had an average of 21.5 years experience (range 1.5 to 48 years) in the fitting of earphones, hearing protectors and/or headsets on real ears, manikins, and/or artificial ear test measurement setups. Six participants were engineers or physicists and six others were audiologists. Nine of the 12 participants worked in research and/or consulting and three participants worked in a clinical setting. Ten of the 12 participants had experience working with a noise dosimeter and/or a sound level meter. All twelve participants had some experience working with an acoustic manikin, artificial ears, the MIRE technique, and/or a hearing aid analyzer, and were expected to conduct noise exposure assessments related to communication headsets or hearing devices as part of their scope of practice or employment.

5.2.2 Audio signals

Four different audio communication signals were used in this study as presented in Table 5.1. ICRA 1 and IEC 60268-1 are two artificial signals simulating the long-term spectral characteristics of speech and speech-music programming, respectively, and exemplify signal transmission over a noiseless communication channel. The two other audio signals consist of real speech mixed with real noises. The speech sentences were from the Hearing-In-Noise Test (HINT), a standardized test designed to evaluate speech recognition in noise. The two

Table 5.1: *Description of the four audio signals tested.*

Selection	Characteristics
ICRA 1 [15] (ICRA1)	Continuous speech spectrum noise
IEC 60268-1 [18] (IEC)	Speech-music program-simulated continuous noise
HINT sentences [49] & plane noise [32] (HP)	Real sentences mixed with continuous noise
HINT sentences [49] & riveter noise [51] (HR)	Real sentences mixed with impact noise

noise signals (coast guard plane and industrial riveter) are examples of background noises that can be picked up by the talker's microphone and transmitted over communication channels together with the talker's voice. The plane is a low frequency continuous noise and the riveter is a high frequency impact noise (26.5 impacts/s). Background noises and HINT sentences were mixed at a signal-to-noise ratio (SNR) of 0 dB to mimic transmission over a noisy communication channel. Tests were conducted to verify that the choice of SNR reflected challenging but realistic conditions of speech intelligibility. At an SNR of 0 dB, the extended speech intelligibility index [45] corresponding to the HINT/plane (HP) and HINT/riveter (HR) mixtures is 0.45 and 0.49 respectively, slightly above the limit for poor communication systems (ANSI S3.5 [3]). Informal listening of the two mixtures indicated word intelligibility around 90%.

The spectral characteristics of the four audio signals are shown in Figure 5.1. The four signals were concatenated into a sound file for presentation to the headsets, as shown in Figure 5.2. Each audio signal was 12 s long, separated by 3 s of silence. The analysis window consisted of the middle 10 s section of each signal. Tests with longer analysis windows of 20 and 30 s confirmed that a 10 s window was optimal to obtain accurate results (within 0.2 dB) while keeping the experimental session as short as possible (within 2 h). The four different audio signals were equalized to the same A-weighted root-mean-square amplitude on the sound file.

5.2.3 Headsets

Four different headsets used in a wide range of occupational settings and applications were chosen for this experiment (Table 5.2). The David Clark 40642G-01 (DVC) is a computer

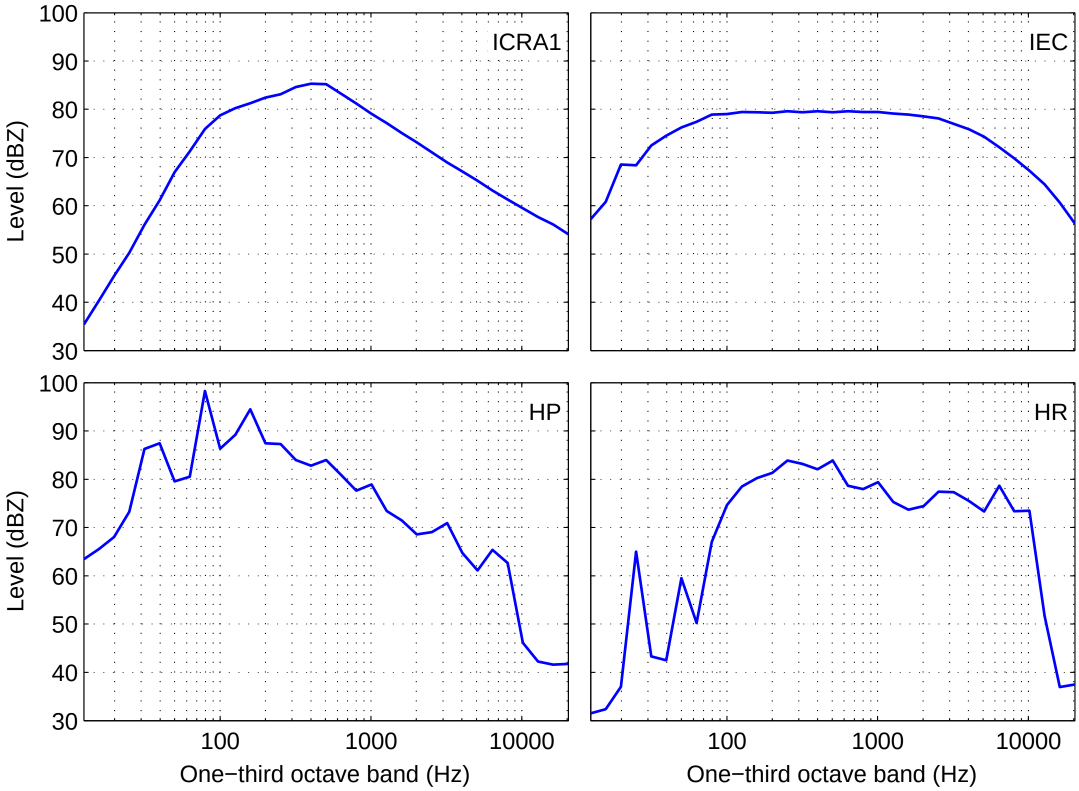

Figure 5.1: *Third-octave band spectra for the four audio signals used.*

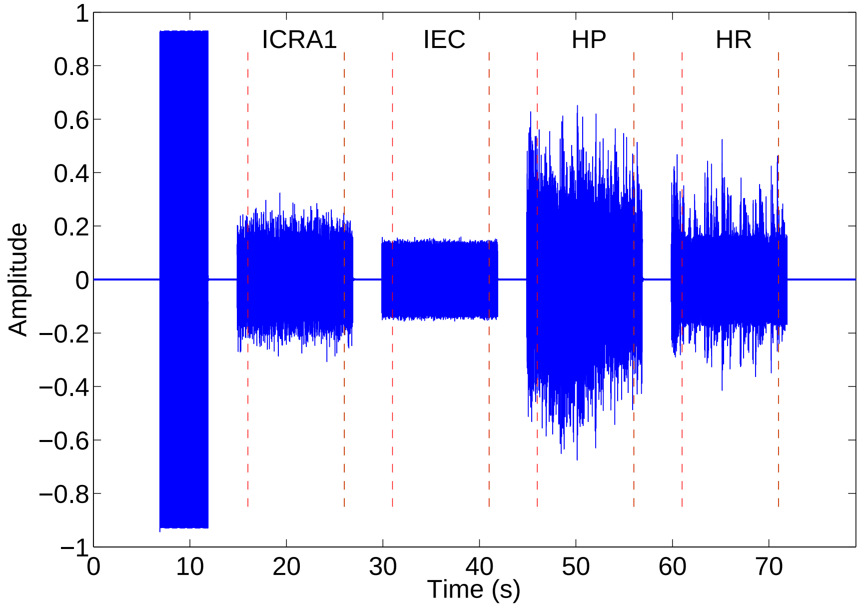

Figure 5.2: *Time waveform of the electrical signal of the complete sound excerpt used. The recording is preceded by a 1000 Hz initial pure tone to synchronize the data analysis. Dashed vertical lines delimit the sound measurement analysis window for each audio signal.*

Table 5.2: *Description of headsets used.*

Headset	Manufacturer	Type
David Clark 40642G-01 (DVC)	David Clark Company, Inc. (Worcester, MA, USA)	Circum-aural
Plantronics HW261N (PLA)	Plantronics (Santa Cruz, CA, USA)	Supra-aural
3M$^{\text{TM}}$ Peltor$^{\text{TM}}$ MT32H01 (PEL)	3M (Maplewood, MN, USA)	Supra-aural
Sensear SP1 (SES)	Sensear (Perth, Australia)	Insert with silicon tips
(SEF)		Insert with foam tips

compatible circum-aural headset designed for high noise environments. The Plantronics HW261N (PLA) is a supra-aural telephone headset typically found in call centers. The 3M$^{\text{TM}}$ Peltor$^{\text{TM}}$ MT32H01 (PEL) is a lightweight single-sided nonattenuating supra-aural headset intended for military, police and industry. Finally, the Sensear Smart Plug SP1 is an insert device designed for high noise environments such as industrial, commercial or military settings. The Sensear SP1 is available with different ear tips; in this study, we tested the headset with silicon (SES) and foam (SEF) tips. The frequency response of these four headsets, measured on an acoustic manikin (KEMAR$^{\circledR}$ Manikin G.R.A.S. Type 45BA), is shown in Figure 5.3. Responses are within 5 dB in the range of 500-2500 Hz across headsets, but much larger differences are found at higher and lower frequencies.

5.2.4 Measurement setups

Four different measurement setups (Table 5.3), covering the array of techniques proposed in ISO 11904-2 [26], AS/NZS 1269.1 [5] and CSA Z107.56 [13], were used to measure the level of the different audio signals under the headsets (Figure 5.4).

The acoustic manikin (MAN) provides a full head, torso, pinna and ear simulator IEC 60318-4 [21] (formerly IEC 60711 [23] or IEC 711 simulator) built according to worldwide averages of men and women dimensions. Placement of headsets on the manikin is applicable to all device types and is facilitated by the anthropomorphic features allowing an adjustment of all parameters relevant to fitting (e.g., depth of insertion, headband force, etc.).

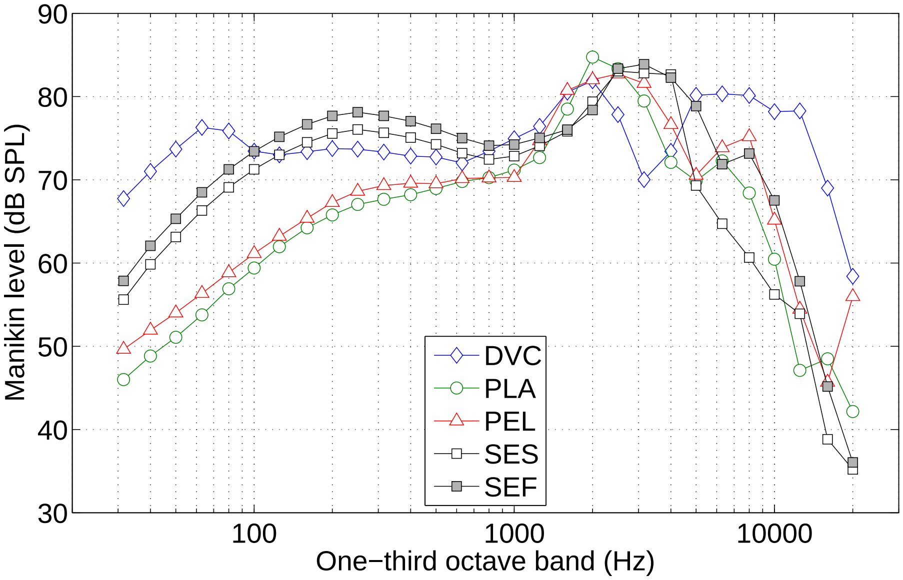

Figure 5.3: *Frequency response of the headsets measured on an acoustic manikin. The input is a pink noise electrical signal. The output from each device is scaled to an in-ear manikin level of 90 dBA for comparison purposes.*

The pinnae come in two sizes (”small“ and ”large“) and two levels of hardness (Shore-OO 55 and Shore-OO 35). The large size, typical of American and European males, was used in this study. The softer version (Shore-OO 35), recommended in IEC/TS 60318-7 [22] and ITU Rec. P.57 [29], was used with all headsets. The harder version (Shore-OO 55) was also used with the supra-aural headsets (PLA, PEL) to determine the effects of pinna hardness on measured levels. These two adaptations of the manikin with large soft and large hard pinnae are referred to as MAN.SP and MAN.HP, respectively. All headsets (DVC, PLA, PEL, SES, SEF) were tested on the right side of the manikin.

The Type 3.3 artificial ear (AE3.3) allows for testing with a flat cheek, large right soft pinna, and ear simulator (IEC 60318-4 [21]) providing a more compact test setup than the acoustic manikin. However, since it does not provide a full head size, special provisions must be applied for fitting the circum-aural (DVC) and supra-aural (PLA, PEL) headsets to ensure realistic headband pressure and placement over the simulated pinna. With the Type 3.3 resting on a table, the test ear cup or earpiece was placed on the artificial ear while the other side of the headset was placed under the table. A wooden block was fixed under the table to adjust the distance between both sides of the headset to be the same as the width of the head of the acoustic manikin (152 mm) in order to achieve an

Table 5.3: *Description of the measurement setups used. Figure 5.4 for illustrations.*

Setup	Standards	Product	Comments
Acoustic Manikin (MAN)	ITU-T Rec. P.58 [30] ITU-T P.57 [29] IEC/TS 60318-7 [22] IEC 60318-4 [21]	KEMAR® Manikin G.R.A.S. Type 45BA	Used for all headsets. Two types of pinnae used: - Large right soft (MAN.SP) G.R.A.S. KB1065 (Shore-OO 35) - Large right hard (MAN.HP) G.R.A.S. KB0065 (Shore-OO 55)
Type 3.3 Artificial Ear (AE3.3)	ITU-T P.57 [29] IEC 60318-4 [21]	G.R.A.S. Ear and Cheek Simulator Type 43 AG	Used for all headsets. Large right soft pinna: G.R.A.S. KB1065 (Shore-OO 35)
Type 2 Artificial Ear (AE2)	ITU-T P.57 [29] IEC 60318-4 [21]	G.R.A.S. IEC 711 Ear Simulator Type RA0045	Used for insert headsets.
Type 1 Artificial Ear (AE1)	ITU-T P.57 [29] IEC 60318-1 [19] IEC 60318-2 [20]	Brüel & Kjaer Artificial Ear Type 4153	Used for supra- and circum-aural headsets. Three headset fittings used (see Table 5.4).

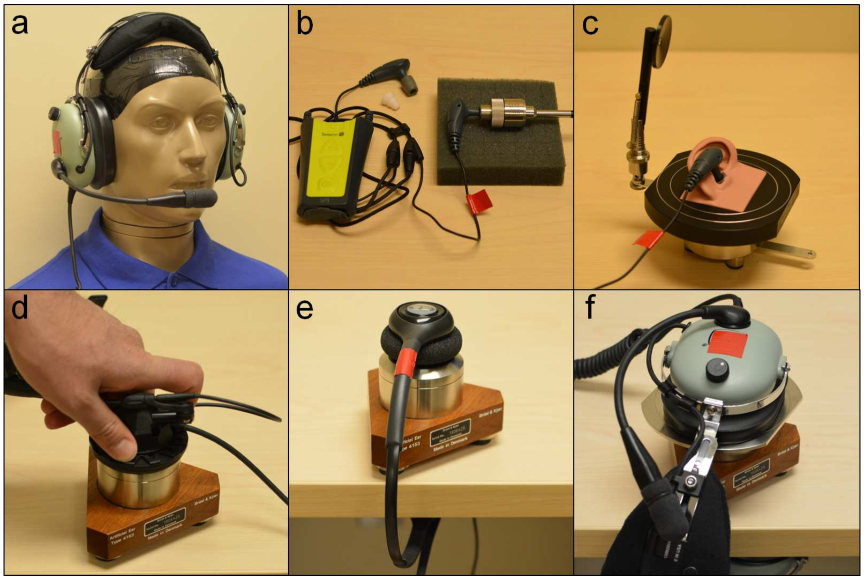

Figure 5.4: *The different measurement setups used. a) DVC headset placed on the acoustic manikin. b) SEF headset inserted in the Type 2 artificial ear. c) SEF headset inserted in the Type 3.3 artificial ear. d) PEL headset held on the Type 1 artificial ear; AE1.CH fitting method. e) PLA headset placed on the Type 1 artificial ear; AE1.CF fitting method. f) DVC headset placed on the Type 1 artificial ear; AE1.MF fitting method. See Tables 2-4 for headset, measurement setup and fitting descriptions.*

equivalent headband force. This fitting method, which simulates the natural headband force for an average human head, was found to provide the closest match to the acoustic manikin among different fitting options tested in the pilot study [36]. In the case of the insert headset (tips SES and SEF), fitting on the Type 3.3 is the same as for the acoustic manikin.

The Type 2 artificial ear (AE2) comprises an ear simulator (IEC 60318-4 [21]) with external-ear extension. In this study, it was used to explore an even simpler setup than the Type 3.3 artificial ear, without cheek and pinna simulator, for use with insert headsets only. The ear simulator is the same as the one used with the acoustic manikin and the Type 3.3 artificial ear. However, due to the absence of a reference pinna with the Type 2, differences in insertion depth or placement may exist when fitting insert headsets in the external ear portion of the Type 2 compared to the Type 3.3 or acoustic manikin. The AE2 setup was used for testing the insert headset with the two different tips (SES and SEF).

The Type 1 artificial ear (AE1), defined in IEC 60318-1 [19] and IEC 60318-2 [20], contains an acoustic coupler with three connected cavities approximating the acoustical impedance of the human ear and different adaptors for the calibration of certain types of supra-aural and circum-aural audiometric earphones. Consequently, the Type 1 was used only with supra-aural (PEL, PLA) or circum-aural (DVC) headsets. As with the AE3.3 setup, care was exercised to provide realistic headband pressure and placement of these headsets. Headsets were fitted in different ways utilizing the conical adapter ring or a metal mounting plate adaptor supplied with the Type 1 artificial ear. The conical adaptor was used in conjunction with two different manners of applying pressure that could be used in the field: headset handheld over artificial ear (AE1.CH) and natural headband force (AE1.CF). The mounting plate adaptor was used only with the natural headband force fitting (AE1.MF). In all, three different fitting methods (AE1.CH, AE1.CF, AE1.MF) were explored with the supra-aural headsets (PLA, PEL), and one fitting method (AE1.MF) was used for the circum-aural headset (DVC), as described in Table 5.4.

Table 5.4: *Description of fitting methods on the Type 1 artificial ear (AE1) for the supra-aural and circum-aural headsets. The abbreviation for each fitting method is between brackets. See Figure 5.4 for illustrations.*

Fitting methods	Headsets	Description
Conical Handheld (AE1.CH)	Supra-aural (PLA, PEL)	The earphone is placed on the artificial ear with the conical adaptor and held in place by the participant during the full measurement. Participants were instructed to apply a pressure approximating the natural headband force of the headset under test.
Conical Headband Force (AE1.CF)	Supra-aural (PLA, PEL)	The test earphone is placed on the artificial ear with the conical adaptor. The other earphone is placed under a table. A wooden block increases the distance (152 mm) between both earphones to achieve a headband force equivalent to that when tested on the acoustic manikin.
Mounting Plate Headband Force (AE1.MF)	Supra-aural (PLA, PEL) Circum-aural (DVC)	The test earphone is placed on the artificial ear with the flat mounting plate. The other earphone is placed under a table. A wooden block increases the distance (152 mm) between both earphones to achieve a headband force equivalent to that when tested on the acoustic manikin.

5.2.5 Experimental protocol

All experiments were conducted under quiet conditions in laboratory settings. In sound-proof facilities, participants were asked to position the headsets on four different test measurement setups and using applicable fitting methods, as described in Table 5.5. The experiment was approved by the Office of Research Ethics and Integrity of the University of Ottawa).

Once the headset was placed on a test setup, the recording of the four audio signals (Figure 5.2) was played from an iPod Touch player (Apple Inc., Cupertino, CA) connected to a Yamaha RX-A820 receiver/amplifier (Yamaha Corp., Hamamatsu, Japan). Prior to the experiment, the volume on the amplifier was adjusted and noted for each headset to produce an in-ear level of 90 dBA on the manikin with the ICRA1 noise, in order to simulate diffuse-field related exposure levels of around 85 dBA. The volume of the amplifier was subsequently kept constant for a given headset for all the different test measurement setups and audio signals. The sound played through the headset was picked up by the microphone in the selected test measurement setup, then stored as a wave file (24 kHz, 16

Table 5.5: *Combination of measurement setups and headsets tested with number of fitting methods for each. Abbreviation for headsets and measurement devices are indicated in the brackets. There are three combinations of AE1 setups for the Plantronics and Peltor headsets for the three fitting methods used with the Type 1 artificial ear with supra-aural headsets, as per Table 5.4.*

Headsets	Manikin (MAN) Hard pinna (HP)	Manikin (MAN) Soft pinna (SP)	Artificial ear Type 3.3 (AE3.3)	Artificial ear Type 2 (AE2)	Artificial ear Type 1 (AE1)
David Clark (DVC)	0	1	1	0	1
Plantronics (PLA)	1	1	1	0	3
Peltor (PEL)	1	1	1	0	3
Sensear SP1; Silicon tips (SES)	0	1	1	1	0
Sensear SP1; Foam tips (SEF)	0	1	1	1	0

bits) using a sound level meter (B&K 2250) with built-in audio recorder. All equipment was calibrated according to manufacturers' specifications, including any corrections supplied for the different ear simulators and calibration couplings accessories.

For each participant, measurements were taken twice in succession (fit and complete re-fit) for each of the 21 headset-measurement setup combinations in Table 5.5, resulting in 42 fits in total. The subjects fitted the headsets on the measurement setup based on manufacturers' instructions and prior experience fitting similar listening devices. The testing order for the measurement setups was counter balanced across participants. Within each setup, participants tested all applicable headsets in random order.

5.2.6 Sound field transformation

The data recorded with the sound level meter with each measurement setup was transferred into Matlab (The Mathworks, Inc., Natick, MA) for further analysis. For each test audio signal, the middle 10 s were extracted for analysis, and the equivalent level in each third-octave frequency band was computed and exported into Excel (Microsoft Corporation). The levels were then A-weighted using the third-octave band factors in IEC 61672-1 [24] and transformed to equivalent diffuse-field levels. The third-octave diffuse-field correction factors specified in ISO 11904-2 [26] were used for measurements obtained with the acoustic manikin, the Type 3.3 and Type 2 artificial ear, as specified in CSA Z107.56 [13] since they share the same ear simulator (IEC 60318-4 [21]). Measurements with the Type 1 artificial ear were transformed using the wide-band artificial ear to eardrum transfer function proposed by Macrae [33] followed by the ISO 11904-2 [26] diffuse-field transformation. The latter transformation published in 2004, instead of the original transmission gain proposed by Macrae in 1995 [33], was used in this study to ensure that the same eardrum to diffuse-field transformation is employed for all test measurement setups. The difference between the two transformations ranges from -1.2 to +1.0 dB across the set of third-octave bands from 200 to 5000 Hz.

5.2.7 Statistical analysis

In method comparison studies, two particular questions are relevant [1]: (1) the statistical properties of each individual method (e.g., variability within and between observers) and (2) the degree of agreement between methods (e.g., average bias between two methods being compared, range of differences between the two methods for single measurements carried out by the same observers).

While common statistical techniques have been used in the context of method comparison studies, such as comparison of means, and correlation or regression analysis, they are not appropriate or designed to answer such questions [1]. In this study, we used Bland-Altman limits of agreement (LoA) approach [9] to compare the different methods of sound measurement from communication headsets. This approach, commonly used in clinical measurements, is particularly well suited when comparing a new or simplified method to an established method [1].

Properties of each method

The A-weighted diffuse-field transformed levels for each participant and trial were used to compute descriptive statistics. For each measurement method, the mean of the two trials (fit-refit) was taken and averaged across the 12 participants ($\bar{X}$) for each headset and audio signal combination. The between-subject standard deviation (s_B) of the participant fit-refit means was also computed to report variability across participants in each experimental condition. In addition, the within-subject standard deviation (s_ω) (i.e., the standard deviation of repeated measurements by the same participant) was calculated by averaging the variance of the two trials of the 12 participants and taking the square root [8]. The difference between a single measurement and the true value for a given method is expected to be less than $1.96s_\omega$ in 95% of cases. Another way of describing the measurement variability for each method is the repeatability coefficient [8, 9] defined as:

$$\text{Repeatability coefficient} = 1.96\sqrt{2}s_\omega$$

This coefficient is useful to quantify how repeatable a method is upon successive measurements; two measurements obtained with the same method under identical experimental conditions are expected to vary by no more than the repeatability coefficient in 95% of cases.

Measurement agreement between methods

Bland-Altman limits of agreement (LoA) approach provides a means of quantifying the 95% range of differences between single measurements performed by two different methods as follows [9]:

$$LoA = \bar{d} \pm 1.96\sqrt{\hat{\sigma}_d^2}$$

where $\bar{d}$ is the bias or difference between the method means $\bar{X}$, and $\hat{\sigma}_d^2$ is the estimated variance of the between-subject differences by each method. The latter was calculated from equation 5.3 in Bland & Altman [9]:

$$\hat{\sigma}_d^2 = s_{\bar{d}}^2 + \frac{s_{x\omega}^2}{2} + \frac{s_{y\omega}^2}{2}$$

where $s_{\bar{d}}^2$ is the observed variance of the differences between the within-subject means of the two methods being compared, and $s_{x\omega}^2$ and $s_{y\omega}^2$ are the within-subject variances of the two replicated trials (fit-refit) for each method (x and y). In this study, the acoustic manikin with soft pinna (MAN.SP) serves as the gold standard or reference method for communication headsets sound measurements from which all other methods are compared. There are 16 possible comparisons between the AE1, AE2, AE3.3 or MAN.HP setups and the reference method MAN.SP over the different measurement setup-headset combinations tested in this study (Table 5.5).

One-way repeated measures ANOVAs were conducted in SPSS (IBM Corp., Armonk, NY) to determine the effect of the four audio signals (ICRA1, IEC, HP, HR) on the bias level $\bar{d}$ between each measurement setup under test and the acoustic manikin reference method. For each headset, this analysis was used to determine whether the limits of agreement between methods could be combined over all four audio signals or computed separately for each different signal.

Validity of single number corrections

The difference between the A-weighted in-ear sound level (measured in test setup) and the A-weighted diffuse-field equivalent sound level (computed using the applicable third-octave band transformation) was calculated for each measurement setup, headset, and audio signal. The in-ear/diffuse-field difference level was then compared to the 8 dB single number correction proposed for the Type 1 artificial ear or to the 5 dB single number correction proposed for the acoustic manikin, Type 3.3 and Type 2 artificial ears. This procedure allowed us to quantify the increased measurement uncertainty, if any, introduced by the simplified single number transformation specified in CSA Z107.56 [13] and AS/NZS 1269.1 [5]. Given that the MAN, AE3.3 and AE2 setups use the same ear simulator (IEC 60318-4 [21]) and diffuse-field transformation function (ISO 11904-2 [26]), tests were carried out to determine whether the in ear/diffuse-field difference levels from these three methods were not statistically different and could be combined. For the supra-aural PLA and PEL headsets, which were tested with the MAN and the AE3.3 setup, a dependent t-test was conducted to compare the two measurement setups for each audio signal. Similarly, for the two ear tips (SES, SEF) of the insert headset, which were tested on the MAN, AE3.3, and AE2 setups one-way repeated measures ANOVAs were conducted for the same purpose.

5.3 Results

5.3.1 Reference method

Figure 5.5 displays the A-weighted measured in-ear levels with the reference MAN.SP setup and the diffuse-field related levels computed using the third-octave conversion procedure in ISO 11904-2 [26], for all headsets and audio signals. The data are averaged over the 12 participants but shown separately for each trial (fit-refit). The in-ear manikin level is very close to 90 dBA for the ICRA1 signal for all headsets, as expected from the experimental protocol which used this audio signal for level adjustment purposes. For each headset, some differences are seen for the other signals due to their different spectra (Figure 5.1) compared to ICRA1. This is most noticeable for the IEC and HP signals which are richer in low-frequency content. Overall, there is very little difference in the mean level between the two trials for both the in-ear and the diffuse-field levels; however, the diffuse-field-related levels are lower than the measured in-ear levels by an amount ranging from about 2 to 11 dB across headsets and signals.

5.3.2 Properties of each method

The descriptive statistics for the 21 headset-measurement setup combinations and four audio signals are summarized in Table 5.6. For each condition, the mean A-weighted diffuse-field equivalent levels ($\bar{X}$), the between-subject standard deviation (s_B), and the within-subject standard deviation (s_ω) are presented. For the reference method (MAN.SP), the between-subject standard deviation (s_B) varied from 0.5 to 1.1 dB and the within-subject standard deviation (s_ω) varied from 0.3 to 1.2 dB. Results for the MAN.HP setup were very similar to MAN.SP for the two supra-aural devices tested. Results for the AE3.3 and AE2 setups were also in close agreement with MAN.SP and MAN.HP, except

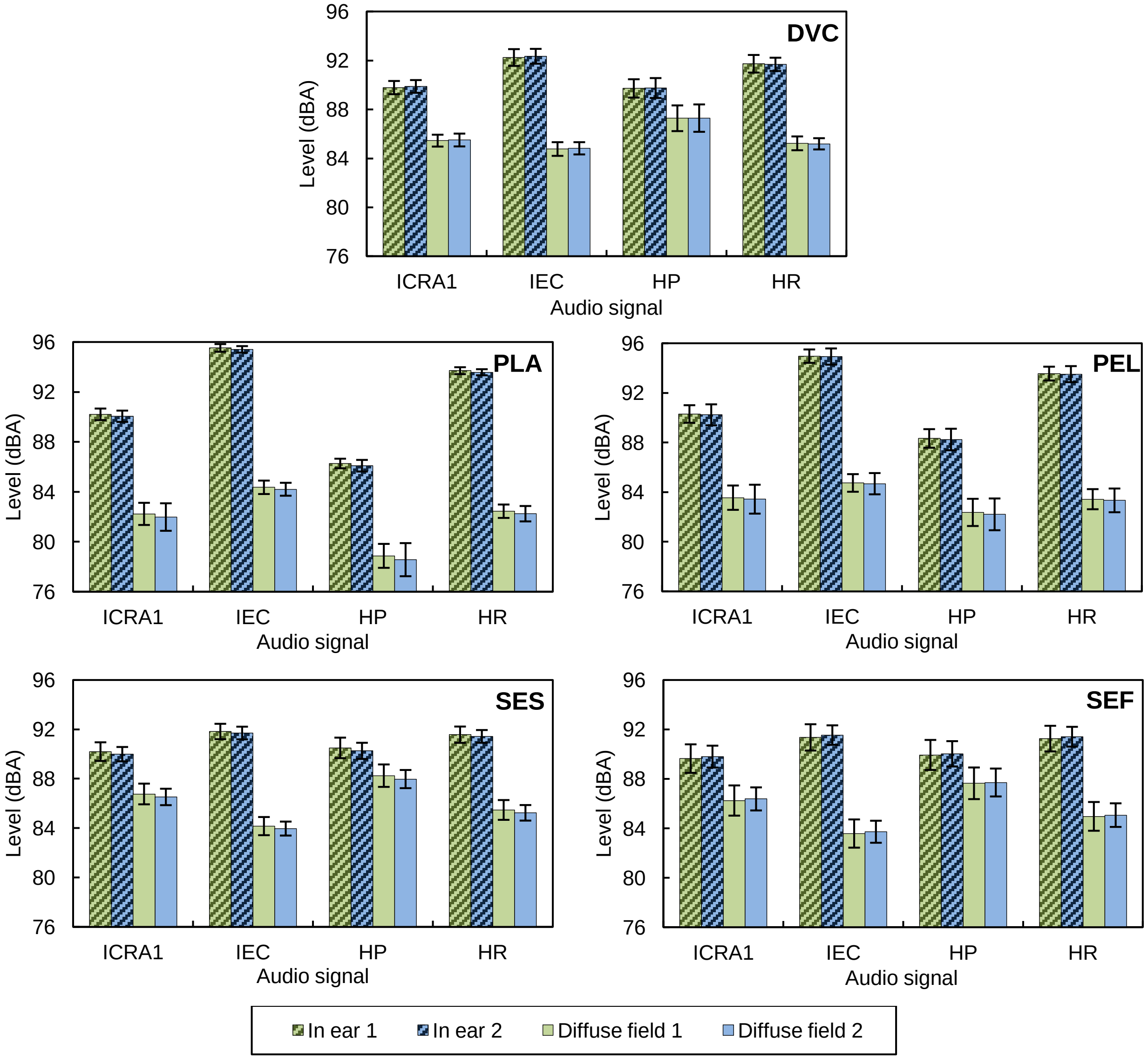

Figure 5.5: *Mean level and standard deviation of measurements taken using the reference acoustic manikin (MAN.SP) with each headset and audio signal (n = 12 participants) for both fits. Measured in-ear levels and diffuse-field related levels obtained with the third-octave correction factors specified in ISO 11904-2 [26] are shown.*

for the higher between-subject standard deviation (s_B) with the AE3.3 in the case of the supra-aural PEL headset (1.2 to 1.9 dB) and the notably smaller within-subject standard deviation (s_ω) with the AE2 (0.1 to 0.4 dB) for both ear tips of the insert headset (SES and SEF).

The AE1 setup produced erratic results (Table 5.6), with descriptive statistics highly dependent on the fitting method (Table 5.4) and headset tested. The AE1.CH setup yielded the largest between-subject standard deviation (s_B) from 3.0 to 6.7 dB among all measurement setups tested, and a within-subject standard deviation (s_ω) often two or three times larger than the MAN and AE3.3 setups for the same headsets. For the AE1.CF setup, the within-subject standard deviation (s_ω) is comparable to the MAN and AE3.3 setups, but the between-subject standard deviation (s_B) with the supra-aural PEL headset are about three times higher than the MAN setups and almost twice higher than the AE3.3 setup. In the case of the AE1.MF setup, results were highly dependent on the headset; very low within-subject (s_ω) (0.1 to 0.2 dB) and between-subject (s_B) (0.2 dB) standard deviations were observed with the circum-aural DVC headset, while large between-subject (s_B) (2.3 to 2.9 dB) and within-subject (s_ω) (3.5 to 4.6 dB) standard deviations were found for the supra-aural PLA headset.

5.3.3 Measurement agreement between methods

One-way repeated measures ANOVAs revealed that bias $\bar{d}$ between the AE1, AE2, AE3.3 or MAN.HP setups and the reference acoustic manikin method (MAN.SP) differed significantly ($p < 0.05$) between audio signals (ICRA1, IEC, HP, HR) in 12 of the 16 possible setup-headset comparisons. Consequently, Bland-Altman's LoA analyses were conducted considering audio signal dependence in all method comparisons. Figure 5.6 displays the LoA between the different measurement setups and the reference acoustic manikin (MAN.SP) for each headset and audio signal. These limits quantify the range within which 95% of the difference between methods will lie for single measurements. As shown in Figure 5.6, the MAN.HP, AE3.3, and AE2 setups produced LoAs with much smaller bias and variability components than the AE1 setups.

Table 5.6: *Mean equivalent diffuse-field levels ($\bar{X}$) in dBA, between-subject standard deviation (s_B) in dB, and within-subject standard deviation (s_ω) in dB for the 21 headset-measurement setup combinations and the four audio signals. The repeatability coefficient is 2.77s_ω. The reference acoustic manikin method (MAN.SP) column is in bold.*

		MAN.SP			MAN.HP			AE3.3			AE2			AE1.CH			AE1.CF			AE1.MF		
		$\bar{X}$	s_B	s_ω	$\bar{X}$	s_B	s_ω	$\bar{X}$	s_B	s_ω	$\bar{X}$	s_B	s_ω	$\bar{X}$	s_B	s_ω	$\bar{X}$	s_B	s_ω	$\bar{X}$	s_B	s_ω
David Clark (DVC)	ICRA1	**85.5**	**0.5**	**0.3**				85.2	0.4	0.3										80.6	0.2	0.1
	IEC	**84.8**	**0.5**	**0.3**				84.5	0.5	0.3										80.9	0.2	0.1
	HP	**87.3**	**1.1**	**0.3**				86.5	0.6	0.6										78.9	0.2	0.1
	HR	**85.2**	**0.5**	**0.3**				84.8	0.5	0.2										79.5	0.2	0.2
Plantronics (PLA)	ICRA1	**82.1**	**0.8**	**1.1**	81.6	0.9	0.7	82.7	0.9	0.6				94.6	3.5	1.8	86.9	0.6	0.6	99.4	2.9	4.6
	IEC	**84.3**	**0.5**	**0.5**	84.0	0.5	0.3	84.4	0.5	0.3				92.8	3.0	1.7	86.8	0.4	0.4	97.3	2.3	3.5
	HP	**78.7**	**0.9**	**1.2**	78.1	1.0	0.9	79.4	1.1	0.8				90.5	3.8	2.2	83.0	0.7	0.6	95.5	2.9	4.5
	HR	**82.3**	**0.5**	**0.6**	82.0	0.5	0.4	82.5	0.7	0.4				91.5	3.5	2.0	85.2	0.5	0.4	96.5	2.6	3.9
Peltor (PEL)	ICRA1	**83.5**	**0.8**	**0.6**	83.4	0.9	0.7	84.9	1.7	1.0				95.4	6.7	1.4	88.7	3.1	1.3	85.8	1.8	0.7
	IEC	**84.7**	**0.6**	**0.5**	84.7	0.7	0.5	85.8	1.2	0.7				93.9	5.5	1.3	88.3	2.4	1.0	86.2	1.4	0.5
	HP	**82.3**	**1.0**	**0.7**	82.2	1.0	0.8	83.8	1.9	1.1				93.0	6.6	1.8	86.6	3.1	1.3	83.6	1.9	0.7
	HR	**83.4**	**0.7**	**0.5**	83.3	0.8	0.6	84.4	1.4	0.8				93.2	5.9	1.6	87.2	2.7	1.1	84.7	1.6	0.6
Sensear, Silicon (SES)	ICRA1	**86.6**	**0.7**	**0.4**				86.9	0.5	0.5	86.9	0.5	0.1									
	IEC	**84.1**	**0.6**	**0.4**				84.3	0.4	0.5	84.1	0.6	0.2									
	HP	**88.1**	**0.8**	**0.5**				88.4	0.5	0.6	88.5	0.5	0.1									
	HR	**85.4**	**0.7**	**0.4**				85.6	0.5	0.5	85.5	0.5	0.1									
Sensear, Foam (SEF)	ICRA1	**86.3**	**0.9**	**0.8**				86.5	1.0	0.4	86.7	0.6	0.3									
	IEC	**83.7**	**0.9**	**0.7**				83.9	0.9	0.4	83.9	0.7	0.4									
	HP	**87.7**	**1.1**	**0.7**				88.0	1.1	0.6	88.3	0.7	0.3									
	HR	**85.0**	**0.9**	**0.7**				85.3	0.9	0.5	85.4	0.6	0.4									

For the MAN.HP, which was tested with the two supra-aural headsets, bias was slightly negative ranging from -0.3 to -0.6 dB for the PLA headset and from -0.1 to 0.0 dB for the PEL headset across the four audio signals, while variability was from 1.0 to 2.4 dB across these test conditions. For the AE3.3, bias was either slightly negative or slightly positive for the DVC, PLA, SES and SEF headsets, ranging from 0.8 to +0.7 dB across headsets and audio signals, while variability was from 0.8 to 2.9 dB. For the PEL headset, a larger positive bias was observed from +1.1 to +1.5 dB together with an increased variability from 2.5 to 3.7 dB across audio signals. For the AE2, which was tested with the two ear tips of the insert headset, bias was comparable to that with the MAN.HP setup, from +0.1 to +0.6 dB across audio signals, and variability was consistent across audio signals at about 2.0 dB. Overall, measurements taken with the MAN.HP, AE3.3, and AE2 produced 95% limits of agreement always overlapping with, and nearly centered on, the zero-difference value, with relatively small bias and variability components indicating a good agreement with the reference acoustic manikin (MAN.SP).

The AE1, which was tested with circum-aural and supra-aural headsets, produced much larger bias and variability components that were highly dependent on the fitting methods (Table 5.4) and headsets, as shown in Figure 5.6. For the AE1.CH setup, bias was similar across headsets from +8.6 to +12.5 dB while the variability was largest with the PEL headset from 10.5 to 12.6 dB, across audio signals. For the AE1.CF, bias was also similar across headsets from +2.5 to +5.2 dB, and the variability was again largest with the PEL headset from 5.1 to 6.7 dB, across audio signals. The AE1.MF setup produced noticeably different results for the two supra-aural headsets. For the PEL headset, bias ranged from +1.3 to +2.3 dB and the variability was about 4.2 dB, across audio signals. For the PLA headset, this setup produced the highest bias from +13.0 to +17.3 dB with a variability ranging from 6.7 to 8.6 dB, across audio signals. In addition to the very large bias and variability observed for the AE1 setup, in many cases the 95% LoA also did not even overlap with the zero-difference value (e.g., AE1.MF with the DVC and PLA, AE1.CH with the PLA and for one audio signal with the PEL, AE1.CF with the PLA). These results indicate a very poor agreement with the reference acoustic manikin (MAN.SP) for all fitting options of the AE1 setup.

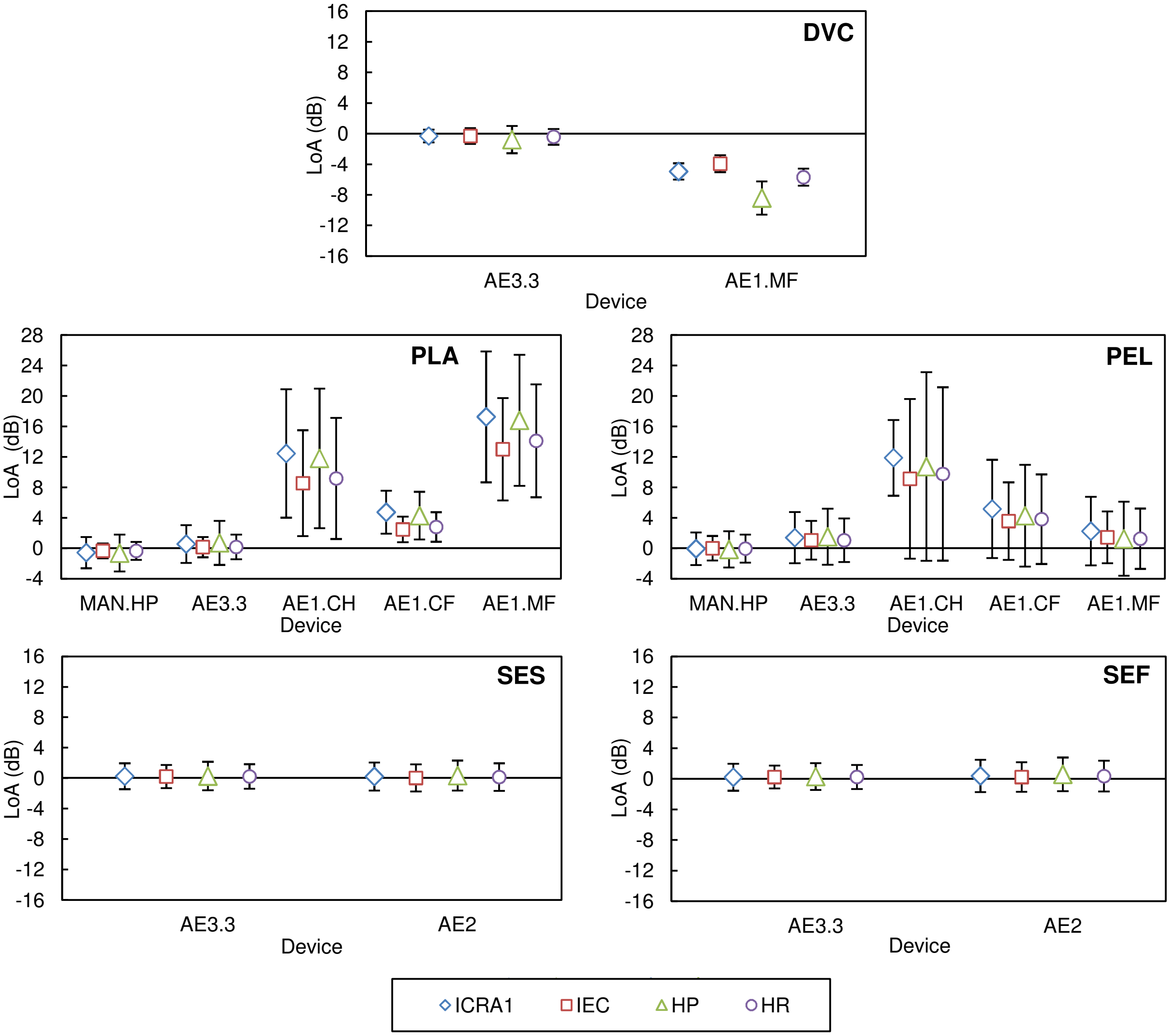

Figure 5.6: *Bland-Altman limits of agreement comparing each measurement setup to the reference acoustic manikin (MAN.SP) for the 16 possible setup-headset comparisons and four audio signals. The limits of agreement comprise a bias (symbol) and a variablity component (error bar) indicating the 95% interval of the difference between single measurements on the two setups. A negative bias indicates a lower diffuse-field related level with the measurement setup under test than the reference acoustic manikin.*

5.3.4 Validity of single number corrections

The dependent t-tests and one-way repeated measures ANOVAs conducted on the A-weighted in-ear/diffuse-field difference levels for the MAN.SP, AE3.3 and AE2 setups revealed a mixture of significant ($p < 0.05$) and insignificant differences across audio signals, headsets and setups. The difference between measurement setups (range: 0.0 to 0.6 dB) was much smaller than the difference between headsets (range: 0.0 to 5.2 dB) and audio signals (range: 0.0 to 5.5 dB). Consequently, the data were pooled over the MAN.SP, AE3.3 and AE2 setups to highlight the A-weighted in ear/diffuse-field difference levels over all audio signals and headsets when the third-octave conversion procedure is used, as per ISO 11904-2 [26]. These results are shown in Figure 5.7a. The mean A-weighted in-ear/diffuse-field difference ranged from 2.2 dB (SES headset with HP audio signal) to 11.1 dB (PLA headsets with the HR audio signal). In 14 of the 20 differences across audio signals and headsets, the A-weighted in-ear/diffuse-field difference was higher than the proposed 5 dB single number correction proposed in AS/NZS 1269.1 [5] and CSA Z107.56 [13]. The IEC and HR signals produced larger differences than the ICRA1 and HP audio signals. Standard deviations were relatively stable, from 0.6 to 1.7 dB across audio signals and headsets.

Mean A-weighted in-ear/diffuse-field differences for the AE1.CH, AE1.CF and AE1.MF setups are shown in Figure 5.7b. The difference ranged from 5.3 dB (PLA headset on AE1.MF with IEC audio signal) to 8.0 dB (DVC headset on AE1.MF with HP audio signal). In all 28 differences across audio signals and headsets, the A-weighted in-ear/diffuse-field difference was smaller or equal to the 8 dB single number correction. The HP and HR signals produced slightly larger differences than the ICRA1 and IEC audio signals. Standard deviations were not consistent, ranging from 0.3 to 9.5 dB across audio signals and headsets; they were notably smaller for the DVC headset from 0.3 to 0.4 dB, and larger for the PEL headset from 7.5 to 9.5 dB.

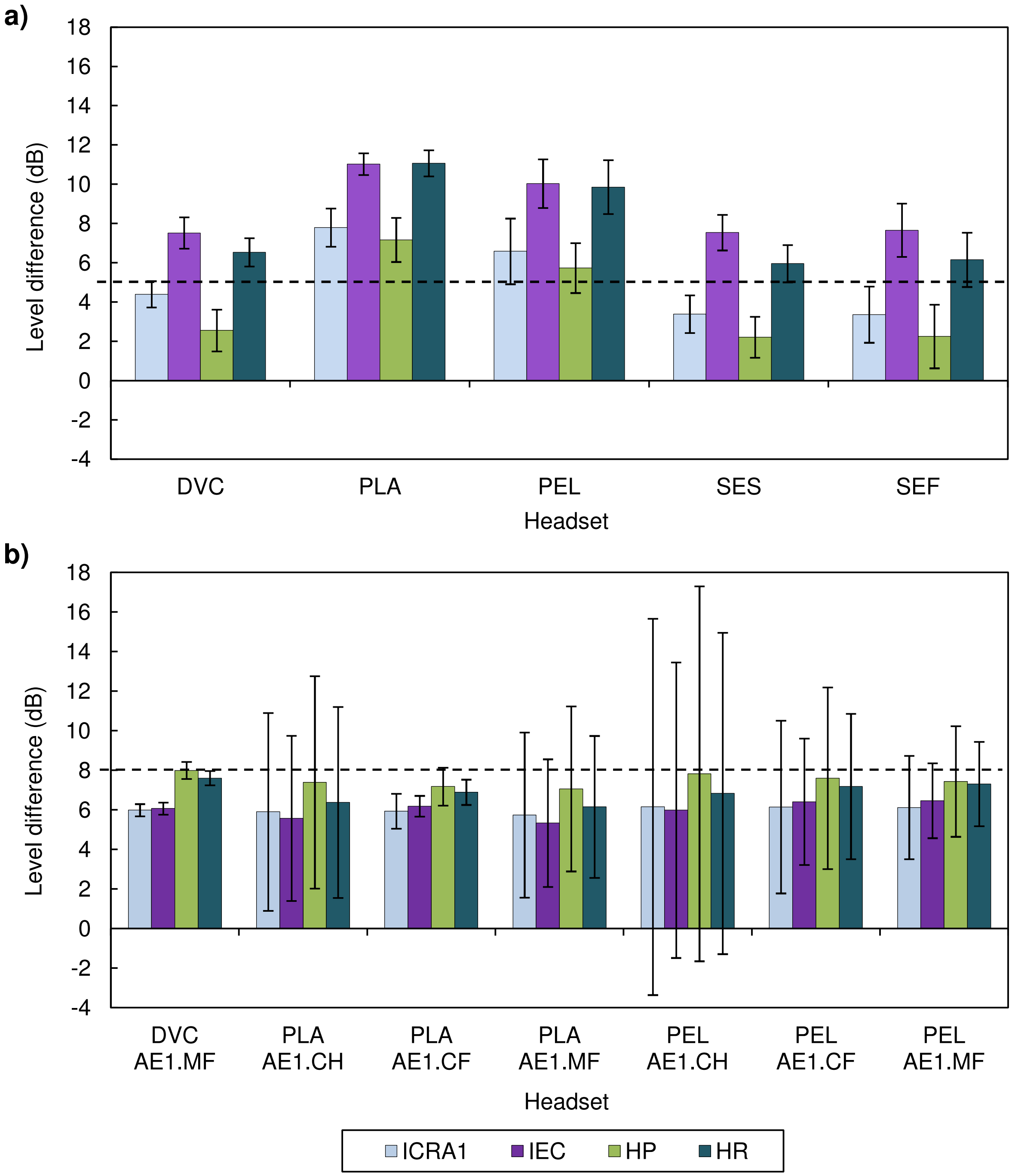

Figure 5.7: *a) Mean A-weighted in-ear/diffuse-field differences for the pooled MAN.SP, AE3.3, AE2 measurement levels using the third-octave correction factors specified in ISO11904-2 [26] for all audio signals and headsets. The 5 dB single number correction is shown as a dashed line. The between-subject standard deviation of the level differences is also shown. b) Mean A-weighted in-ear/diffuse-field differences for the AE1.MF, AE1.CH, AE1.CF setups using the third-octave correction factors based on Macrae [33] and ISO11904-2 [26] for all audio signals and applicable headsets. The 8 dB single number correction is shown as a dashed line. The between-subject standard deviation of the level differences is also shown.*

5.4 Discussion

Due to complicated field logistics and data transformation steps, specialized measurement methods, such as the use of MIRE and acoustic manikin techniques, can be technically challenging and are not often used by occupational health and safety professionals and other stakeholders in hearing loss prevention to assess sound exposure from communication headsets. Standard ISO 11904-2 [26], for example, describes the use of an acoustic manikin measurement setup with full head and torso simulator together with third-octave band sound conversion procedures to relate in-ear manikin measurements to the equivalent free or diffuse sound field. More compact measurement setups and simpler conversion procedures have been proposed in some standards (CSA Z107.56 [13] and AS/NZS 1269.1 [5]) and were evaluated in this study. Measurements on four test setups (manikin and Type 3.3, Type 2, and Type 1 artificial ears) with different methods of headset fitting were carried out in conjunction with third-octave band and single number conversion procedures. In all, data were collected over 21 different headset-measurement setup combinations and four different audio signals. Twelve participants experienced in the placement of hearing devices on real ears and/or artificial fixtures fitted the communication headsets twice on each measurement setup.

The KEMAR acoustic manikin (G.R.A.S. Type 45BA) with soft pinna (MAN.SP) served as the gold standard or reference method for testing the other measurement setups. The manikin and its variants are recognized for anthropomorphic testing in the fields of hearing conservation, telecommunication and noise abatement, as well as sound recording and sound quality. In compliance with the requirements of ITU-T P.58 [30], the manikin is built based on worldwide averages of human head and torso dimensions in order to provide acoustic diffraction and pick-up characteristics resembling those encountered by the median human head and torso. The manikin is designed to be used with one or two installed ear simulators IEC 60318-4 [21] and two artificial pinnae. It can accommodate all types of headsets and is compatible with ISO 11904-2 [26] for acoustic measurements from sources close to the ears.

5.4.1 Properties of each method

Prior to comparisons against the reference acoustic manikin, the statistical properties of each individual method were assessed to determine the various sources of measurement variability. The results, described in Table 5.6, revealed that the acoustic manikin with soft (MAN.SP) and hard (MAN.HP) pinnae, and the AE3.3 and AE2 setups, all produced relatively low levels of measurement variability characterized by between-subject (s_B) and within-subject (s_ω) standard deviations of at most 1.9 dB and 1.2 dB, respectively, over the different headsets and audio signals. In contrast, the AE1 setup produced measurement variability which was highly dependent on the fitting method used and headset tested, with between-subject (s_B) and within-subject (s_ω) standard deviations as high as 6.7 dB and 4.6 dB, respectively, in some conditions.

Of note, Annex B in ISO 11904-2 [26] reports a standard uncertainty of 0.5 dB for the repeatability of the mean of three fits and measurements with supra-aural earphones on the acoustic manikin. Using the within-subject standard deviation data from this study, a comparable estimate ($s_\omega/\sqrt{3}$) is obtained ranging from 0.2 to 0.7 dB over the two supra-aural devices (PLA, PEL) and four audio signals tested. Table 5.6 may thus prove useful in documenting between-subject and within-subject measurement variability associated with the different test setups for the purpose of estimating measurement uncertainty for specific testing conditions in the field. Other sources of uncertainty to consider include the microphone calibration and sound level meter uncertainty, the deviation of the test fixture from human subjects, the fluctuations in the test signal level, the variations in environmental conditions and the rounding error [26].

5.4.2 Agreement between methods

Bland-Altman's (LoA) were computed for the 16 possible comparisons between the reference acoustic manikin method (MAN.SP) and the other measurement setups. Since one-way repeated measures ANOVAs revealed an effect of the audio signal type on the bias component, Bland-Altman analyses were conducted independently for each audio signal and reported in Figure 5.6.

The AE1 method provided by far the largest bias among all test setups under comparison against the reference acoustic manikin (Figure 5.6). In addition, a much larger variability component for the LoA was observed with the AE1. Such a poor agreement of the AE1 with the reference acoustic manikin prompted more investigation into the third-octave diffuse sound field conversion procedure used, which was based on the work of Macrae [33]. As an alternative, use of the free-field transformation specified in Annex A of ANSI/ASA S3.6 [4] was investigated. In this standard, the free-field correction is based on the difference between the free-field equivalent sensitivity level and the coupler sensitivity level for two types of supra-aural audiometric earphones (Telephonics TDH 39, Telephonics TDH 49/50) and for a circum-aural headset (Sennheiser HDA 200). The average of the TDH 39 and TDH 49/50 free-field correction values was applied to measurement data obtained with the PEL and PLA supra-aural headsets on the AE1 setup. Similarly, the Sennheiser free-field equivalent correction was applied to the measurements taken with the DVC circum-aural headset. These new A-weighted free-field related estimates with the AE1 were then compared to the reference acoustic manikin (MAN.SP) measurements corrected for the free-field transformation specified in ISO 11904-2 [26]. While the variability component of the LoA hardly changed for the PLA, PEL, and DVC, bias increased for the PLA and PEL headsets when using the AE1 with the transformation specified in ANSI/ASA S3.6 [4] instead of the original transformation based on Macrae [33]. Bias was slightly closer to zero for the DVC headset when using the ANSI/ASA S3.6 [4] transformation specific for the Sennheiser audiometric headset. Overall, however, the results obtained with the AE1 setup were largely different from the reference acoustic manikin method using either sound field transformation procedure and provided much larger limits of agreement for both bias and variability components than all other measurement methods under comparison against the reference acoustic manikin (MAN.SP). This is not surprising since the transformation proposed in ANSI/ASA S3.6 [4] and the wide-band artificial ear to eardrum transfer function implicit in the method developed by Macrae [33] are very specific to certain types of audiometric earphones and cushion characteristics, and not to general-purpose headsets such as the PLA, PEL and DVC used in this study. Given the lack of agreement between the AE1 setup and the reference acoustic manikin (MAN.SP), as demonstrated by the overly large LoA (Figure 5.6), and the large between-subject and within-subject measurement variability obtained with the AE1 (Table 5.6), our results imply the non-suitability of the Type 1 artificial ear setup for sound measurements under communication headsets.

The AE3.3 and AE2 setups were also explored in this study and compared to the reference acoustic manikin (Figure 5.6). Bias for these two measurement devices was small (typically less than 1 dB), and in most cases negligible. The variability component of the LoA also proved to be relatively small (about 2 to 3 dB). Since the AE3.3 and AE2 measurement setups use the same ear simulator (IEC 60318-4 [21]) as the reference manikin (MAN.SP), the third-octave diffuse field correction specified in ISO 11904-2 [26] was used for all these setups, as specified in CSA Z107.56 [13]. The good agreement between the AE3.3 or AE2 setups and the reference acoustic manikin were therefore not surprising and confirmed their usability in the context of sound exposure measurement under communication headsets.

Finally, in addition to the use of the reference acoustic manikin with the soft pinna (MAN.SP), measurements were also taken on the acoustic manikin with a harder pinna (MAN.HP) to determine the effects of pinna hardness on measured levels for the supra-aural headsets (PLA, PEL). The variability component of the LoA was small and similar with both headsets (about -0.6 to 0.0 dB); however, the bias was slightly negative for measurements taken with the PLA headset while it was essentially nil for the PEL headset (Figure 5.6). The markedly more compliant headband of the PLA headset produced less pressure on the pinna than the stiffer PEL headset and therefore may have contributed to a small placement effect when fitted on the hard versus softer pinna. The mean negative bias introduced by the hard pinna on the PLA headset was however less than 0.5 dB over the four audio signals. Nevertheless, the use of the softer pinna (Shore-OO 35) is recommended in IEC/TS 60318-7 [22] and ITU Rec. P.57 [29] for acoustic manikin measurements.

5.4.3 Single number corrections

As an alternative to frequency-dependent transformations, diffuse-field levels can be estimated using single number corrections of 8 dB for the Type 1 artificial ear or 5 dB for the acoustic manikin, Type 3.3 artificial ear and Type 2 artificial ear, applied directly to the A-weighted in-ear measurements, as proposed in some national standards (AS/NZS 1269.1 [5], CSA Z107.56 [13]). However, the increased measurement uncertainty associated with this simplified transformation has not been established.

For the results pooled over the MAN.SP, AE3.3 and AE2 setups (Figure 5.7a), the mean A-weighted in-ear/diffuse-field difference levels ranged from 2.2 to 11.1 dB across headsets and audio signals. As such, the corresponding deviation from the proposed 5 dB single number correction ranged from 2.8 to +6.1 dB. As shown in Figure 5.7a the IEC and the HR audio signals, both richer in high frequencies (Figure 5.1), provided higher A-weighted in-ear/diffuse-field difference levels than the two other audio signals. Since more weight is given to the higher frequencies with the third-octave transformation, such results are expected. Likewise, the higher difference levels shown for the two supra-aural headsets (PLA, PEL) in Figure 5.7a are related to the poorer low frequency response of these headsets compared to the other headsets (Figure 5.3), which again increased the importance of the high frequency acoustic energy when converting the measured in-ear levels to the diffuse sound field.

For the AE1 setup, the mean A-weighted in-ear/diffuse-field difference levels ranged from 5.3 to 8.0 dB across headsets, audio signals and fitting methods (Figure 5.7b); thus, the corresponding deviation from the proposed 8 dB single number correction ranged from +0.0 to +2.4 dB. While the deviation from the proposed single number correction appears smaller for the AE1 setup than for the MAN.SP/AE3.3/AE2 setups, the between-subject standard deviation of the A-weighted in-ear/diffuse-field difference levels is much larger for the AE1 than for the other setups, up to 9.5 dB in some conditions (Figure 5.7b). The latter may indicate that fitting differences among participants introduced a strong frequency-dependent variability in the transmission of audio signals to the AE1 microphone.

In all, while simpler to use, single number correction values are by definition frequency-independent and therefore cannot account for the spectral differences in the different audio signals that can be received through communication headsets, nor the frequency response of different headsets that can be used. The difference between measured levels and the equivalent diffuse-field levels was expectedly dependent on the frequency responses of the headset and the spectra of the audio signal, in accordance with previous work [36]. Even though the 5 dB and 8 dB single number corrections are covered in the range of level differences (Figure 5.7), a large measurement uncertainty is introduced when using single number conversion factors instead of frequency-dependent functions such as provided in ISO 11904-2 [26].

5.4.4 Implications for field use

As discussed above, owing to the poor agreement with the reference acoustic manikin (Figure 5.6) and the large measurement variability (Table 5.6), use of a Type 1 artificial ear is not warranted for the measurement of the sound exposure from communication headsets at any stage of an assessment. In contrast, Type 2 and Type 3.3 artificial ears are in good agreement with the reference acoustic manikin and produce comparable between-subject and within-subject measurement variability. As such, these two measurement setups offer an alternative to the full acoustic manikin, especially in field situations or environments where a more compact setup is needed or desired. The Type 2 artificial ear was tested with one insert headset and found suitable with both foam and silicone ear tips. The Type 3.3 artificial ear was tested with one circum-aural, two supra-aural, and one insert headsets (foam and silicone tips).

In Figure 5.6, the limits of agreement shown for the different measurement setups were derived considering audio signal as a factor with fixed effect, and therefore they strictly apply to the specific audio signals under study. While the four signals chosen for this study exemplify the acoustical characteristics of different audio signals transmitted over noiseless and noisy communication channels, they do not cover the wide range of possible existing signals in a workplace setting. In practice, the exact nature of the audio signal may differ from the ones chosen in this study, or be a priori unknown. In order to provide more general limits of agreement to guide field use, the Bland and Altman [9] approach was extended assuming that the four audio signals used represented a random sample (with a random effect) from all possible audio signals. Table 5.7 summarizes these limits of agreement generalized over audio signals for the measurement setups (AE2, AE3.3 and MAN.HP) that are deemed to be suitable alternatives to the reference acoustic manikin (MAN.SP). These limits could serve as a guide for individuals who are faced with taking measurements under communication headsets in the field. The bias term is not significantly different from a null bias (0 dB) in 5 of the 9 comparisons and is within ±0.5 dB in all cases except for the +1.3 dB bias found for the supra-aural PEL headset with AE3.3. The variability component of the LoA varies from 1.2 to 3.4 dB across setups and headsets.

It is important to note that the LoA results in Table 5.7 express the 95% range of differences for single measurements performed on the two measurement setups being compared. In practice, multiple measurements may be taken and averaged in the field. This will reduce the range of the expected difference between the chosen measurement setup (AE3.3, AE2, MAN.HP) and the reference acoustic manikin method (MAN.SP). With an increasingly large number of replicated measurements and subjects, the LoA gradually reduces to the residual bias term in Table 5.7.

The generalized LoAs in Table 5.7 are computed assuming one-third octave band factors as per ISO 11904-2 [26] to relate in-ear measurements to diffuse-field sound levels. A large increase in measurement uncertainty was found when using a frequency-independent single number correction, owing to differences in audio signal spectra and headset frequency responses. For the Type 2 and Type 3.3 artificial ears and acoustic manikin, the mean A-weighted diffuse-field levels derived by use of one-third octave band factors and single number correction differed from each other over a range from -2.8 to 6.1 dB across the headsets and audio signals used in this study (Figure 5.7a). This, in effect, amounts to a large measurement bias that depends on the specific headset and audio signal tested, and which cannot be controlled through measurement averaging. From a practical standpoint, the use of a single number correction to approximate the diffuse-field transfer function of

Table 5.7: *Generalized limits of agreement (dB) for the Type 3.3 artificial ear, Type 2 artificial ear, and the acoustic manikin with hard pinna, with audio signals represented as a factor with random effects. The acoustic manikin with soft pinna is the reference method. The p value measures the significance of the bias term using chi-square analysis.*

Setup comparison	Headset type	Headset	$LoA = \bar{d} \pm 1.96\sqrt{\hat{\sigma}_d^2}$	p-value
MAN.SP vs AE3.3	Circum-aural	DVC	-0.4 ± 1.2	0.002†
	Supra-aural	PLA	0.4 ± 2.5	0.09
		PEL	1.3 ± 3.4	0.002†
	Insert	SES	0.3 ± 1.9	0.16
		SEF	0.3 ± 1.9	0.05†
MAN.SP vs AE2	Insert	SES	0.2 ± 1.9	0.43
		SEF	0.4 ± 2.3	0.11
MAN.SP vs MAN.HP	Supra-aural	PLA	-0.5 ± 2.2	< 0.001†
		PEL	-0.1 ± 2.3	0.8

† The bias term is significantly different than zero ($p < 0.05$). MAN.SP = Manikin with soft pinna, MAN.HP = Manikin with hard pinna, AE3.3 = Type 3.3 artificial ear, AE2 = Type 2 artificial ear, LoA = Limits of agreement.

the human ear thus appears to introduce an unacceptably large source of measurement error.

Finally, this study focussed only on methods to assess the sound exposure from the built-in audio channel of the communication headsets. In noisy work environments, the surrounding background noise may also reach the worker and contribute to the overall exposure, making this pathway dependent on the noise level and the amount of attenuation provided by the headset. Artificial ears are not well suited to estimate this exposure component due to possible sound transmission flanking pathways arising from the low acoustic isolation of these setups that are not designed for sound attenuation measurements, as cautioned in CSA Z107.56 [13]. An alternative is to use standardized methods applicable to hearing protectors (e.g. ISO 4869-2 [27]) to estimate the effective A-weighted sound level of the background noise. The overall sound exposure level when headsets are used is then computed from the energy sum of the audio signal and background noise components, both weighted by their relative duration in a typical 8h workday.

5.5 Conclusion

This research compared different measurement tools described in national and international standards for the assessment of noise exposure under communication headsets. Measurements on four test setups (manikin and Type 3.3, Type 2, and Type 1 artificial ears) with different methods of headset fitting were carried out in conjunction with third-octave band and single number conversion procedures. Results indicated the following:

1. The Type 1 artificial ear is not suited for sound measurements under communication headsets given the poor agreement between this test setup and the acoustic manikin technique specified in ISO 11904-2 [26] and the poor measurement repeatability;
2. The Type 2 and Type 3.3 artificial ears yielded a good agreement with the acoustic manikin technique and provided comparable measurement repeatability, making them suitable alternatives for sound measurements under communication headsets when compact test setups are needed; and
3. The use of single number corrections was found to introduce a large measurement uncertainty as they do not account for the spectral difference in the audio signals nor the frequency response of the headsets. Use of the third-octave transformation as per ISO 11904-2 [26] is preferred.

All in all, the results indicated that only measurement setups (Type 2, Type 3.3) based on ear simulator IEC 60318-4 [21] achieved a good agreement with the ISO 11904-2 [26] manikin technique. While widely available, the Type 1 artificial ear used for audiometric earphone calibration was not found to be suited to sound exposure measurements from the audio channel of communication headsets, and one has to look elsewhere for a practical survey method accessible to a wide range of professionals. The Canadian standard CSA Z107.56 [13] specifies a simple calculation method requiring only a sound level meter or noise dosimeter and computational steps relating overall sound exposure to the external background noise, the noise reduction of the device, and the effective listening SNR. However, more research is needed to fully characterize the effectiveness of this indirect method compared to established direct measurement methods such as the manikin and/or MIRE techniques.

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Chapter 6

Indirect Calculation Method

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Abstract

Measurement of noise exposure from the use of communication headsets worn in the workplace is challenging since two sound sources contribute to the overall noise exposure of the headset user. However, access to specialized equipment varies across different types of professionals and is often limited. The Canadian standard CSA Z107.56 proposes a simpler indirect calculation method to assess noise exposure under communication headsets. This method only requires basic equipment (sound level meter or noise dosimeter) and computational steps which consider the communication audio signal, background noise and headset noise reduction. The method assumes a fixed signal-to-noise ratio (SNR) of 15 dB above the protected background noise when listening through the audio communication channel. The goal of the present work is to further investigate the relationship between noise level, noise type, attenuation and speech listening level to test the validity of the single number SNR over different conditions. In a simulated noisy workplace environment, twenty-four participants were asked to adjust the volume of speech communication in different background noise and headset conditions, while executing a visual reaction secondary task. Results illustrate that the fixed SNR does not capture the variations that are introduced by the characteristics of one-sided versus two-sided headsets. A generalized equation is described to improve the accuracy of noise exposure predictions using the indirect calculation method.

6.1 Introduction

Noise in the workplace is a significant risk factor causing on average 16-24% of adult-onset hearing loss worldwide [19]. According to the U.S. National Health and Nutrition Examination Survey, 22 million American workers are exposed to hazardous noise on the job and approximately 10 million Americans suffer from hearing loss as a result [19, 25]. Among other sources, excessive noise exposure can result from the use of communication headsets or other wearable listening devices in the workplace. As such, the increasing use of these wired and wireless devices is raising concerns [22]. Communication headsets are now commonly found in many occupational settings, such as call centers, fast food outlets, airport ground and control tower operations, industrial and construction sites, military sites, etc. [10, 18]. According to an OSHA technical manual, approximately three million American workers can be exposed to hazardous noise levels due to the use of these headsets [21]. Depending on the needs of the workplace environment, the individual is either wearing a low-attenuating headset which enables hands-free communication (e.g., call center operator) or a noise-reducing headset enhancing communication in a noisy background (e.g., airline pilot) [7, 28]. While the use of the headset may vary according to the workplace, in all cases the user is exposed simultaneously to the surrounding workplace noise and the in-headset audio communication signal which is an important factor on the worker's overall noise exposure [18].

Assessments of noise exposure under communication headsets are complex and pose several methodological challenges related to field logistics and data transformation. Firstly, two sound sources contribute to the overall noise exposure of the headset user and must therefore be considered. The audio communication signal (e.g., speech) is generated by the headset and is typically adjusted by the user to overcome the masking effects of background noise entering the device in order to ensure proper reception. Secondly, since the headset produces sound at or in the ear, the acousto-mechanical properties of the head, pinna, and ear canal must be accounted for [7]. Thirdly, in order to obtain a realistic assessment, measurements must be taken while the worker is operating normally and conducting typical daily tasks. Finally, following data collection, in-ear measurements must be transformed to diffuse-field measurements to enable a comparison with occupational regulatory limits [7, 10].

Specialized equipment and techniques are typically required for direct sound measurements under communication headsets. ISO 11904 describes two procedures for the direct measurement of sources close to the ear such as noise under communication headsets: the Microphone in a Real Ear (MIRE) technique [14] and the acoustic manikin technique [15]. Since the MIRE technique requires special expertise and the manikin method can be cumbersome to use in the workplace, the Australian and New Zealand Standards AS/NZS

1269.1 [2] proposed a general-purpose artificial ear (the Type 1 artificial ear) for headphones and the use of an ear simulator (the Type 2 artificial ear) for insert earphones. In addition, the Type 3.3 artificial ear has also been proposed in the Canadian standard Z107.56 as another alternative to conducting measurements under communication headsets [5].

A recent survey distributed to Canadian occupational health and safety professionals and hearing loss prevention stakeholders indicated that there is a wide range of expertise regarding noise measurement from communication headsets. Moreover, access to basic or specialized equipment varies across the different types of professionals and is limited in some cases [18]. For some occupational settings (e.g., call centers, retail stores), conducting direct exposure measurements could cost as much or more than it would cost to reduce background sound levels by controlling reverberation or purchasing headsets that provide superior attenuation [10]. Therefore, as an alternative to the other direct measurement methods, an indirect calculation method has been proposed to predict noise exposure in workplace settings where communication headsets are worn [3, 5, 10]. This calculation procedure requires only the use of a sound level meter or noise dosimeter and simple computational steps. It is based on the assumption that to hear and understand the communication signal, workers must adequately adjust the headset audio volume depending on the level of the surrounding background noise and the headset attenuation. The calculation steps are represented by Equation 6.1 below, which is based on the energetic sum of sound levels from two interdependent components of the exposure: the surrounding background noise (term 1) and the communication audio signal (term 2). In the first term, the headset noise reduction (NR) is subtracted from the A-weighted external background noise level (BN) to estimate the protected noise level when the headset is worn. In the second term, listening through the audio communication channel is assumed to take place at a fixed signal-to-noise ratio (SNR) above the protected noise level (BN-NR), corrected for the listening duration (t) over the noise assessment period (T) [5, 10].

$$L_{eq,t,headset} = 10log\left(10^{(BN-NR)/10} + \frac{t_{on}}{t}10^{(BN-NR+SNR)/10}\right) \tag{6.1}$$

The effective listening SNR in Equation 6.1 derives from a relationship between the total headset noise exposure ($L_{ex,T}$), and the background noise and attenuation of the device found in a secondary analysis of earlier field studies involving communication headsets [10]. These studies reported measurements in a wide range of occupations, where various headsets, background noise types, and background noise levels were noted. In the first study [7, 17], measurements were conducted in noisy and quieter settings in nine different work sites where various intra-aural, supra-aural, and circum-aural devices were worn. In the second study [4], measurements were taken under five passive and active communication devices worn by crew members of a Hercules Aircraft. Analysis of the results indicated a mean A-weighted SNR of 13.7 dB (+/- 5.9 dB) averaged over all measurements [10]. For simplicity, standard CSA Z107.56 adopted an A-weighted effective listening SNR of 15 dB, a value slightly above the mean value from the field data in order to capture slightly more than 50% of possible cases when using Equation 6.1 [5]. It is interesting to note that in a review of studies on portable music devices, an average listening SNR of approximately 13 dB was established [27]. This preferred listening value is within the same range as that of listening to speech through communication headsets [10].

In another set of studies, the effect of headset attenuation and earphone type on the chosen preferred listening level was investigated. A study by Hodgetts and colleagues [13] illustrated the influence of earphone type and attenuation in addition to background noise (babble and street noise) on preferred music listening levels ranging from 8 to 17 dB. Studies conducted by Fligor and colleagues [8, 9] investigated the effect of earphone attenuation on preferred listening levels of portable music device users in different background noise types and levels. When headset attenuation was considered, equivalent free-field music levels against background noise were identical across devices indicating that listening level differences were directly related to attenuation. Similar results were presented by Henry and Foots [12] who also indicated that users of portable music devices increased listening levels in noise compared to a quiet condition. Lastly, Portnuff and colleagues [23] found that music levels were set higher with supra-aural earphones that provided little attenuation, than with circum-aural earphones that provided more attenuation. While music levels increased proportionally with background noise levels, the SNR decreased slightly when background noise was high.

In summary, the above-mentioned studies describe strong interactions between headset type, headset attenuation, background noise type, background noise level, and preferred listening levels. While the proposed indirect calculation procedure (Equation 6.1) offers a simple approach that occupational health and safety stakeholders can use in the early stages of a noise assessment program or in situations when there is no or little access to more complex sound measurement equipment, it is based on a number of assumptions. In particular, the 15 dB SNR proposed in the standard CSA Z107.56 [5] is a simple approximation of the field data. The use of a fixed SNR assumes that the in-headset communication signal level is independent of the background noise level and noise type, and the headset configuration (e.g., one-sided versus two-sided).

The goal of the present work is to further investigate the relationship between the different factors affecting speech listening levels when communications headsets are used. In a simulated noisy workplace environment, participants were asked to adjust the headset listening volume for effective speech communication while carrying out a secondary task. The latter involves visual reaction and even/odd number discrimination to simulate divided attention, which is common when carrying out aural communication in the workplace. Different background noise conditions (noise level and type) and headset conditions (headset type and attenuation) were explored. This study was designed to test the validity of using a single number listening SNR over a wide range of conditions with the indirect calculation method or propose refinements tailored to different noises and headset characteristics or configurations.

6.2 Materials and methods

6.2.1 Participants

Twenty four English speaking adults (12 males, 12 female) of working age, from 19 to 39 years (mean = 27, SD = 5) participated in this study. Participants were required to have learned English before the age of eleven to be eligible. Prior to the participation, a basic four step auditory screening was conducted. Participants were first asked to complete a brief questionnaire on their auditory history and exposure to noisy activities. Examination of the external auditory canal was then performed with an otoscope and tympanometry was conducted to provide information on the middle ear and the mobility of the eardrum. Pure tone audiometry was also conducted in a double-walled audiometric room to determine if hearing thresholds were within normal limits established for this study. Normal hearing was defined as hearing thresholds better or equal to 20 dB HL in the speech frequency range (0.5 - 4 kHz) and below or equal to 25 dB HL at 0.25, 6kHz and 8 kHz.

All experiments were conducted at the Hearing Research Laboratory at the University of Ottawa. Recruitment of participants was carried out by means of posters displayed in various settings including the University of Ottawa and community centers. The experiment was approved by the Office of Research Ethics and Integrity of the university.

6.2.2 Headsets

Two headsets used in different occupational settings were chosen for this experiment. The David Clark 40642G-01 (DVC) is an attenuating two-sided circum-aural headset designed for high noise environments. The Peltor MT32H01 (PEL) headset is a non-attenuating one-sided supra-aural headset used in military and industrial settings. The frequency response of the communication channel of these two headsets was measured on a KEMAR® G.R.A.S. Type 45BA acoustic manikin and is presented in Figure 6.1. Responses are within 5 dB in the range of 250-1600 Hz for both headsets, but much larger differences are found at higher and lower frequencies.

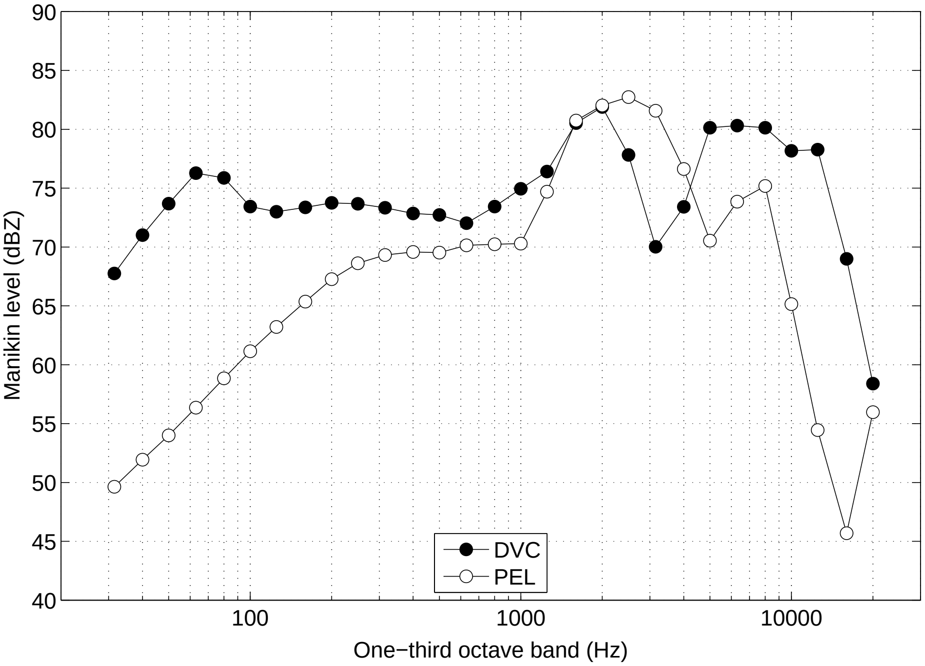


Figure 6.1: *Frequency response of the headsets measured on an acoustic manikin. The input is a pink noise electrical signal. The output from each device is scaled to an in-ear manikin level of 90 dBA for comparison purposes.*

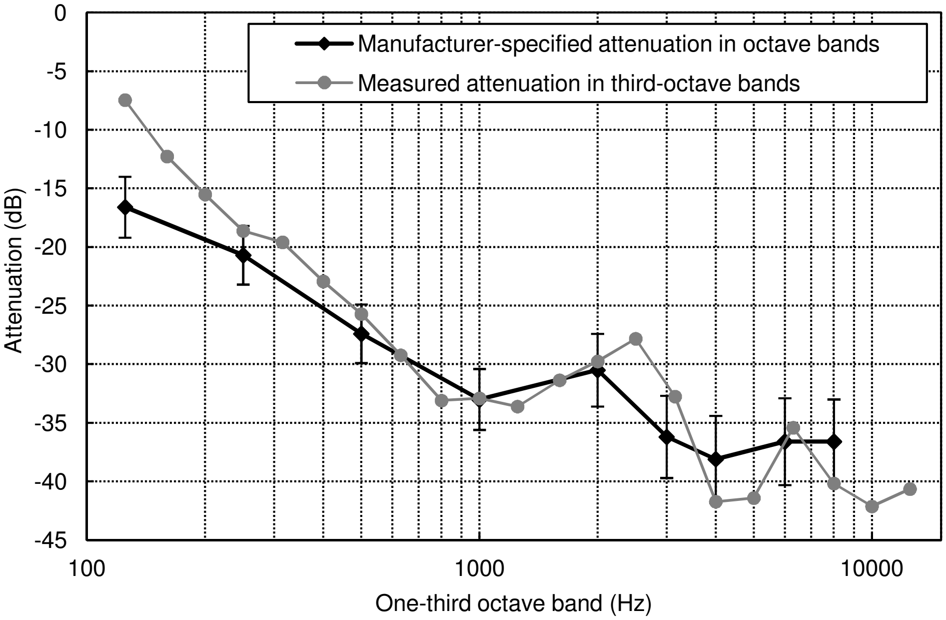


Figure 6.2: *Attenuation curves for the DVC headset provided by the manufacturer and measured in-lab on an acoustic manikin. The standard deviation provided by the manufacturer is also displayed.*

Table 6.1: *Example HINT sentences including accepted variations in responses [26].*

1. (A/the) boy fell from (a/the) window.
2. (A/the) wife helped her husband.
3. Big dogs can be dangerous.
4. Her shoes (are/were) very dirty.
5. (A/the) player lost (a/the) shoe.
6. Somebody store the money.
7. (A/the) fire (is/was) very hot.
8. She's drinking from her own cup.
9. (A/the) picture came from (a/the) book.
10. (A/the) car (is/was) going too fast.

According to manufacturer's specifications, the DVC headset has a noise reduction rating (NRR) of 23 dB, calculated from laboratory attenuation data performed according to ANSI S3.19 [1]. In addition, attenuation at octave-band frequencies is provided by the manufacturer. Third-octave band attenuation measurements were obtained for this headset on the KEMAR® G.R.A.S. Type 45BA acoustic manikin with a pink noise signal. The manufacturer-specified and measured attenuation curves for the DVC headset are illustrated in Figure 6.2. Since there is no attenuation data provided by the manufacturer for the PEL headset, and considering that it is non-attenuating, its noise reduction is assumed to be zero for the purpose of estimating communication headset exposure [5].

6.2.3 Stimuli

Speech communication signals

Sentences from the Hearing-In-Noise Test (HINT) were used as the communication signal in this study. The American English version of the HINT [26] consists of simple short sentences spoken clearly and naturally in a conversational style [24]. Table 6.1 provides example sentences from the American English HINT [20]. The complete speech material consists of 240 sentences. Speech-shaped noise, a continuous signal with a long-term spectrum equivalent to that of an average HINT sentence list, is also included in the HINT material. This signal was used to calibrate the sentences presented through the headset

Table 6.2: *Description of the three background noises tested.*

Selection	Abbreviation	Description of noise recording
Construction	CST	Urban street road construction in Toronto.
Crowd	CRW	Busy commuter train station in Toronto.
Plane	PLA	Royal Canadian Air Force Hercules airplane.

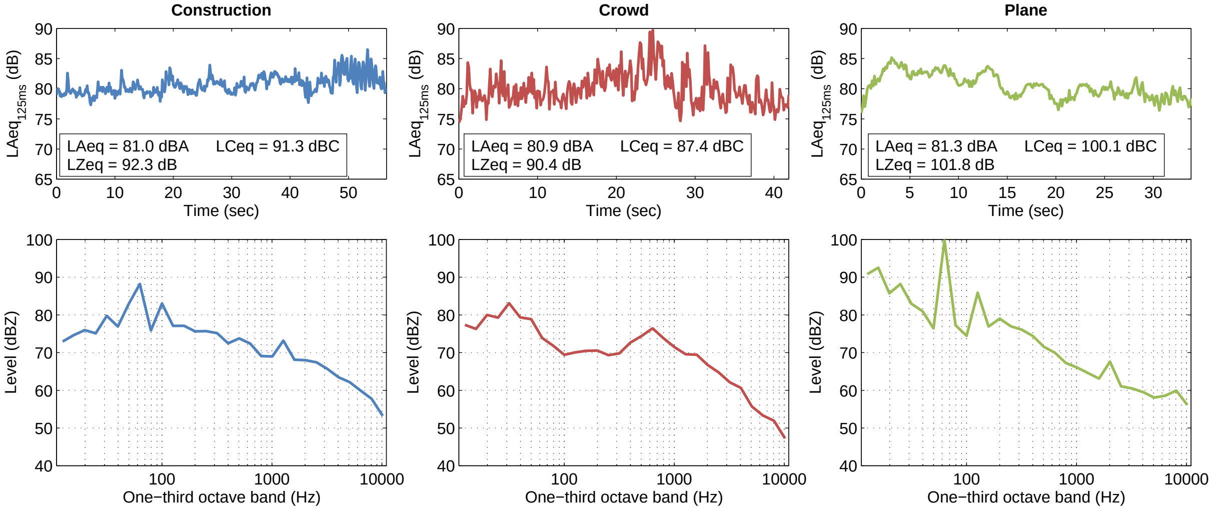


Figure 6.3: *Short-term sound level and one-third octave band spectrum for each background noise.*

in terms of the A-weighted diffuse-field related sound level using an acoustic manikin and the procedure in ISO 11904-2 [15].

Background noises

Three different background noises were used in this study (Table 6.2). Each noise exemplifies a background noise that can be encountered in the noisy workplace and that could hinder communications. The short-term temporal evolution of the sound level and the average spectrum of these noises are presented in Figure 6.3. Background noises were calibrated to the same A-weighted sound pressure level and played at 50, 60, 70, and 80 dBA with the non-attenuating PEL headset and 70, 80, 90, and 100 dBA with the attenuating DVC headset. Noises were between 30 to 60-s long and were looped continuously for the entire duration of each experimental condition.

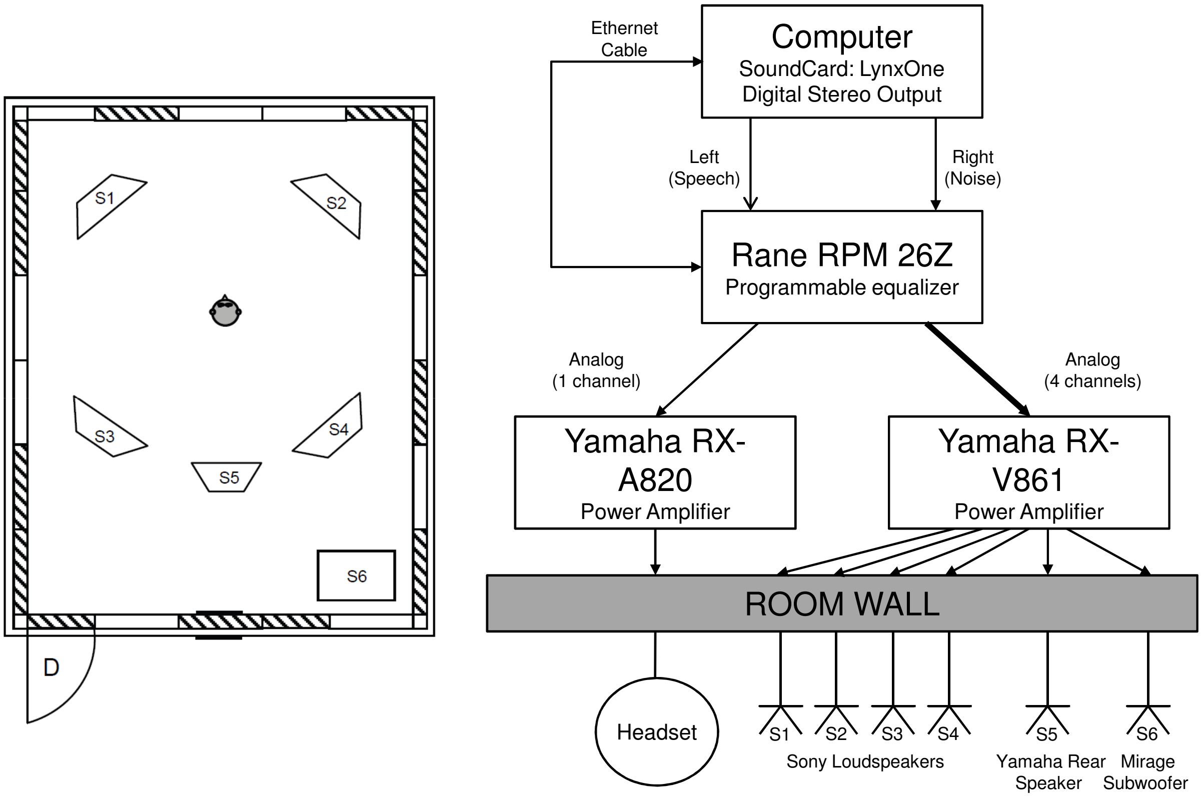


Figure 6.4: *The left panel illustrates the layout of the simulation room and loudspeaker configuration. Sound absorptive and reflective panels are represented by shaded and unfilled rectangular shapes respectively. The loudspeakers used to generate a diffuse noise field are represented with S1 to S6.The right panel schematizes the hardware system for generating background noise and in-headset speech audio signals.*

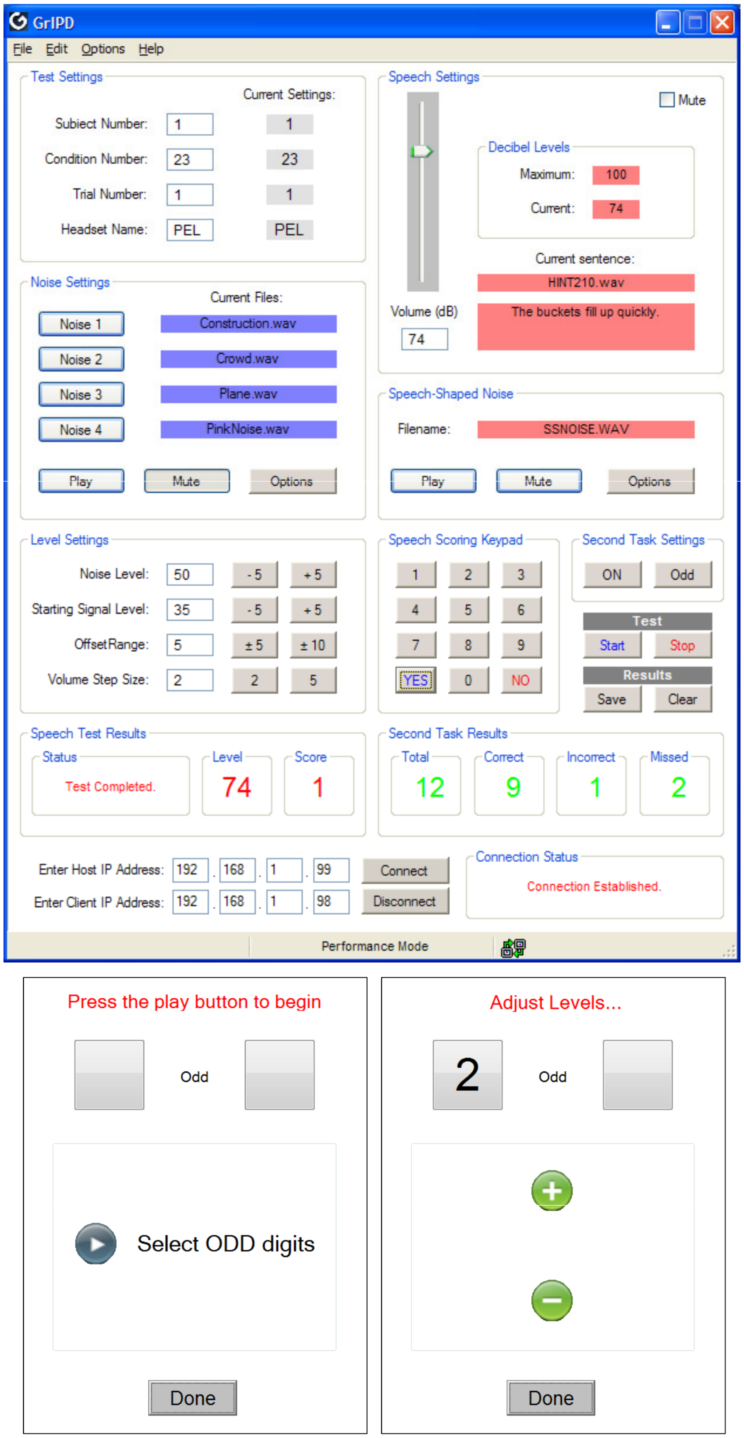
6.2.4 Experimental setup

The experimentation was conducted in a noise simulation room (4.29m long x 3.65m wide x 2.42m high) with 35 wall and ceiling panels (22 sound absorptive and 15 sound reflective). Figure 6.4 (left panel) presents a layout of the room. A diffuse noise field was created within the room by a speaker system consisting of four tower loudspeakers S1 S4 (Sony MF600H), a bookshelf speaker S5 on a stand (Yamaha NS-C155) and a subwoofer S6 (Mirage Sub12). The participant was seated at the center of the diffuse noise field, facing the back of the room, with the speech communication signal presented through a headset. Figure 6.4 (right panel) illustrates the system used to generate the background noise and in-headset speech communication signals. These signals were produced on a desktop computer outside the simulation room through two channels of a stereo soundcard (LynxOne): right channel for noise and left channel for speech. The noise channel was spectrally equalized to compensate for the room response via a programmable multiprocessor unit (RANE RPM 26Z) and sent to the six-speaker system via a power amplifier (Yamaha RX-V861). The operator controlled the presentation of the background noise and other experimental parameters by means of a dedicated software interface (Figure 6.5).

6.2.5 Testing procedure

Primary task

From the control center, the experimenter presented background noise and in-headset speech at pre-determined levels using an Operator interface (Figure 6.5 (top panel)) by entering four parameters (i.e. subject number, condition number, trial number, headset name). The participant was handed a tablet with a Level Adjustment interface prepared with the Pure Data visual programming language (Figure 6.5 (bottom panel)). Upon simultaneous presentation of the background noise and the in-headset speech signal, the participant was asked to adjust the volume of consecutive HINT sentences. Specific instructions were given for the execution of the task: "Adjust the headset volume to a level which ensures comfortable understanding in conditions where communication is essential to job performance while executing another task (e.g., airplane pilot, firefighter). The level will start low. Raise it, and adjust up and down when you get closer. Take as much time as you want when adjusting, don't feel rushed." Additional information was given to instruct the participant to explore the range of levels that could be considered comfortable by raising the speech signal to a very high level and refining the adjustment on the way down. The starting level of the in-headset sentences was randomly chosen between -10 dB and -20 dB SNR assuming a headset attenuation of 20 dB for DVC and 0 dB for PEL. When satisfied with the volume of the speech signal, the participant was given a test sentence which s/he was asked to repeat. The selected headset level and the correctness of the repeated sentence were recorded. The sentences were used as a control. To meet the inclusion criterion, the participant was required to repeat at least 80% of the sentences correctly.



Test Settings

	Current Settings:
Subject Number: 1	1
Condition Number: 23	23
Trial Number: 1	1
Headset Name: PEL	PEL

Noise Settings

Current Files:
Noise 1: Construction.wav
Noise 2: Crowd.wav
Noise 3: Plane.wav
Noise 4: PinkNoise.wav

Speech Settings

☐ Mute

Decibel Levels
Maximum: 100
Current: 74

Current sentence: HINT210.wav
The buckets fill up quickly.

Volume (dB): 74

Speech-Shaped Noise
Filename: SSNOISE.WAV

Level Settings
Noise Level: 50
Starting Signal Level: 35
OffsetRange: 5
Volume Step Size: 2

Second Task Settings

Speech Test Results

Status	Level	Score
Test Completed.	74	1

Second Task Results

Total	Correct	Incorrect	Missed
12	9	1	2

Enter Host IP Address: 192 . 168 . 1 . 99
Enter Client IP Address: 192 . 168 . 1 . 98

Connection Status: Connection Established.

Press the play button to begin
Odd
Select ODD digits

Adjust Levels...
2 Odd

Figure 6.5: *Top panel: Operator interface. The experimenter enters the subject, condition, and trial number, and triggers the start of a given condition. The chosen preferred level and the results of the secondary task are displayed once the test is completed. Bottom panel: Participant level adjustment interface (2 examples). The green buttons are used to control the level of the speech in the headset. The boxes are the secondary task.*

Secondary task

A secondary task involving a visual reaction and even/odd number discrimination was presented simultaneously with the primary auditory task. This simulated a situation of divided attention and execution of multiple tasks as commonly found in the workplace. This task was integrated on the same screen as the volume adjustment interface on the tablet computer (Figure 6.5 (bottom panel)). On the monitor, two boxes were presented and a digit between 1 and 8 appeared at quasi-random intervals in one of these two boxes. Upon presentation of the number, the participant was asked to touch the box containing the digit if the number was odd or to touch the box not containing the digit if the number was even. To increase the difficulty of the task, the desired parity could be inverted randomly throughout the experiment and the participant was asked to respond in the opposite manner. Participants had to react quickly while maintaining a high level of accuracy. Each digit remained on the screen until the participant touched one of the two boxes or for a maximum of 2.5 seconds. This timeout was to encourage fast responses where misses or false positives reflect workplace distraction. The next digit appeared after a random interval of time between 2 and 5 seconds after the previous digit had disappeared. The number of correct answers as well as misses and false positives were recorded for each trial. Like the sentence correctness data, the data from the secondary task was only used as an inclusion criterion. The participant was required to have reacted, correctly or incorrectly, to 80% of digit presentations.

Experimental conditions

Each participant completed 24 test conditions for all headset-noise-level combinations (two headsets x three background noises x four levels) and each condition was tested twice. Listening in a quiet setting was carried out with each headset before and after the noise conditions, resulting in 52 trials in total. The testing order for headsets and background noises was counterbalanced across participants. Noises were presented at different levels in either ascending (trial 1) then descending (trial 2) order or vice-versa. Prior to the experimentation, four practice conditions were executed with the first headset used to test that participant (quiet and a moderate noise level with each background noise). Following each trial, the system displayed and stored the A-weighted diffuse-field related speech level, sentence correctness, and score on the secondary task (correct, incorrect, and missed responses, and total digits presented).

6.3 Results

6.3.1 Individual results

All twenty-four participants met the requirement of having reacted to 80% of digit presentations and having repeated at least 80% of the sentences correctly. Figure 6.6 displays the A-weighted diffuse-field related speech levels for selected participants with both DVC and PEL headsets. Results for two participants are shown for each headset to illustrate the range of listening speech level observed between participants in the Quiet and Noise conditions. As shown, when the participant selected a lower speech listening level in the Quiet condition, subsequent listening levels increased rapidly and nearly proportionally with the level of the construction, crowd or plane noises. When the participant selected a higher speech listening level in the Quiet condition, the listening levels in the noise conditions did not increase as rapidly, creating a much flatter growth curve as a function of noise level.

6.3.2 Group results

The mean A-weighted diffuse-field listening level of speech and standard deviation across the twenty-four participants is displayed in Figure 6.7 for the three background noises and two headsets. For each noise in a given headset, the increase in speech level as a function of noise level follows a very similar curve. However, there are large differences between headsets. In quiet, the mean A-weighted diffuse-field listening levels for the DVC and PEL headsets were 62 dBA and 68 dBA, respectively. In noises ranging from 70 to 100 dBA, listening levels with the DVC headset increased from 69 to 84 dBA in the construction and crowd noises, and similarly from 70 to 86 dBA in the plane noise. With the PEL headset,

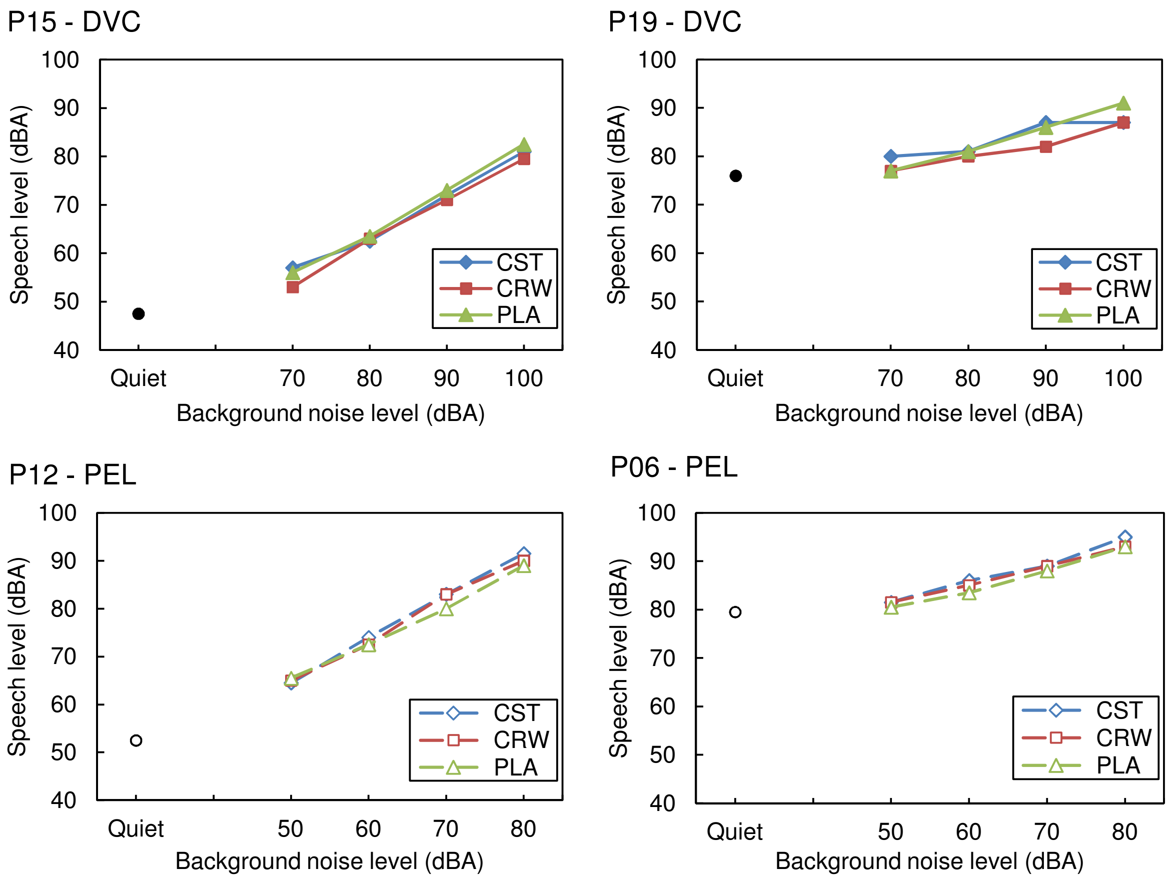


Figure 6.6: *Examples of A-weighted diffuse-field related speech listening levels selected by four participants in quiet and in four different levels of construction (CST), crowd (CRW) and plane (PLA) background noises with the David Clark (DVC) and Peltor (PEL) headsets. Results are averaged over two trials. The noise attenuation of DVC headset is not considered in these graphs.*

listening levels increased from 74 to 87 dBA in all noise types over the range 50-80 dBA. The standard deviation was largest in quiet, ±11 dB for DVC and ±12 dB for PEL, and decreased as the background noise becomes louder to ±4 to 5 dB for DVC and ±4 dB for PEL at their respective highest noise level.

A two-way repeated measures analysis of variance was conducted to explore the impact of background noise type (CST, CRW, PLA) and level on the A-weighted diffuse-field speech listening level with each headset. For the DVC, there was a statistically significant interaction between noise type and noise level on the speech listening level [F(6, 138)=3.10, p=0.029]. Simple main effect analyses showed that the speech listening level was signif-

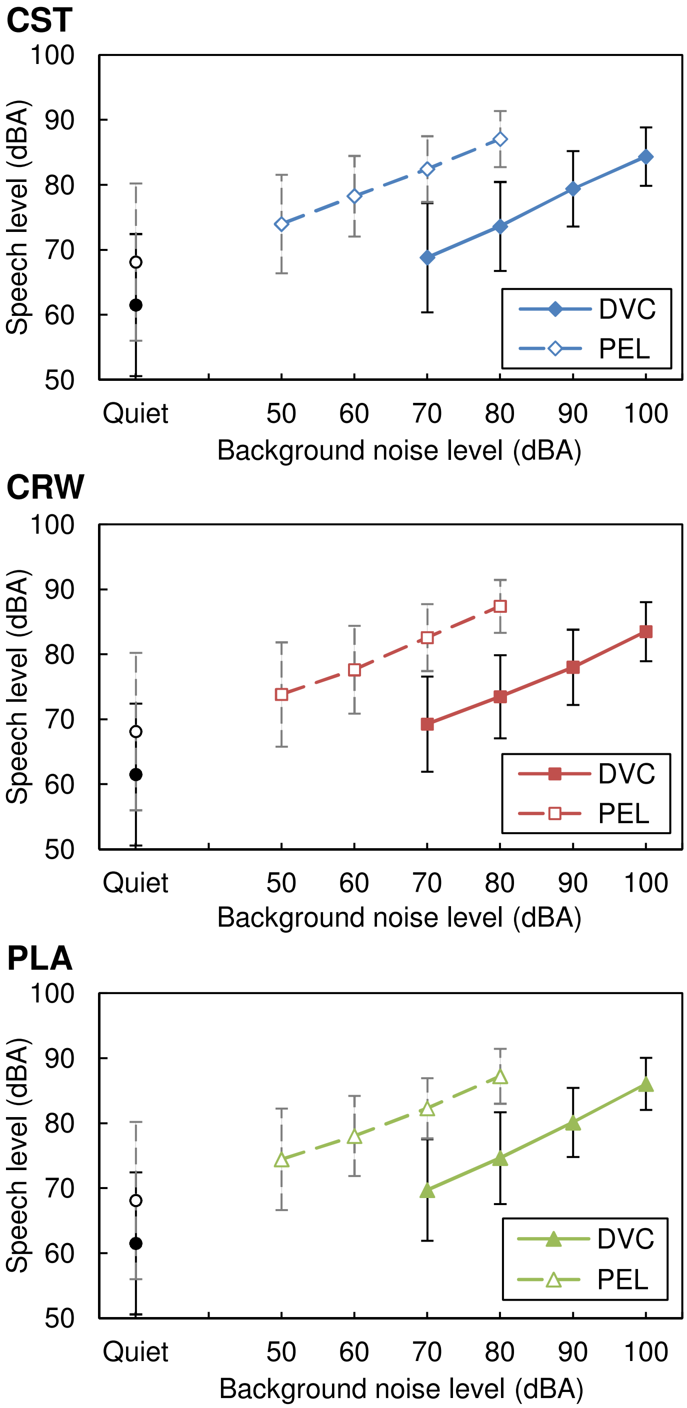


Figure 6.7: *Mean and standard deviation (n=24) of A-weighted diffuse-field related speech listening level with the David Clark (DVC) and Peltor (PEL) headsets in quiet and in construction (CST), crowd (CRW), and plane (PLA) noises at different levels. The noise attenuation of DVC headset is not considered in these graphs.*

icantly different across noise levels for each noise type: CST [F(3, 69)=56.17, p<.0001], CRW [F(3, 69)=61.07, p<.0001], and PLA [F(3, 69)=62.01, p<.0001], all with a large effect size (partial eta-squared of about 0.9). Speech level differences were about 15 dB from the lowest (70 dBA) to the highest (100 dBA) noise level. There were no differences between noise types when the noise level was at 70 dBA [F(2, 46)=1.18, p=3.18] and 80 dBA [F(2, 46)=3.07, p=0.056]. At 90 dBA, speech listening level in CRW noise (78.0 dBA) was significantly different [F(2, 46)=11.33, p<.0001] to the levels in noises CST (79.4 dBA) and PLA (80.1 dBA) noises. Similarly, at 100 dBA speech listening level in PLA noise (86.1 dBA) was significantly different [F(2, 46)=15.60, p<.0001] to the levels in CST (84.4 dBA) and CRW (83.5 dBA) noises. Two-way repeated measures analysis of variance for the PEL revealed no significant main effect for noise type [F(2, 46) = 0.074, p=.929] and for the interaction effect between noise type and noise level [F(6, 138) = 0.963, p=.453]. Again, a significant effect for noise level was determined [F(3, 69) = 115.215, p<.0001], with a large effect size (partial eta-squared of about 0.8). Speech level differences were about 15 dB from the lowest (50 dBA) to the highest (80 dBA) noise level.

For the DVC headset, the protected noise level when the headset is worn was estimated by taking into account the manufacturer's laboratory attenuation data by octave band according to ANSI S3.19 [1] or by using the NRR value specified by the manufacturer. The A-weighted noise reduction of the DVC headset for each noise was then calculated using four different approaches specified in CSA Z94.2 [6], as follows:

- Octave-band (OB) procedure without derating: Steps 1 to 11 of octave-band procedure in Table B.2 of the standard were carried out. No derating was applied to calculate the A-weighted noise reduction.
- Octave-band (OB) procedure with derating: Steps 1 to 12 of octave-band procedure in Table B.2 were carried out. The derating multiplier of 70% specified for earmuffs was applied.
- Single number derated NRR calculation for use with C-weighted sound measurements: The A-weighted noise reduction was obtained according to Table 2 of the

Table 6.3: *A-weighted noise reduction values obtained with four methods specified in CSA Z94.2 [6].*

Noise	Noise reduction			
	OB without derating	OB with derating	NRR C-weighting	NRR A-weighting
CST	23.0	16.1	16.1	13.1
CRW	25.8	18.1	16.1	13.1
PLA	19.9	13.9	16.1	13.1

standard by subtracting 70% of the NRR value from the C-weighted background noise level.

- Single number derated NRR calculation for use with A-weighted sound measurements: The A-weighted noise reduction was obtained according to Table 2 of the standard by subtracting 70% of the NRR, reduced by 3 dB, from the A-weighted background noise level.

Table 6.3 list the A-weighted noise reduction values estimated for the DVC headset in each noise using the different methods of calculation. These values were used to shift the DVC curves of Figure 6.7 to show the mean A-weighted diffuse-field related speech levels as a function of the protected noise level. This is shown in Figure 6.8 for the four different methods of calculating the noise reduction. Because the PEL is non-attenuating, a noise reduction of 0 dB is assumed in all noise conditions and the protected noise level is identical to the external noise level for this headset.

In comparing Figures 6.7 and 6.8 we notice that the gap between the headsets diminishes considerably in the noise conditions once the DVC curves are corrected for the amount of noise reduction; however, differences persists that vary according to the method of calculating the noise reduction. When the octave-band procedure is applied, a gap of about 6 dB in speech levels is found between the one-sided PEL headset and the two-sided DVC headset when derating is used (Figure 6.8b), while a less noticeable gap is found when derating is not considered (Figure 6.8a). The largest difference between both headsets, about 10 dB, is noted when the derated NRR for use with C-weighting is applied (Figure 6.8c). When the derated NRR for use with A-weighted noise levels is applied

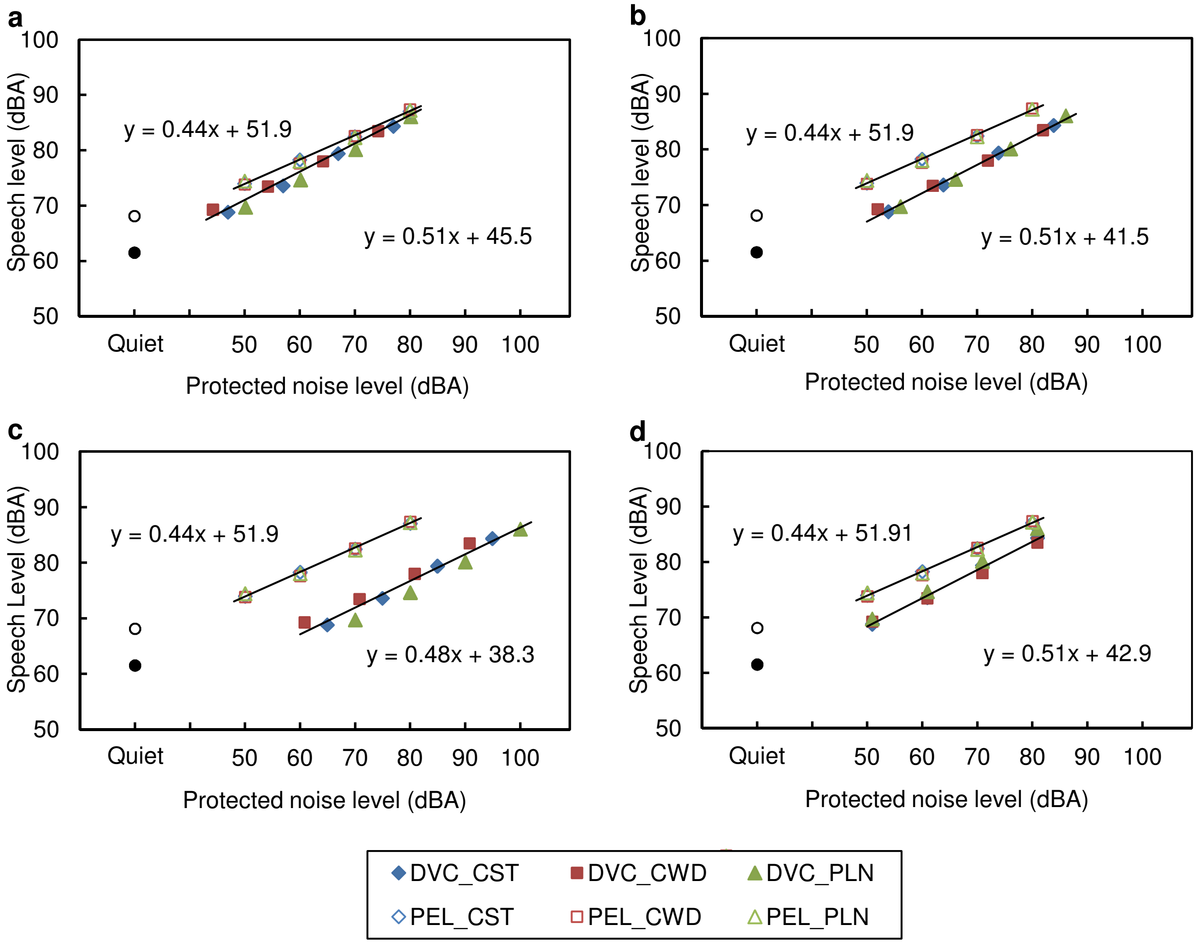


Figure 6.8: *Mean A-weighted diffuse-field related speech listening level (n=24) with the DVC and PEL headsets in construction (CST), crowd (CRW), and plane (PLA) background noise as a function of the protected noise level. The protected level when the DVC headset is worn is computed according to CSA Z94.2 [6] using (a) the octave-band method without derating, (b) the octave-band method with derating, (c) the NRR with derating for use with C-weighted noise levels, and (d) the NRR with derating for use with A-weighted noise levels.*

(Figure 6.8d), the gap between the two headsets is close to the one with the octave-band method with derating (Figure 6.8b). Because the noise reduction of the DVC headset does not affect the quiet condition, the gap between both headsets (about 6 dB) is identical in all cases.

6.4 Discussion

While national and international standards specify direct methods of noise exposure measurements for sources close to the ears, the CSA Z107.56 [5] standard also proposes a simple calculation procedure to assess the equivalent sound level arising from work activities involving headsets. A fixed listening SNR value of 15 dB is specified to estimate the value at which a worker would adjust the headset speech level above the assumed protected level in order to calculate overall diffuse-field related sound level when communication headsets are used. This study was designed to test whether this relationship holds true for different listening conditions. Preferred listening levels were obtained from 24 participants with different headset types (one-sided PEL and two-sided DVC devices) and attenuation, background noise conditions (construction, crowd, plane), and background noise levels (from 50 to 80 dBA with PEL and from 70 to 100 dBA with DVC).

6.4.1 Interpretation of results

Listening levels varied across participants in the quiet condition (Figure 6.6). When the participant selected a lower listening level in quiet, the following adjustments increased rapidly with the background noise level at a rate of about one dB per dB. When the participant selected a higher listening level in quiet, subsequent adjustments did not increase as rapidly, creating a flatter growth curve. In addition, the standard deviation was largest in quiet as well as for the lower background noise settings, and smallest in the higher background noise settings. An average of 62 dBA was noted for DVC and 68 dBA for PEL in quiet, resulting in a 6 dB difference between headsets.

In noise, Figure 6.7 illustrates that the increase of speech level was similar with the three noises. To enable a better comparison of both headsets, the speech listening level was plotted as a function of the protected noise level. This value is the difference between the A-weighted background noise level (BN) at the listener's position and the A-weighted noise reduction of the device (NR). The PEL headset is a one-sided non-attenuating supra-aural device according to the manufacturer, and its noise reduction is therefore assumed to be zero [5]. The DVC is a two-sided circum-aural device, complete with manufacturer-specified attenuation data obtained according to ANSI S3.19 [1]. For this device, four different methods of calculating the A-weighted noise reduction in the three background noises based on CSA Z94.2 [6] were used: the octave-band approach with and without derating, and the single number NRR approach for use with C-weighted and A-weighted sound measurements and derating (Table 6.3). Figure 6.8 shows the resulting speech listening levels as a function of protected noise levels obtained with each method. Since a linear relationship was clearly apparent between speech listening levels and protected noise levels for each headset independently of noise type, overall trend lines were calculated for each headset and method of estimating the protected noise level. Differences in speech listening levels emerged between the headsets. The size of these differences was dependent on the method of estimating the noise reduction of the DVC headset. For example, when the noise reduction of the DVC headset was calculated according to the octave-band approach without the derating factor, speech listening levels increased nearly identically with the protected noise level and the trend lines were almost overlapping (Figure 6.8a). Differences of about 3-5 dB, 5-7 dB, and 10 dB were noted between headsets when the protected noise level was obtained using the derated NRR for use with A-weighted sound measurements (Figure 6.8d), the octave-band method with derating (Figure 6.8b), and the derated NRR for use with C-weighted sound measurements (Figure 6.8c), respectively. Of note, the speech level difference obtained in noise using the octave-band method with derating (Figure 6.8b) is nearly the same size as the difference of 6 dB found between headsets in quiet.

The speech listening level differences between headsets in Figure 6.8 depend on the method of estimating the noise reduction of the DVC headset, but may also be related to other factors such as differences in the frequency response of the communication channel between headsets (Figure 6.1) or differences due to monaural (one-sided PEL headset) versus binaural (two-sided DVC headset) listening. The latter involves binaural summation of speech signals, which typically provides a significant listening advantage of 6 to 10 dB over monaural listening [11]. To test the influence of binaural summation in this study, a post-hoc experiment was conducted with the DVC headset connected in monaural (right ear

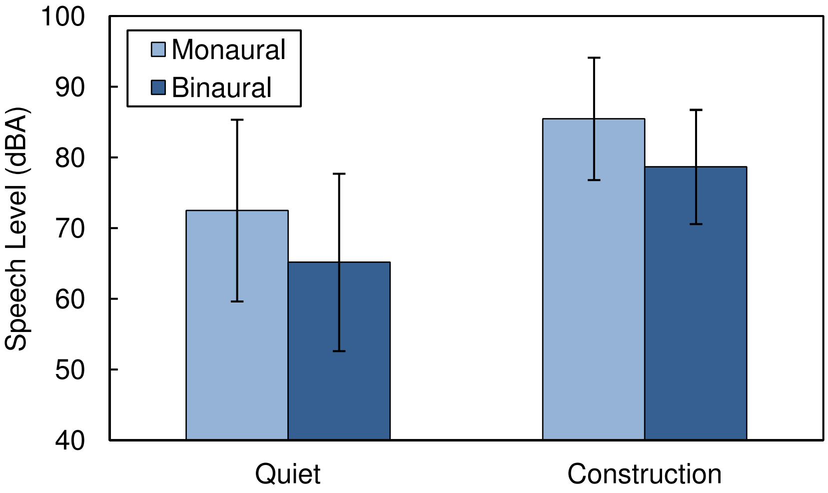


Figure 6.9: *Mean A-weighted diffuse-field related speech listening level and standard deviation with the DVC used with a monaural and binaural configuration in quiet and in construction noise at 90 dBA (n = 4).*

only) and binaural configurations. Using the same instruction as in the main experiment, four participants were asked to adjust the speech level in quiet and in construction noise at 90 dBA wearing the DVC headset in the two listening configurations. As shown in Figure 6.9, the mean speech listening levels differed by approximately 7 dB between the monaural and binaural configurations in both quiet (monaural 72.5 dBA, binaural 65.2 dBA) and in construction noise (monaural 78.7 dBA, binaural 85.5 dBA). The size of the effect is consistent with the broader literature on binaural summation. Therefore, the latter is an important factor to consider when assessing the speech listening level with one-sided and two-sided communication headsets. Given that the effect of binaural summation was found to be the same in both quiet and in noise (Figure 6.9) and that the size of the effect corresponds very closely to the speech listening level differences found between the two headsets when using the octave-band method with derating (Figure 6.8b), the latter method seems the best suited to estimate noise exposure from communication headsets. This is not unexpected since the octave-band method with derating for calculating attenuation is described as the method with the greatest potential accuracy [6].

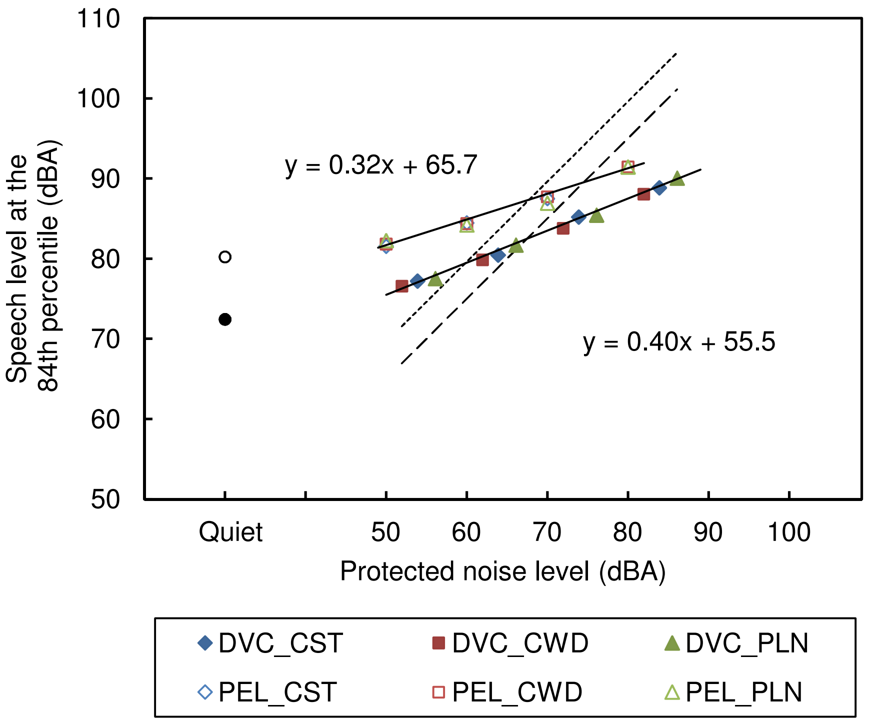


Figure 6.10: *A-weighted diffuse-field related speech listening level at the 84th percentile with the DVC and PEL headsets in construction, crowd, and plane background noises at different protected noise levels depending on the headset ($n = 24$). A trend-line considering the data points of each noise is traced and the corresponding equation is displayed. The 15 dB SNR suggested in standard CSA 107.56 is represented with a dashed line. The 19.6 dB SNR (mean plus one standard deviation) is derived from Giguère and colleagues [10] and is represented with a dotted line.*

6.4.2 Implications for field use

Typically, a population coverage factor of 80 or 84% is used to estimate the exposure level not exceeded by a proportion of workers wearing hearing protectors (e.g., ISO 4869-2 [16]). Extending this approach to communication headset exposure, the mean speech listening level plus one standard deviation is considered here. Figure 6.10 shows the resulting speech listening levels at the 84th percentile as a function of protected noise levels for the two headsets. It is based on the data from the octave-band approach with derating (Figure 6.8b), which was found to be the best suited to estimate communication headset exposure. Figure 6.10 enables a comparison between the findings of this study and the fixed 15 dB single number SNR suggested in standard CSA Z107.56 [5] or the SNR of 19.6 dB (mean of

13.7 dB plus one standard deviation of 5.9 dB) from Giguère and colleagues [10]. Use of a fixed SNR clearly overestimates the slope of the growth function for speech listening levels in noise. As a result, the 15 dB SNR proposed in CSA Z107.56 [5] matches the results from this study only over a narrow range of protected noise levels around 65-75 dBA, with corresponding speech exposure levels around 80-90 dBA. At higher protected noise levels, speech exposure is overestimated with a fixed SNR, and the converse occurs at lower protected levels. Consequently, the fixed SNR approach currently specified in standard CSA Z107.56 [5] appears adequate only for basic screening of a potential exposure above 90 dBA or below 80 dBA, but does not adequately capture the variations that are introduced by the characteristics of the headset (one-sided versus two-sided) and the growth of speech listening levels with increased protected noise levels. These two elements are necessary for more accurate exposure assessments.

A modified calculation procedure is proposed to consider the different factors uncovered in the present study, such that:

$$L_{eq,t,headset} = 10log\left(10^{(BN-NR)/10} + \frac{t_{on}}{t}10^{[m(BN-NR)+b]/10}\right) \tag{6.2}$$

The first term in Equation 6.2 corresponds to the noise component of the exposure and is identical in the original procedure in Equation 6.1. The second term has been adjusted to account for the growth of speech listening levels according to Figure 6.10 and involves two parameters (a slope m and a constant value b) instead of a single SNR. Furthermore, these parameters depend on whether the headset is one-sided or two-sided. For two-sided headsets, m = 0.40 and b = 55.5 dBA whereas for one-sided headsets, m = 0.32 and b = 65.7 dBA. With these parameters, Equation 6.2 is scaled to represent the 84th percentile of expected exposure (mean plus one standard deviation). Note that because of the decreasing standard deviation with noise level (Figure 6.7), the slope in the 84th percentile plot in Figure 6.10 is slightly lower than the mean slopes in Figure 6.8.

6.5 Conclusion

The CSA Z107.56 [5] standard describes an indirect calculation procedure as a simpler method compared to specialized techniques involving an acoustic manikin, artificial ears or microphone in a real ear setups for estimating exposure from the use of communication headsets. This calculation procedure only requires the use of a sound level meter or noise dosimeter to estimate the background noise around the user, as well as the manufacturer's specifications regarding the noise reduction of the headset, and thus can be viewed as an extension of current standardized methods for hearing protectors. Based on a survey distributed to Canadian occupational health and safety professionals and hearing loss prevention professionals, expertise regarding noise measurement from communication headsets and access to basic or specialized equipment varies across the different types of professionals and is limited in some cases [18]. Therefore, such an indirect measurement method could often be useful when a quick assessment of noise exposure is required, when specialized equipment is not available, or when the professionals lack the required training to uses more advanced measurement techniques.

The calculation procedure described in CSA Z107.56 [5] considers the energetic sum of sound levels from two interdependent components of the exposure: the surrounding background noise and the speech communication signal. Based on the findings of this study, a generalized equation is suggested to improve the accuracy of the method to better model the growth of speech listening levels as a function of the protected noise level and to account for the effect of binaural summation when both one-sided and two-sided headsets are considered. The current work did not uncover differences in quasi-continuous noise types that would affect the calculation method. Further investigations are warranted in highly fluctuating noises as well as with level-dependent devices to provide more insight on the impact of these factors on the speech listening levels when using communication headsets.

6.6 Acknowledgements

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Chapter 7

General Discussion and Conclusion

This doctoral thesis studied the topic of communication headsets in the workplace and examined the measurement methods used to estimate noise exposure under these devices. The following chapter summarizes the work and its contributions to the fields of health and safety and hearing loss prevention. In addition, findings of this thesis are discussed in terms of implications for standardization and hearing loss prevention programs. Finally, limitations of this study are presented along with future research directions and concluding remarks.

7.1 Summary of research and knowledge contributions

With the increased use of wired and wireless headset devices, this work addressed an important gap on measurement methods used to evaluate noise exposure under communication headsets in the workplace, as well as knowledge of measurement methods and access to equipment by OHS and HLP stakeholders. This three-step study consisting of a survey questionnaire, and two laboratory experiments investigated these topics.

7.1.1 Questionnaire to stakeholders

In the first article of this thesis (Chapter 3), stakeholders in occupational health and safety (OHS) and hearing loss prevention (HLP) in Canada were surveyed to assess their knowledge of the measurement of noise exposure under communication headsets in the workplace and their access to the various devices needed to conduct such measurements. A bilingual questionnaire, created and reviewed by several professionals with relevant expertise in the field, was distributed to different groups of OHS and HLP professionals including audiologists, occupational hygienists, researchers, acoustical consultants, and individuals from standardization bodies, among others. Data were analyzed by tallying the frequency of responses for the close-ended questions and by extracting key words from the open-ended questions. The questionnaire results contributed new data documenting the level and variation of expertise amongst OHS and HLP stakeholders in Canada regarding noise measurements under headsets and the access to basic (i.e. sound level meter, noise dosimeter) and specialized (i.e., acoustic manikin, artificial ears, Microphone in a Real Ear) equipment. Different needs and levels of expertise were uncovered for the different groups of OHS and HLP stakeholders thereby validating the need to propose several methods to conduct communication headsets noise exposure assessments (e.g. direct specialized methods and the indirect calculation procedures). Within this thesis, results of the questionnaire reinforced the need to conduct the following two studies where measurement methods are compared and the indirect calculation method is further investigated. Subsequently, these methods should be tailored to the different groups of professionals and appropriate guidelines or training material should be developed in order to integrate the use of communication headsets in a hearing loss prevention program at the noise measurement and education levels.

7.1.2 Comparison of direct measurement methods

Research was warranted to investigate the compatibility of the different measurement methods for communication headsets. To this end, the second article (Chapter 4) was a pilot study that compared measurement setups, headset fitting methods, and conversion factors for the measurement of noise exposure under communication headsets. A single participant, expert in the field of interest, positioned four types of headsets (David Clark, Plantronics, Etymotic, Sensear) on four measurement setups (acoustic manikin, Type 3.3, Type 2, and Type 1 artificial ears) while acoustic measurements were collected for six different audio signals (ICRA 1, ICRA 5, IEC 60268-1, HINT sentences, plane noise, crowd noise) from 12 fits/refits. This work provided a preliminary examination of the differences between measurement methods and conversion factors. It contributed mainly to the development of the full experimental protocol described in the following chapter by giving insight on the best fitting configurations to use with the Type 3.3 and the Type 1 artificial ears to compare them with the acoustic manikin and best simulate field measurements in a laboratory setting.

The experiment in the next article (Chapter 5) expanded on the pilot study using multiple participants (e.g., engineers, audiologists, and researchers) who had, within their scope of practice, experience in the fitting of earphones, hearing protectors and/or headsets on real ears, manikins, and/or artificial ear test measurement setups. Twelve participants positioned four types of headsets (David Clark, Plantronics, Peltor, Sensear) on four measurement setups (acoustic manikin, Type 3.3, Type 2, and Type 1 artificial ears) described in international and national standards while acoustic measurements were collected for four different audio signals (ICRA 1, IEC 60268-1, HINT sentences and plane noise, HINT sentences and riveter noise). This research provided empirical data to answer questions on the measurement repeatability for each individual setup, the measurement agreement between the different test setups, and the accuracy of the third-octave band procedure in comparison to single number corrections to convert in-ear sound levels to the diffuse field. Results indicated that the Type 1 artificial measurements widely deviate from the acoustic manikin and that this setup is not suitable for sound exposure measurements under communication headsets. The Type 2 and the Type 3.3 artificial ears were in close agreement with the acoustic manikin, and either measuring device was deemed suitable for use in the field when more compact test setups are needed and/or for convenience. Furthermore, the use of the third-octave transformation described in ISO 11904-2 [5] was favoured over single number corrections, which were found to introduce a large measurement uncertainty.

These findings contributed new knowledge for future revisions of existing standards and to develop more comprehensive guidelines on the use of different measurement setups for the assessment of noise exposure under communication headsets in the workplace.

7.1.3 Indirect calculation method

The last article of this thesis (Chapter 6) investigated the indirect calculation method described in CSA Z107.56 [2] as a simpler alternative to complex measurements of noise under communication headsets. Currently, the standard adopts a fixed A-weighted effective listening signal-to-noise ratio of 15 dB above the protected noise level to estimate exposure when listening through the audio channel of communication headsets. This research further studied the relationship between noise level, noise type, attenuation and speech listening level to test the validity of this single number signal-to-noise ratio (SNR) over different conditions. In a laboratory setting, twenty-four participants adjusted the in-headset speech level in three different background noises (construction, crowd, plane) at different levels (50 dBA to 100 dBA) while wearing two different headsets (David Clark, Peltor). To simulate a workplace environment where multi-tasking and divided attention is common, participants were also asked to respond to a concurrent secondary task. This study provided new data to answer questions regarding the effect of various factors on speech listening level with the use of communication headsets. It was found that the growth of speech listening levels as a function of noise levels is less than one. Furthermore, this data illustrated a difference in speech listening levels of 6-7 dB between a one-sided and two-sided headset. These observations implied that the fixed SNR suggested in the standard CSA Z107.56 [2] does not capture the variations introduced by different noise levels or listening configurations of the headset. Therefore, a new set of equations was proposed in this thesis to refine the calculation method.

7.2 Practical implications of the work

This work impacts standardization bodies and the implementation of hearing loss prevention programs. The integration of knowledge from this work in a hearing loss prevention program (HLPP) could provide an upstream approach towards the prevention of hearing loss in the workplace.

7.2.1 Implications for standardization

Findings from this work impact current standardization documents such as CSA Z107.56 [2] and future revisions. Firstly, results from the last study of this thesis (Chapter 6) warrant refinement of the indirect calculation method presently defined in this Canadian standard where a fixed listening SNR of 15 dB is suggested for exposure estimation. Considering our findings, a new equation can be proposed which better addresses some of the key factors that affect the in-headset speech level exposure. The indirect calculation method proposed in CSA Z107.56 [2] is an efficient mean to obtain preliminary assessments in occupational settings where high noise levels are suspected. Therefore, refining this simple method is invaluable to stakeholders in HLP who often do not have access to specialized measurement equipment. Secondly, the second (Chapter 4) and third studies (Chapter 5) illustrate the unsuitability of the Type 1 artificial to conduct noise exposure assessment when headsets are used. While this artificial ear is appropriate for calibrating certain types of supra-aural and circum-aural audiometric earphones, standardization bodies should consider removing it from current standards on noise measurements under communication headsets (e.g., CSA Z107.56 [2], AS/NZS 1269.1 [1]) due to large test-retest variability and poor agreement with more established methods such as the acoustic manikin. Finally, as uncovered from the questionnaire survey (Chapter 3), knowledge and access to different measurement tools for noise exposure evaluations under communication headsets is not homogeneous across professionals in the field. This validates the need for specifying different methods addressing the needs and expertise of various groups of OHS and HLP stakeholders in standards documents in order to maximize opportunities for proper noise exposure assessments when communication headsets are used in the workplace.

7.2.2 Implications for hearing loss prevention programs

While the use of communication headsets in the workplace is creating concerns, hearing loss prevention programs, more specifically at the noise measurement and education levels, have often not been adapted or even considered scenarios where workers use these devices in occupational settings. Assessment of exposure due to communication headsets are seldom conducted within HLPP partially due to the complicated technical and field logistics or lack of knowledge. Several factors must be considered to integrate headset noise exposure assessments in a hearing loss prevention program such as the different sources of noise, the lack of monitoring by health and safety in occupational settings that are not typically considered high risk, and the need for specialized measurement methods to assess exposure from sources close to the ears. This thesis contributes new knowledge on these three factors and could help the integration of noise exposure measurements under communication headsets more routinely in hearing loss prevention programs as well as the creation of guidelines to inform the appropriate groups of stakeholders.

In terms of the different sources of noise and lack of monitoring, the last study (Chapter 6) supports the need for integration of headset noise exposure assessment in HLPP by providing examples of the elevated speech level adjustment of participants at high noise levels and the resulting overall exposure due to the different sources of noise. While some occupational settings such as retail stores are not considered high risk, results from this research show that the sound exposure from the use of communication headsets could exceed regulatory limits in environments where the background noise is only moderately loud, especially when one-sided headsets are used. For this reason, a better understanding of the measurement tools for conducting noise assessments under headsets is important. To this end, this research provides better knowledge on the different direct and indirect methods for noise exposure assessments when communication headsets are used in the workplace. More specifically, this thesis documents the degree of agreement between methods proposed in national standards and the acoustic manikin proposed in the international standard. It also quantifies the increase in measurement uncertainty associated to the single number correction over the third-octave transformation for converting at-ear measurements to the diffuse field (Chapters 4 and 5). Findings on the limits of each method could be integrated in HLPPs to guide the use of different measurement tools by stakeholders and would consequently have effects at the noise measurement level. Considering the differences in access to equipment and knowledge of the methods for noise exposure measurements under headsets by various groups of professionals, as noted in the results of the survey questionnaire (Chapter 3), informative documents on the advantages and disadvantages of each method could be helpful.

7.3 Limitations and future work

Although this research has reached its aim and made several contributions to the field, it is important to note some limitations which could lead to future work on the topic.

The first study of this thesis (Chapter 3) was a questionnaire distributed to OHS and HLP stakeholders. As is commonly observed with surveys distributed over an online platform, the response rate was lower and subjected to sampling bias. Nevertheless, patterns were clearly apparent within the responses of the groups of stakeholders interested in this topic and results still provided valuable information on knowledge and access to equipment by these professionals.

The second and third studies (Chapters 4 and 5) of this thesis compared measurement methods suggested in national standards, the Type 3.3, Type 2, and Type 1 artificial ears, with the reference acoustic manikin described in the international standard. While the acoustic manikin proposed in ISO 11904-2 [5] can be considered a gold standard against which to compare simplified measurement test setups based on the use of a simulated ear, and was used as such in this work, the international standard ISO 11904-1 [4] also describes the Microphone in a Real Ear (MIRE) technique as a specialized method for sources close to the ears. The MIRE technique can be invasive and requires expertise for probe/microphone placement but it provides the most direct estimate of the worker's sound exposure and is generally believed to possess the best face validity. Use of this technique is warranted in future studies for a more comprehensive evaluation of all possible methods to assess noise exposure from communication headsets. New sound measurement products that facilitate the implementation of the MIRE technique in the field have recently been introduced on the market.

While there were many possible testing combinations in studying the effect of headset types, noise types, and noise levels on preferred listening level of speech under communication headsets, choices had to be made to isolate certain factors of interest and to limit the duration of the experimental session. Several avenues remain possible for future research, especially regarding the last study (Chapter 6) of this thesis. Firstly, background noises with slow long term fluctuations (construction, crowd, plane) were selected to represent real noises common in some workplaces. While results indicated that these noise types did not affect speech listening levels selected by the participants, background noises with short term fluctuations, or impact and impulse noises are also common in different workplace settings. Such signals could affect speech listening levels as it is well known that speech recognition thresholds are lower in fluctuating noises than in continuous noises [6]. Secondly, when estimating noise exposure from communication headsets, individuals with hearing loss should be considered. Compared to normal hearing individuals, this population often requires an SNR 2 to 10 dB higher for the same speech recognition [3]. Future considerations could compare listening speech levels between normal hearing and individuals with hearing loss wearing headsets to further understand this effect on listening speech levels to refine the calculation procedure to this specific case. Thirdly, a one-sided non-attenuating supra-aural headset (Peltor) and a two-sided attenuating circum-aural headset (David Clark) were selected for the work in this thesis and results indicated that headset configuration (one-sided versus two-sided) was a factor affecting speech listening levels. Future investigations with different headsets for example with active noise cancellation or level-dependent devices, and/or intra-aural devices are warranted to further understand the relationship between headset type and the listening level of speech. Lastly, while much effort was made to simulate a workplace environment, it is difficult to completely replicate a field environment where the worker's attention is divided between multiple tasks in a laboratory setting. To this end, tests conducted in the field could help obtain more accurate results of speech listening levels.

7.4 Concluding remarks

In conclusion, the research presented in this thesis is an important step towards understand and refining methods for assessing noise exposure under communication headsets. New information is provided on the expertise of different Canadian stakeholders on the topic of noise measurement under communication headsets and their access to the necessary equipment. A comprehensive set of data were collected and analyzed regarding the degree of agreement between various test measurement setups, including the impact of different transformations to estimate the diffuse-field related sound level from communication headsets. Finally, factors affecting the speech listening level set by users of communication headsets were investigated. Several presentations, posters and publications have arisen from this work and future publications are being considered. Knowledge from the present work has important applications for occupational health and safety and hearing loss prevention professionals as well as for standardization bodies with the ultimate goal of creating an upstream approach towards preventing hearing loss in the workplace.

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Chapter 8

Statement of Contributions

8.1 Co-authors

The following section outlines the contributions of the authors to the journal articles included in this thesis.

Flora Nassrallah, the doctoral candidate, assumed responsibility for this research project under the direction of Professor Christian Giguère. The interdisciplinary team of authors included Professor Christian Giguère, at the School of Rehabilitation Sciences, Professor Hilmi R. Dajani, at the School of Electrical Engineering and Computer Science, and Dr. Nicolas Ellaham, research associate at the laboratory. The authors provided support and expertise in the fields of hearing sciences, acoustics and engineering. Both professors were involved in the conception of the project. Meetings were held regularly throughout the process to discuss progress, experimental design, methodology, and interpretation of the results.

This project was conceived as part of the research unit in noise and communication in the Hearing Research Laboratory and funded by the Workplace Safety Insurance Board of Ontario. In collaboration with the co-authors, Flora Nassrallah was responsible for the project through the ethics approval, the data collection, the data analysis and the interpretation stages. Dr. Nicolas Ellaham was responsible for preparing hardware and software procedures for audio stimulus delivery and analysis. Flora Nassrallah prepared all the manuscripts included in this thesis with guidance from the co-authors who provided feedback, reviewed the documents, and approved the documents prior to submission.

8.2 Other contributors

The expertise of other individuals was also sought for different parts of this work as required.

For the first study (Chapter 3), the authors Flora Nassrallah and Professor Christian Giguère, turned to experts in the field to review the content and format of the questionnaire. In addition to revisions from the authors, the English version of the questionnaire was carefully reviewed and validated by Dr. Stephen Keith, an expert on noise in the workplace. The French version of the questionnaire was also reviewed and validated by audiologists Pauline Fortier and Véronique Vaillancourt, and Professor Chantal Laroche, experts in the field.

For the third study (Chapter 5), we enlisted the help of Professor Jérémie Voix to use a sound proof room at École de technologie supérieure in Montréal to conduct part of our data collection. Also, the expertise of a statistician, Professor Gilles Lamothe, was sought for the data and statistical analyses of this study.

Appendix A

Complete Questionnaire (English)

Communication Headsets

Use and Noise Measurements in the Workplace

INTRODUCTION

Thank you for agreeing to answer this questionnaire on the use of communication headsets in the workplace and noise exposure measurements associated to these devices. For more information on this study and on your voluntary participation, please consult this Information Letter.

This questionnaire is divided in four parts: 1) General Information, 2) Noise Measurement in the Workplace, 3) Experience in Noise Measurement Under Communication Headsets in the Workplace (if applicable), and 4) Availability of Information on Communication Headset Usage in the Workplace. The questionnaire should take approximately 10-15 minutes to answer and will have to be completed in one sitting. Please note that a couple of specific questions (e.g., type, manufacturer, model) on noise measurement equipment will be asked. As a suggestion, it may be helpful to have this documention at hand if needed when completing the survey.

For the purpose of this questionnaire, the term "communication headset" includes all systems or personnel listening devices allowing communication between workers at a distance (e.g., construction site, airplane pilot) or with a client (e.g., drive-thru services). The communication audio signal can be transmitted to one or two ears in many ways (e.g., via circum-aural, supra-aural, intra-concha, and intra-aural earphones, or with hearing protectors integrated within a communication system).

Please answer as many questions as you can. Note that you are free to stop answering at any point.

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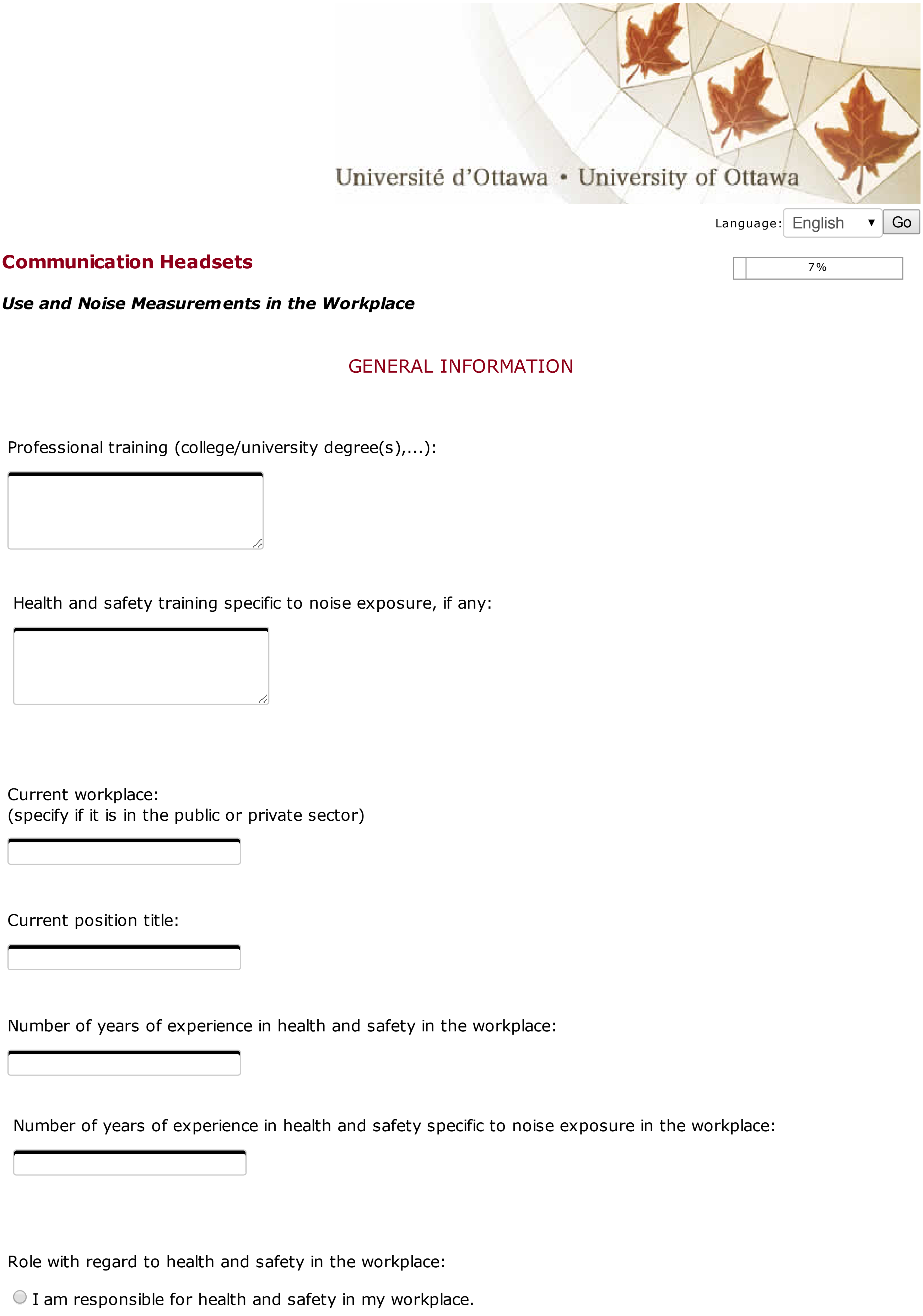

Communication Headsets

Use and Noise Measurements in the Workplace

GENERAL INFORMATION

Professional training (college/university degree(s),...):

Health and safety training specific to noise exposure, if any:

Current workplace:
(specify if it is in the public or private sector)

Current position title:

Number of years of experience in health and safety in the workplace:

Number of years of experience in health and safety specific to noise exposure in the workplace:

Role with regard to health and safety in the workplace:

○ I am responsible for health and safety in my workplace.

○ I am a health and safety consultant (self-employed or hired).

○ I am an acoustical consultant.

○ I am a health worker in the public health sector.

○ I am a health worker in a provincial workplace compensation board (e.g., WorkSafeBC, WSIB). - Please specify...

○ Other - Please specify...

Comments:

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Communication Headsets

Use and Noise Measurements in the Workplace

NOISE MEASUREMENT IN THE WORKPLACE

How would you judge your level of awareness on **noise measurement and hearing loss prevention** in the workplace?

○ Excellent knowledge; expert
○ Good knowledge
○ Little knowledge
○ No knowledge

Comments:

Do you have access to **basic equipment** (e.g., sound level meter, dosimeter) to measure noise levels in the workplace?

○ Yes
○ No

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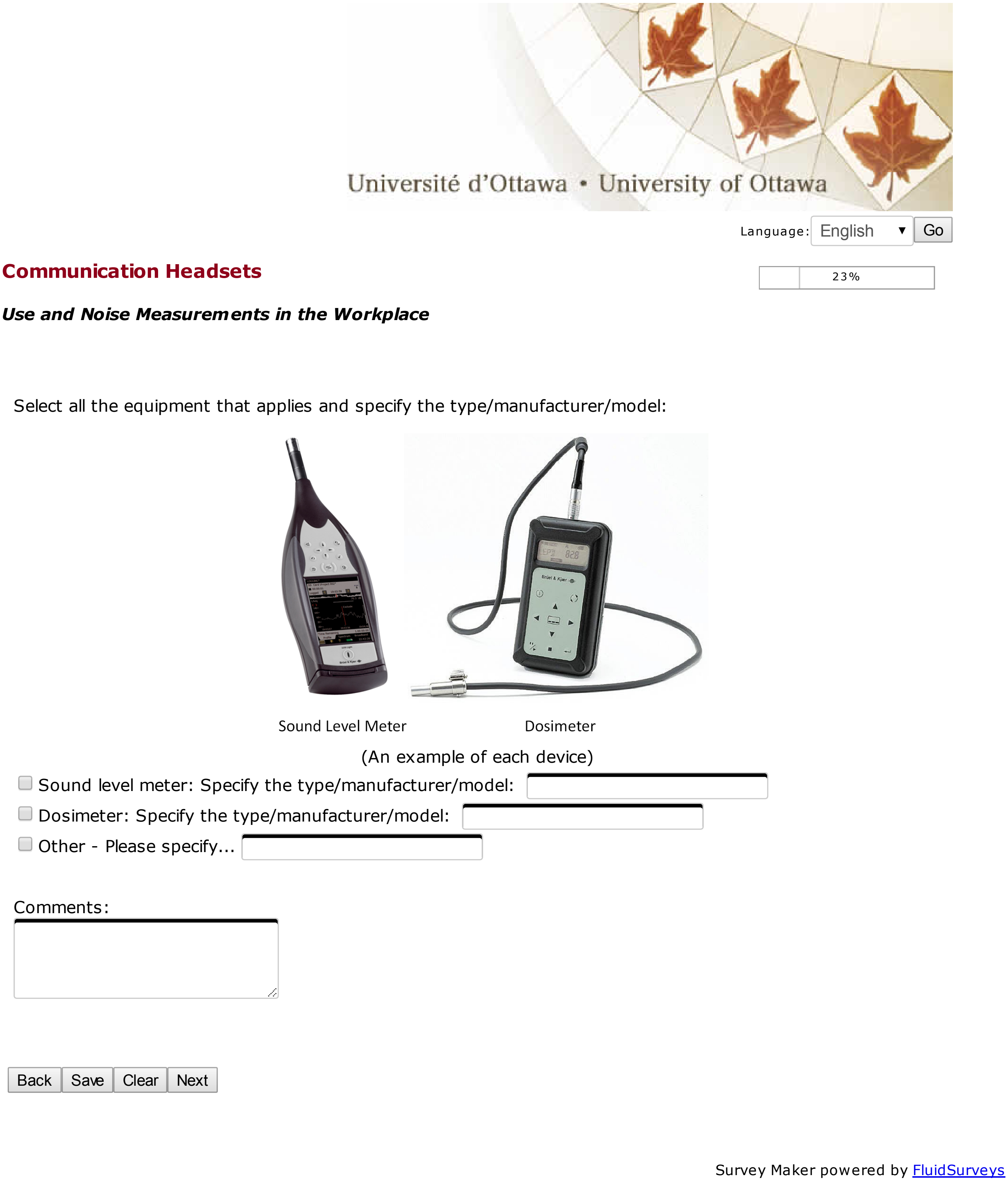

Communication Headsets

Use and Noise Measurements in the Workplace

Select all the equipment that applies and specify the type/manufacturer/model:

Sound Level Meter Dosimeter

(An example of each device)

☐ Sound level meter: Specify the type/manufacturer/model: ____

☐ Dosimeter: Specify the type/manufacturer/model: ____

☐ Other - Please specify... ____

Comments:

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Language: English ▾ Go

Communication Headsets

30%

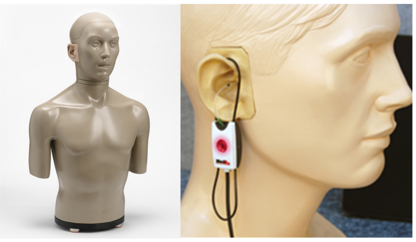
Use and Noise Measurements in the Workplace

How would you judge your level of awareness on the problem of noise exposure from the **use of communication headsets in the workplace**?

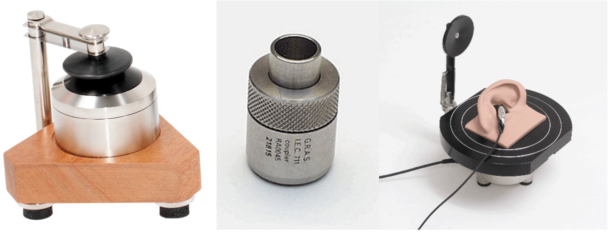
○ Excellent knowledge; expert
○ Good knowledge
○ Little knowledge
○ No knowledge

Comments:

How would you judge your level of awareness on the **techniques of noise measurement** under headphones and communication headsets, more specifically using an acoustic manikin, a microphone in the real, or artificial ears?



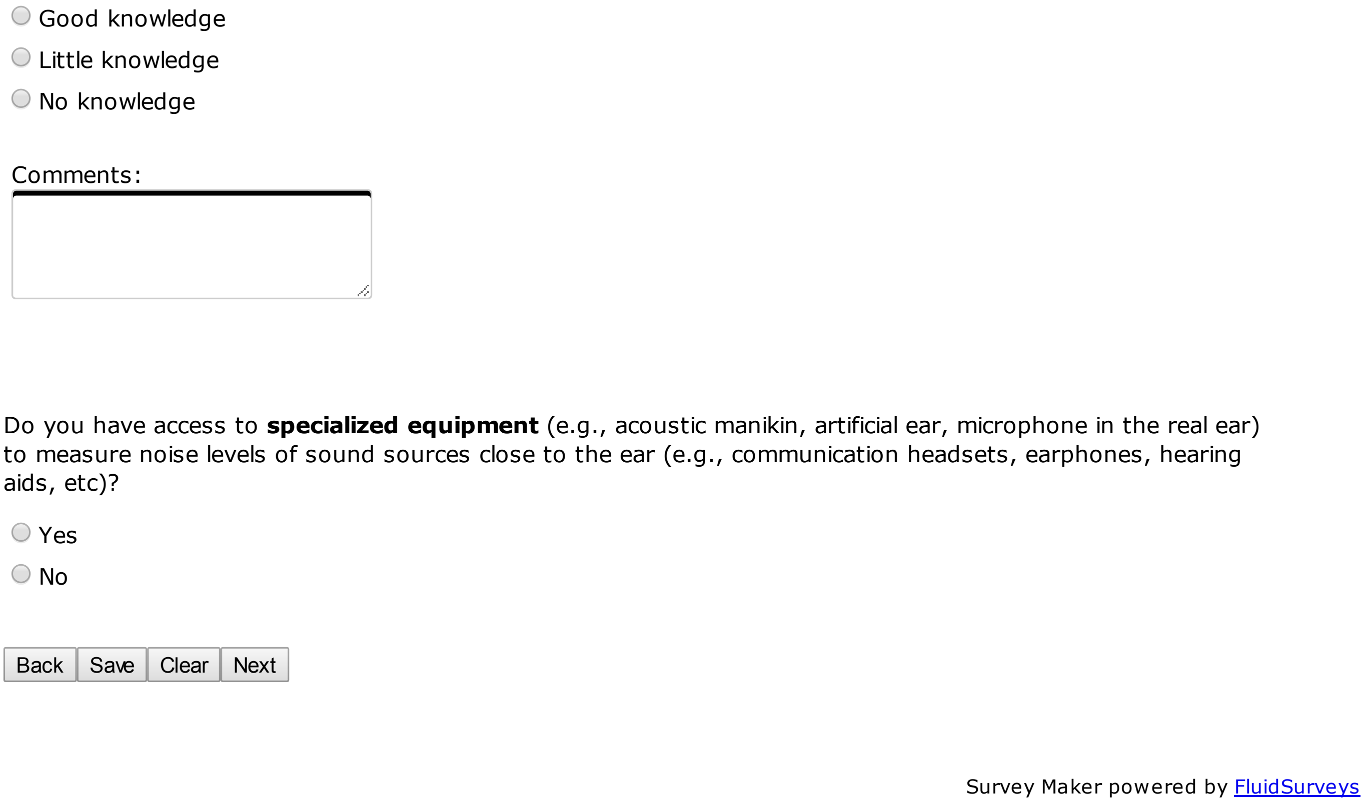
Manikin | Microphone in the Real Ear



Type 1 Artificial Ear | Type 2 Ear Simulator | Type 3.3 Artificial Ear

(An example of each device)

○ Excellent knowledge; expert



○ Good knowledge
○ Little knowledge
○ No knowledge

Comments:

Do you have access to **specialized equipment** (e.g., acoustic manikin, artificial ear, microphone in the real ear) to measure noise levels of sound sources close to the ear (e.g., communication headsets, earphones, hearing aids, etc)?

○ Yes
○ No

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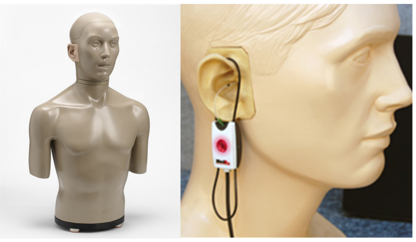
Language: English ▾ Go

38%

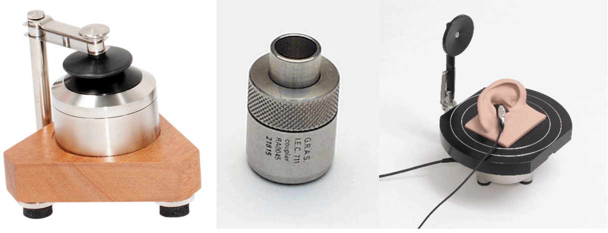
Communication Headsets

Use and Noise Measurements in the Workplace

Select all the equipment that applies and specify the type/manufacturer/model:



Manikin   Microphone in the Real Ear



Type 1 Artificial Ear   Type 2 Ear Simulator   Type 3.3 Artificial Ear

(An example of each device)

☐ Acoustic manikin: Specify the type/manufacturer/model: ________

☐ Artificial ear: Specify the type/manufacturer/model: ________

☐ Microphone in the real ear (MIRE): Specify the type/manufacturer/model: ________

☐ Other - Please specify... ________

Comments:

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Language: English ▾ Go

Communication Headsets

46%

Use and Noise Measurements in the Workplace

Have you ever done interventions (e.g., measurements, discussions, proper headset selection) with regard to the use of communication headset in the workplace?

- ○ Never
- ○ Once
- ○ 2-5 times
- ○ 5-10 times
- ○ 10 times or more - Please specify... ______

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Communication Headsets

Use and Noise Measurements in the Workplace

During your interventions, have you taken measurements of noise exposure under communication headsets?

○ Yes

○ No

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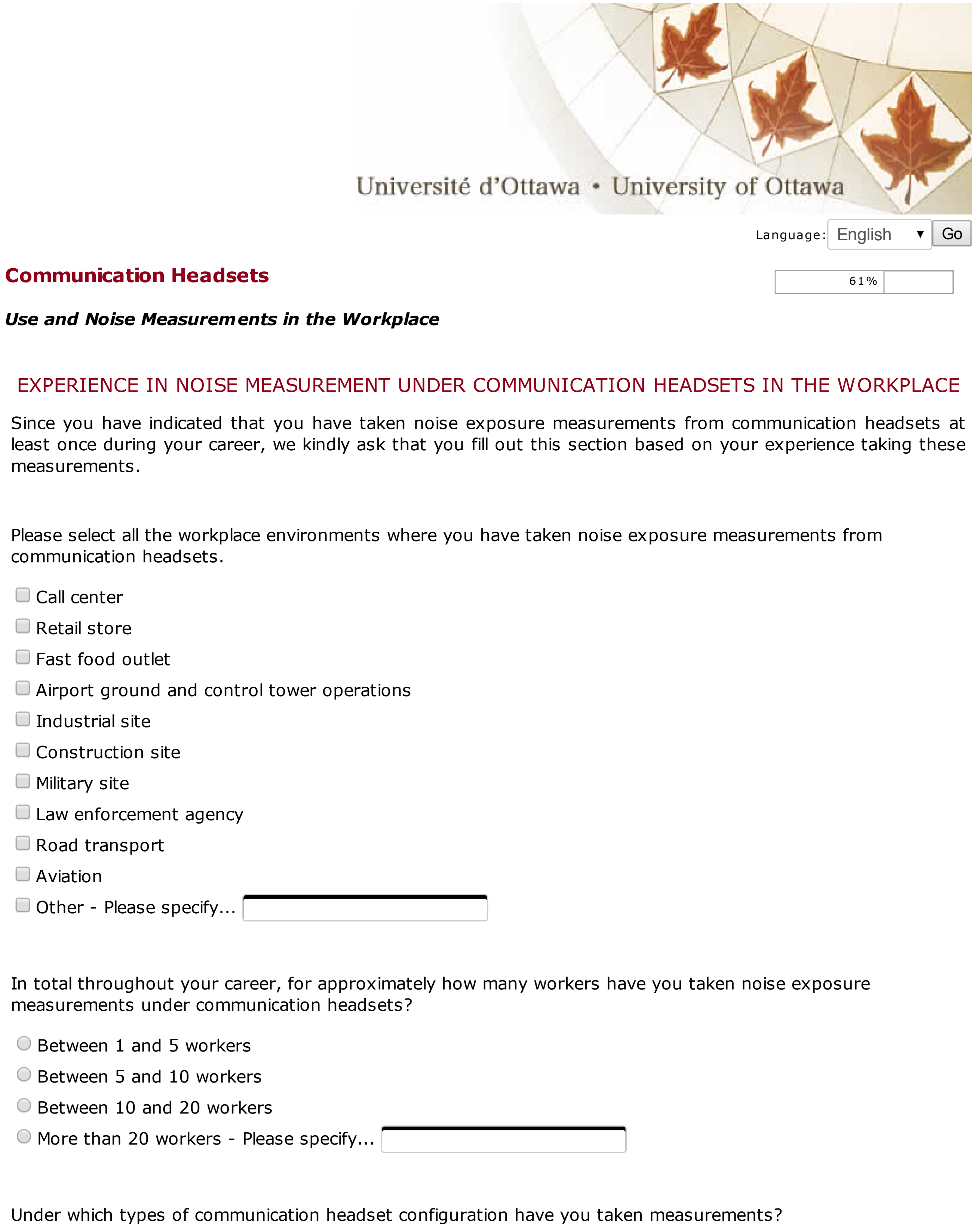


Communication Headsets

Use and Noise Measurements in the Workplace

EXPERIENCE IN NOISE MEASUREMENT UNDER COMMUNICATION HEADSETS IN THE WORKPLACE

Since you have indicated that you have taken noise exposure measurements from communication headsets at least once during your career, we kindly ask that you fill out this section based on your experience taking these measurements.

Please select all the workplace environments where you have taken noise exposure measurements from communication headsets.

- ☐ Call center
- ☐ Retail store
- ☐ Fast food outlet
- ☐ Airport ground and control tower operations
- ☐ Industrial site
- ☐ Construction site
- ☐ Military site
- ☐ Law enforcement agency
- ☐ Road transport
- ☐ Aviation
- ☐ Other - Please specify...

In total throughout your career, for approximately how many workers have you taken noise exposure measurements under communication headsets?

- ○ Between 1 and 5 workers
- ○ Between 5 and 10 workers
- ○ Between 10 and 20 workers
- ○ More than 20 workers - Please specify...

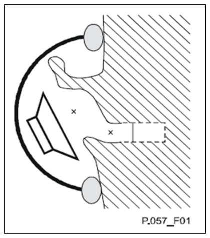
Under which types of communication headset configuration have you taken measurements?

Single-sided Headset Double-sided Headset

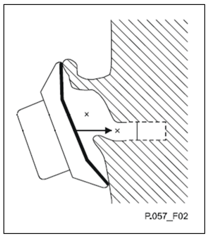
(An example of each configuration)

☐ Single-sided headset
☐ Double-sided headset
☐ I don't know

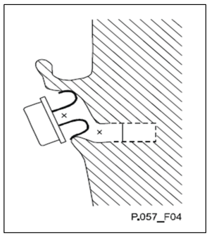
Under which types of earphones on the communication headsets have you taken measurements?



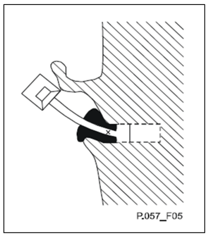
Circum-aural



Supra-aural



Intra-concha



Intra-aural/Inserts

*These images were taken from the International Telecommunication Union (ITU-T P.57 2005).

☐ Circum-aural
☐ Supra-aural
☐ Intra-concha
☐ Intra-aural/Inserts
☐ I don't know

Did the communication headsets have the following elements?

	Yes	Some	No	I don't know
Variable volume	○	○	○	○
Volume/sound level limiter	○	○	○	○
Integrated hearing protection	○	○	○	○

Other - Please specify...

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Language: English ▾ Go

Communication Headsets

69%

Use and Noise Measurements in the Workplace

What equipment have you used to measure noise exposure under communication headsets?

Manikin

Microphone in the Real Ear

Type 1 Artificial Ear

Type 2 Ear Simulator

Type 3.3 Artificial Ear

Sound Level Meter

Dosimeter

(An example of each device)

☐ Acoustic manikin: Specify the type/manufacturer/model:

☐ Artificial ear: Specify the type/manufacturer/model:

☐ Microphone in the real ear (MIRE): Specify the type/manufacturer/model:

☐ Sound level meter/dosimeter under the communication headset: Specify the type/manufacturer/model:

☐ Other - Please specify...

Did you correct the measured values to be representative of the worker's exposure for the following?

	Yes	Sometimes	No	I don't know
Diffuse or free field corrections (or audio communication)	○	○	○	○
Duration of audio communication headset use	○	○	○	○
Background noise	○	○	○	○

Did the results obtained from the noise exposure measurements demonstrate that an intervention programme should be put in place in this/these workplace(s)?

	Yes	Some	No	I don't know
Reducing surrounding noise	○	○	○	○
Choosing a communication headset with better hearing protection	○	○	○	○
Reducing listening volume	○	○	○	○
Reducing duration of noise exposure	○	○	○	○

Other - Please specify...

Back Save Clear Next

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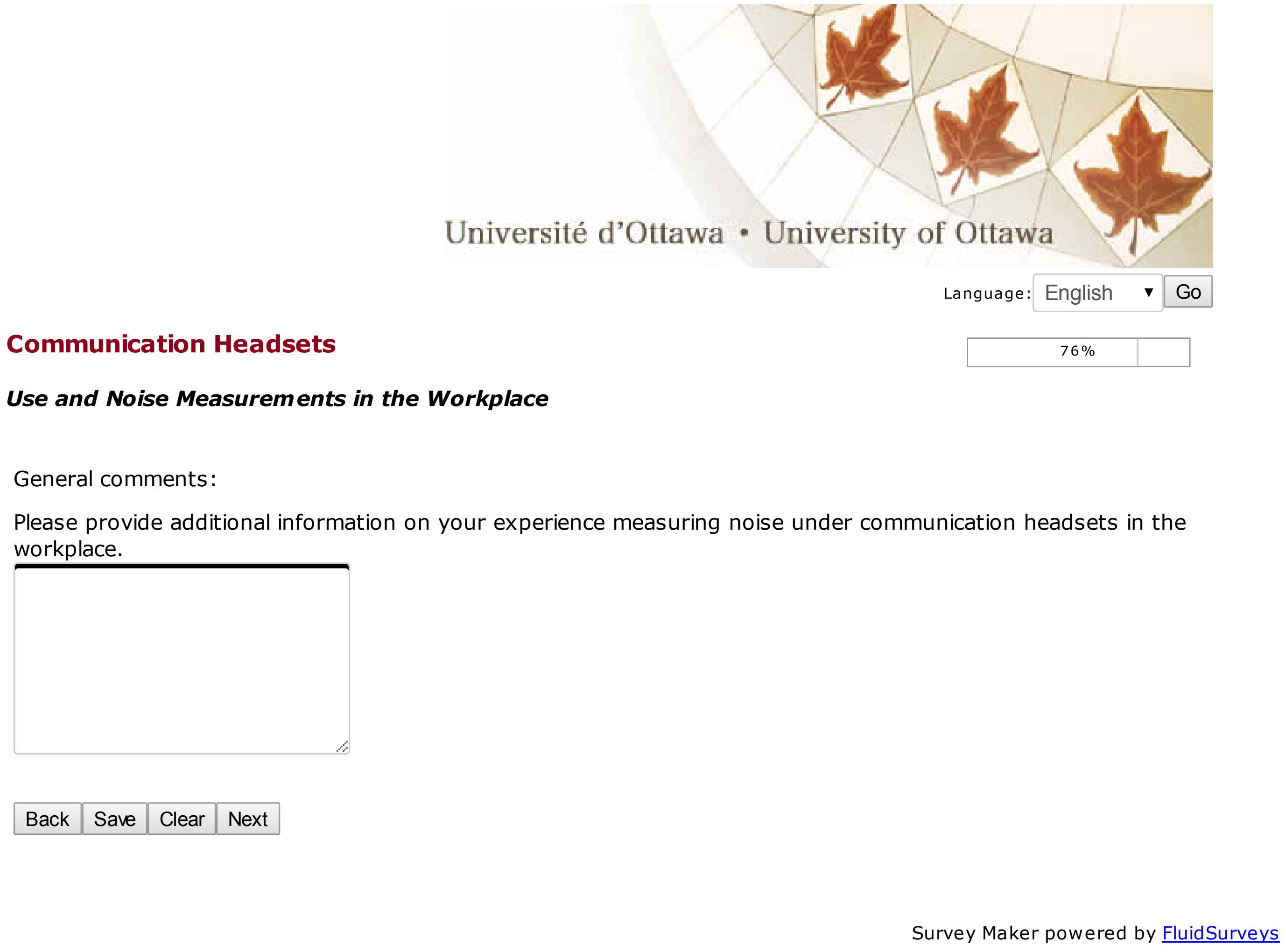

Communication Headsets

Use and Noise Measurements in the Workplace

General comments:

Please provide additional information on your experience measuring noise under communication headsets in the workplace.

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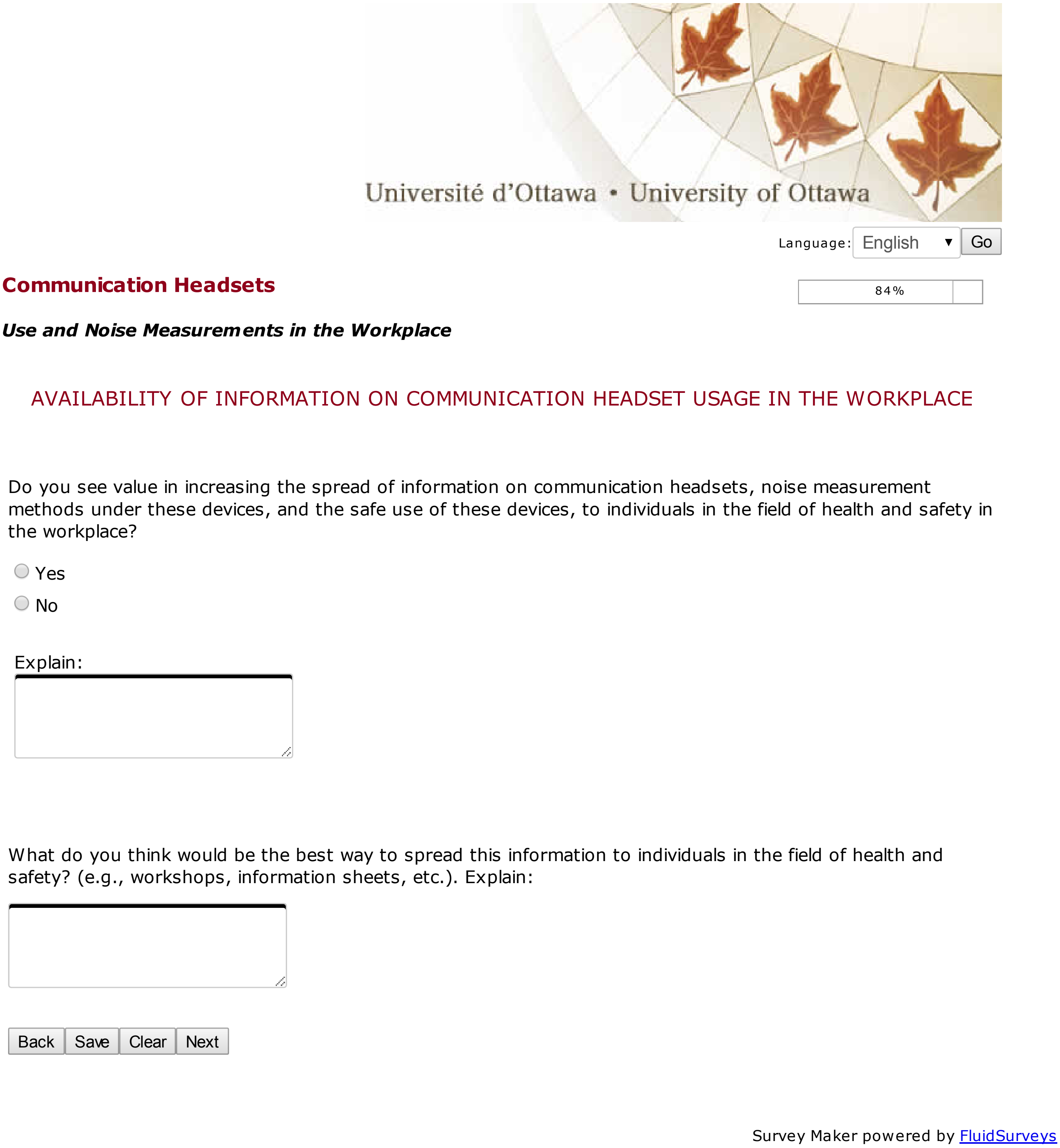

Communication Headsets

Use and Noise Measurements in the Workplace

AVAILABILITY OF INFORMATION ON COMMUNICATION HEADSET USAGE IN THE WORKPLACE

Do you see value in increasing the spread of information on communication headsets, noise measurement methods under these devices, and the safe use of these devices, to individuals in the field of health and safety in the workplace?

○ Yes
○ No

Explain:

What do you think would be the best way to spread this information to individuals in the field of health and safety? (e.g., workshops, information sheets, etc.). Explain:

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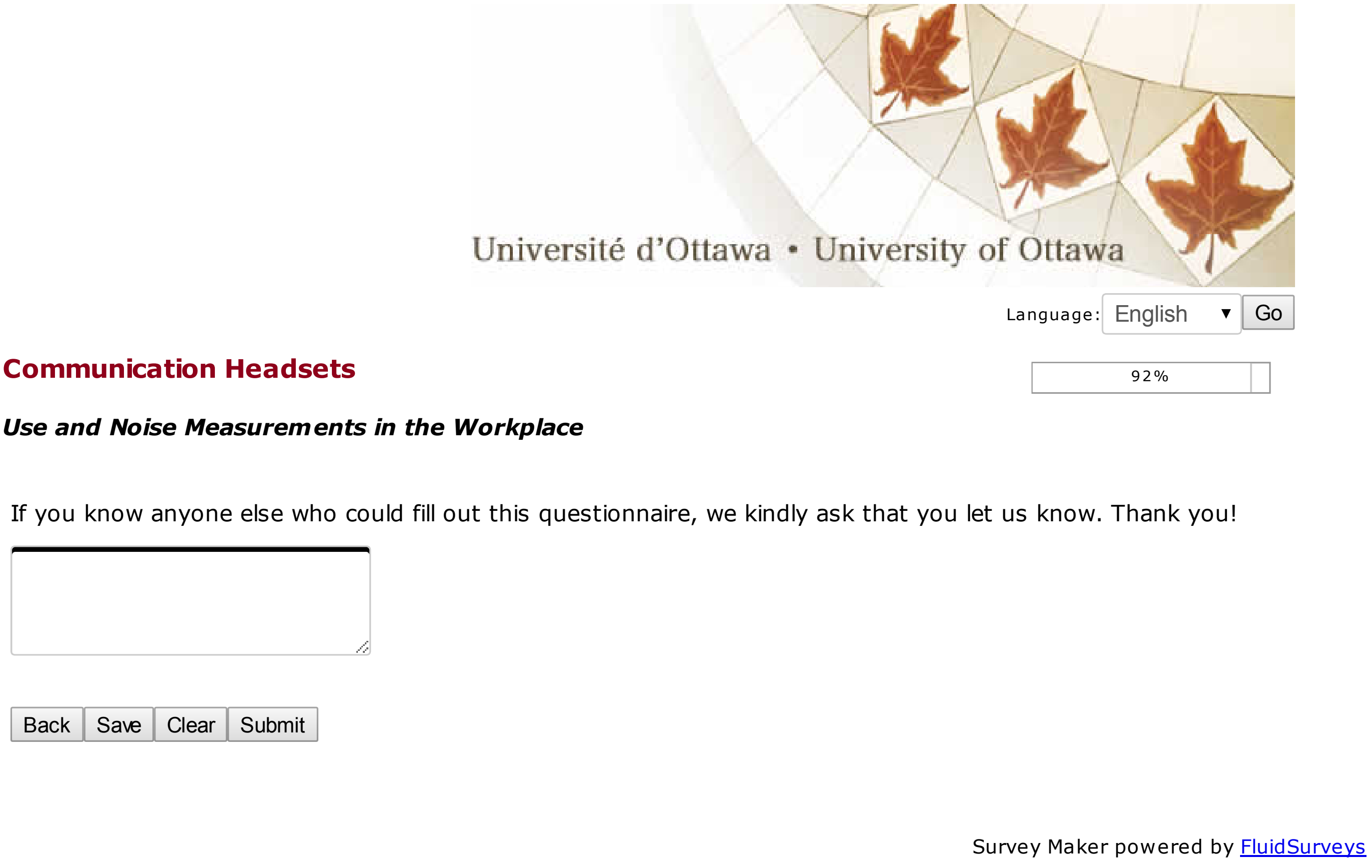

Communication Headsets

Use and Noise Measurements in the Workplace

If you know anyone else who could fill out this questionnaire, we kindly ask that you let us know. Thank you!

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Appendix B

Complete Questionnaire (French)

Casques de communication

L'utilisation en milieu de travail et la mesure d'exposition au bruit associée

INTRODUCTION

Merci d'avoir accepté de répondre à ce questionnaire qui porte sur l'utilisation des casques de communication en milieu de travail et la mesure de l'exposition au bruit qui y est associée. Pour plus d'information sur cette étude et votre participation volontaire, veuillez consulter cette Lettre d'information.

Ce questionnaire est divisé en quatre parties : 1) Renseignements généraux, 2) Mesure du bruit dans le milieu de travail, 3) Experience de mesure du bruit sous les casques de communication dans le milieu de travail (si applicable), et 4) Accès à l'information sur les casques de communication en milieu de travail. Le questionnaire vous prendra environ 10-15 minutes à remplir et devra être complété en une session. Veuillez noter que quelques questions spécifiques (p. ex., type, fabricant, modèle) sur des outils de mesure du bruit seront posées. Comme suggestion, il serait donc utile d'avoir la documentation à ce sujet à portée de la main au besoin.

Pour les besoins du questionnaire, « casque de communication » inclut tout système ou dispositif d'écoute personnel permettant aux travailleurs de communiquer entre eux à distance (p. ex., chantier de construction, pilote d'avion) ou avec un client (p. ex., service au volant). Le signal de communication audio peut être transmis à une seule oreille ou aux deux oreilles par l'entremise d'écouteurs circum-auriculaires, supra-auriculaires, intra-conques, et intra-canaux, ou à l'aide de protecteurs auditifs avec système de communication intégré.

Essayez, si possible, de répondre à toutes les questions. Sachez que vous pouvez arrêter de répondre à n'importe quel moment.

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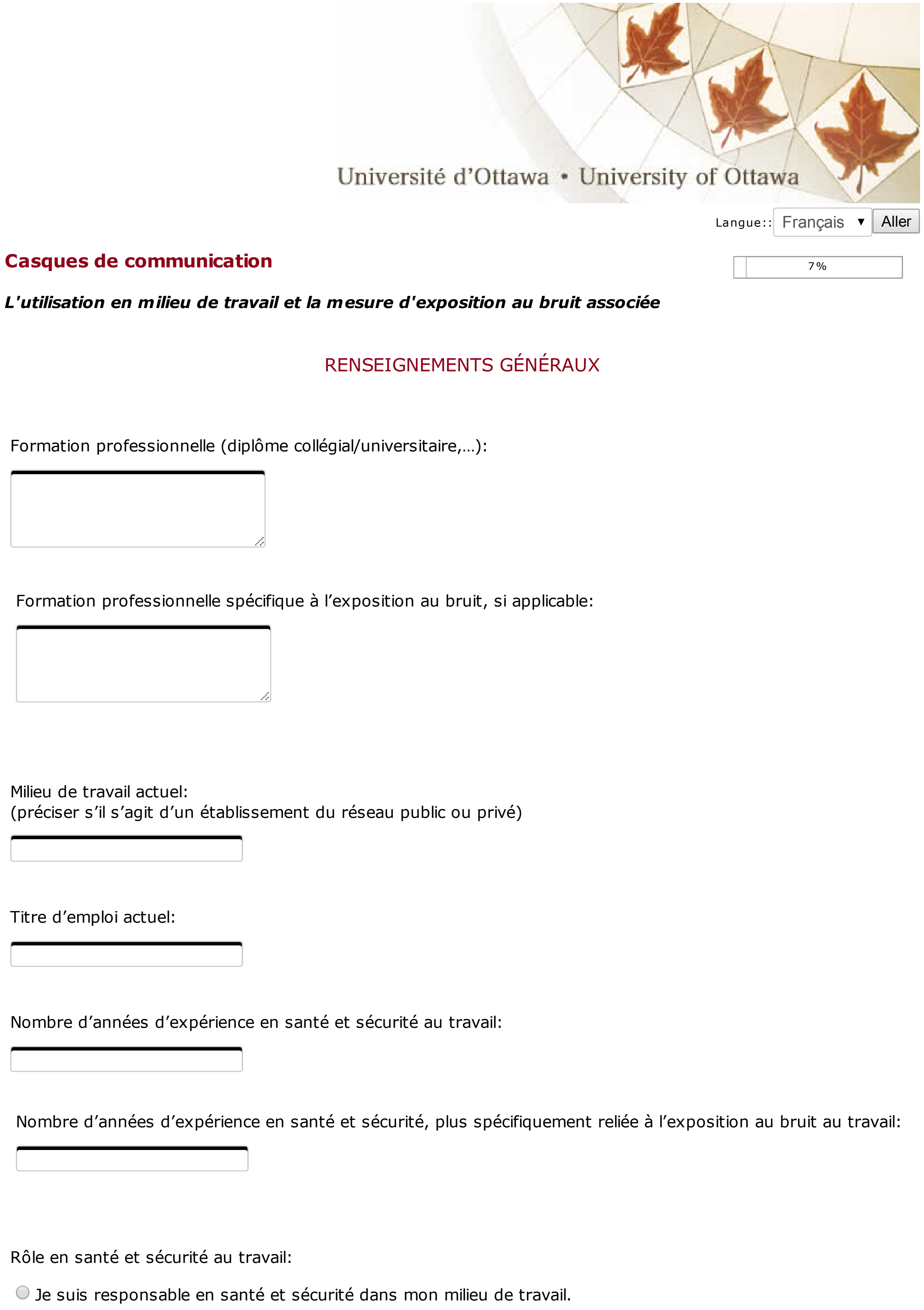


Langue:: Français

Casques de communication

L'utilisation en milieu de travail et la mesure d'exposition au bruit associée

RENSEIGNEMENTS GÉNÉRAUX

Formation professionnelle (diplôme collégial/universitaire,...):

Formation professionnelle spécifique à l'exposition au bruit, si applicable:

Milieu de travail actuel:
(préciser s'il s'agit d'un établissement du réseau public ou privé)

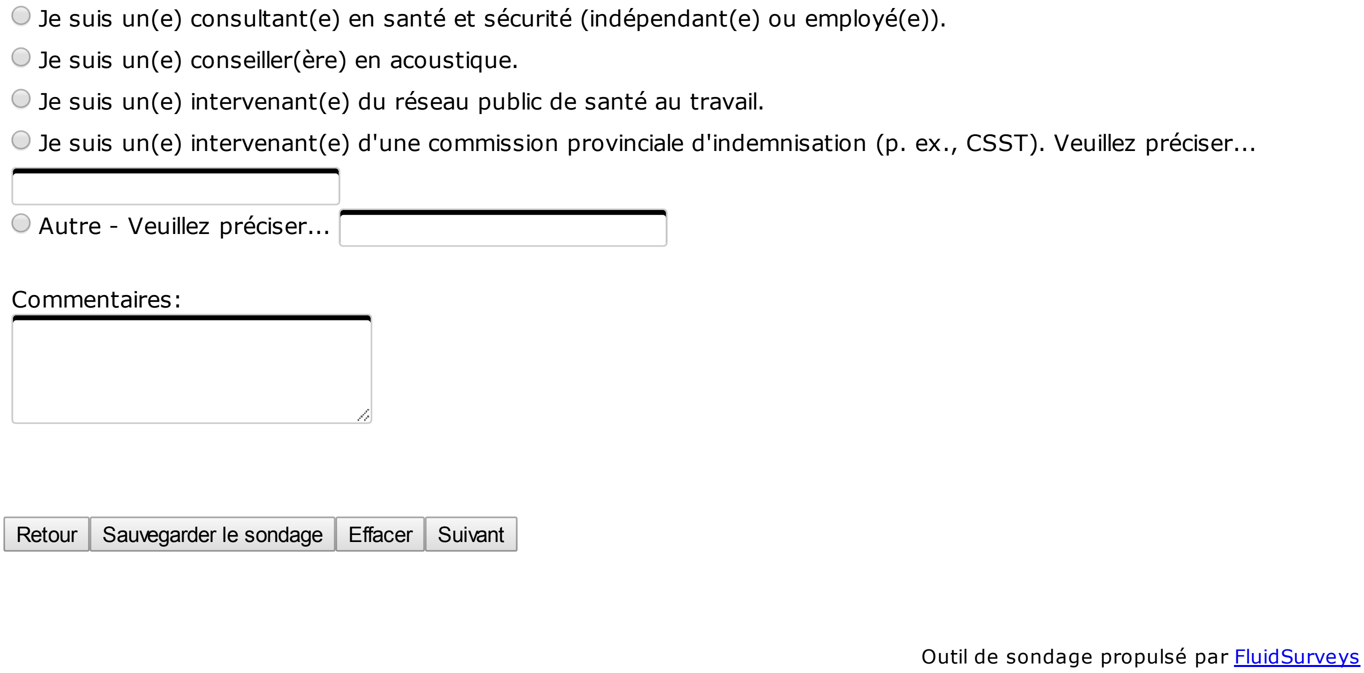
Titre d'emploi actuel:

Nombre d'années d'expérience en santé et sécurité au travail:

Nombre d'années d'expérience en santé et sécurité, plus spécifiquement reliée à l'exposition au bruit au travail:

Rôle en santé et sécurité au travail:

○ Je suis responsable en santé et sécurité dans mon milieu de travail.



○ Je suis un(e) consultant(e) en santé et sécurité (indépendant(e) ou employé(e)).
○ Je suis un(e) conseiller(ère) en acoustique.
○ Je suis un(e) intervenant(e) du réseau public de santé au travail.
○ Je suis un(e) intervenant(e) d'une commission provinciale d'indemnisation (p. ex., CSST). Veuillez préciser...
○ Autre - Veuillez préciser...

Commentaires:

Outil de sondage propulsé par FluidSurveys

Casques de communication

L'utilisation en milieu de travail et la mesure d'exposition au bruit associée

MESURE DU BRUIT DANS LE MILIEU DE TRAVAIL

Comment évaluez-vous votre niveau de connaissance sur **la mesure du bruit et la prévention de la perte auditive** en milieu de travail ?

○ Excellentes connaissances; expert(e)
○ Bonnes connaissances
○ Peu de connaissances
○ Aucune connaissance

Commentaires:

Avez-vous accès à de **l'équipement de base** (p. ex., sonomètre, dosimètre) pour mesurer le niveau de bruit en milieu de travail?

○ Oui
○ Non

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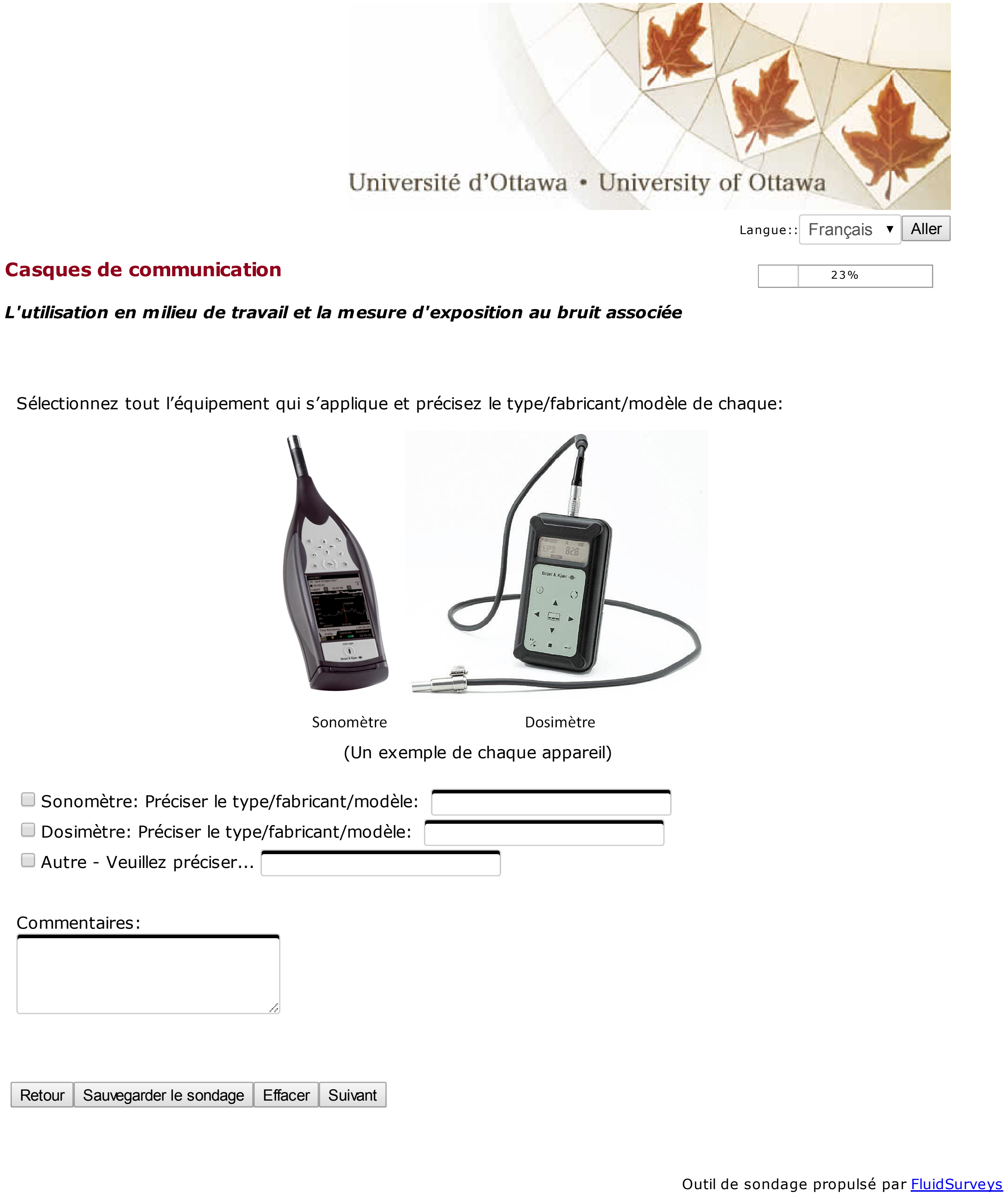


Casques de communication

L'utilisation en milieu de travail et la mesure d'exposition au bruit associée

Sélectionnez tout l'équipement qui s'applique et précisez le type/fabricant/modèle de chaque:

(Un exemple de chaque appareil)

☐ Sonomètre: Préciser le type/fabricant/modèle:
☐ Dosimètre: Préciser le type/fabricant/modèle:
☐ Autre - Veuillez préciser...

Commentaires:

Outil de sondage propulsé par FluidSurveys

Casques de communication

L'utilisation en milieu de travail et la mesure d'exposition au bruit associée

Comment évaluez-vous votre niveau de connaissance de la problématique de l'exposition au bruit associée à **l'utilisation des casques de communication au travail**?

○ Excellentes connaissances; expert(e)
○ Bonnes connaissances
○ Peu de connaissances
○ Aucune connaissance

Commentaires:

Comment évaluez-vous votre niveau de connaissance **des techniques de mesure du bruit** sous les écouteurs et les casques de communication dans le milieu de travail, plus particulièrement en ce qui concerne l'utilisation d'un mannequin acoustique, de la sonde microphonique dans l'oreille, ou des oreilles artificielles?

Mannequin acoustique

Sonde microphonique dans l'oreille

Oreille artificielle Type 1

Simulateur d'oreille Type 2

Oreille artificielle Type 3.3

(Un exemple de chaque appareil)

○ Excellentes connaissances; expert(e)

○ Bonnes connaissances

○ Peu de connaissances

○ Aucune connaissance

Commentaires:

Avez-vous accès à de **l'équipement spécialisé** (p. ex., mannequin acoustique, oreilles artificielles, sonde microphonique dans l'oreille) pour mesurer le niveau sonore de sources proches de l'oreille (p. ex., casques de communication, écouteurs, appareils auditifs, etc.)?

○ Oui

○ Non

Outil de sondage propulsé par FluidSurveys

Langue:: Français

38%

Casques de communication

L'utilisation en milieu de travail et la mesure d'exposition au bruit associée

Sélectionnez tout l'équipement qui s'applique et précisez le type/fabricant/modèle de chaque:

Mannequin acoustique

Sonde microphonique dans l'oreille

Oreille artificielle Type 1

Simulateur d'oreille Type 2

Oreille artificielle Type 3.3

(Un exemple de chaque appareil)

☐ Mannequin acoustique: Préciser le type/fabricant/modèle:

☐ Oreille artificielle: Préciser le type/fabricant/modèle:

☐ Sonde microphonique dans l'oreille (MIRE): Préciser le type/fabricant/modèle:

☐ Autre - Veuillez préciser...

Commentaires:

Outil de sondage propulsé par [FluidSurveys](#)

Casques de communication

L'utilisation en milieu de travail et la mesure d'exposition au bruit associée

Avez-vous déjà fait des interventions (p. ex., mesures, discussions, sélections de casque) liées à l'utilisation des casques de communication en milieu de travail?

○ Jamais
○ 1 fois
○ 2-5 fois
○ 5-10 fois
○ 10 fois ou plus - Veuillez préciser... ______

Outil de sondage propulsé par FluidSurveys

Casques de communication

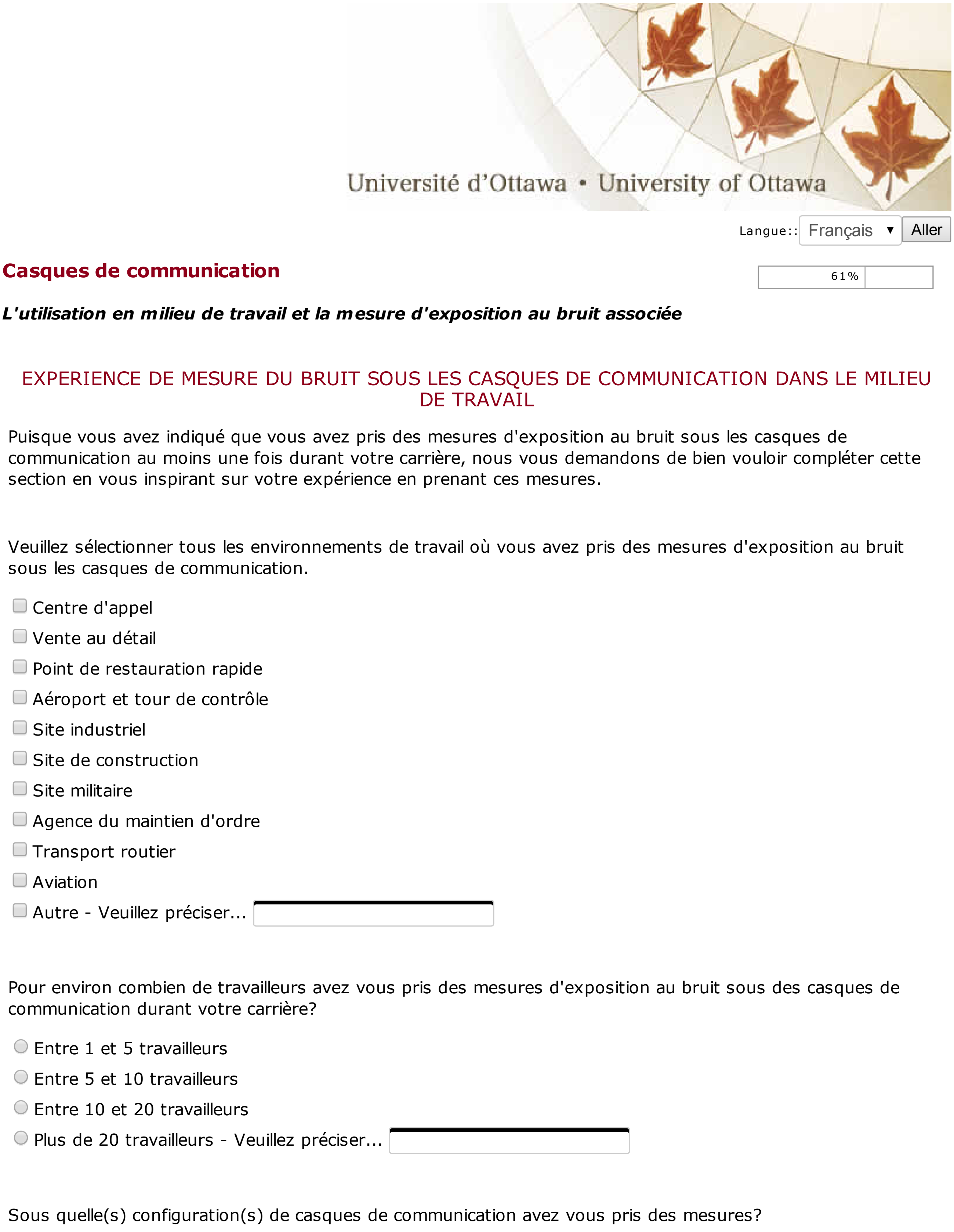
L'utilisation en milieu de travail et la mesure d'exposition au bruit associée

Lors de vos interventions, avez-vous déjà pris des mesures d'exposition au bruit sous les casques de communication?

○ Oui

○ Non

Outil de sondage propulsé par FluidSurveys



Casques de communication

L'utilisation en milieu de travail et la mesure d'exposition au bruit associée

EXPERIENCE DE MESURE DU BRUIT SOUS LES CASQUES DE COMMUNICATION DANS LE MILIEU DE TRAVAIL

Puisque vous avez indiqué que vous avez pris des mesures d'exposition au bruit sous les casques de communication au moins une fois durant votre carrière, nous vous demandons de bien vouloir compléter cette section en vous inspirant sur votre expérience en prenant ces mesures.

Veuillez sélectionner tous les environnements de travail où vous avez pris des mesures d'exposition au bruit sous les casques de communication.

☐ Centre d'appel
☐ Vente au détail
☐ Point de restauration rapide
☐ Aéroport et tour de contrôle
☐ Site industriel
☐ Site de construction
☐ Site militaire
☐ Agence du maintien d'ordre
☐ Transport routier
☐ Aviation
☐ Autre - Veuillez préciser...

Pour environ combien de travailleurs avez vous pris des mesures d'exposition au bruit sous des casques de communication durant votre carrière?

○ Entre 1 et 5 travailleurs
○ Entre 5 et 10 travailleurs
○ Entre 10 et 20 travailleurs
○ Plus de 20 travailleurs - Veuillez préciser...

Sous quelle(s) configuration(s) de casques de communication avez vous pris des mesures?

Casque monophonique

Casque stéréophonique

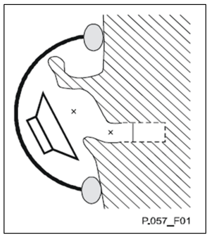
(Un exemple de chaque type de configuration)

☐ Monophonique

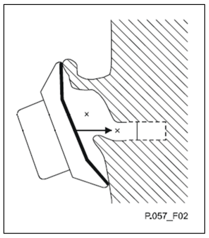
☐ Stéréophonique

☐ Je ne sais pas

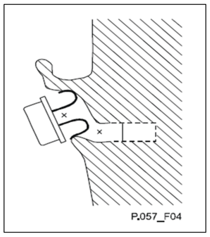
Sous quel(s) type(s) d'écouteurs de casques de communication avez-vous pris des mesures?



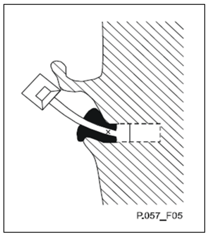
Circum-auriculaires



Supra-auriculaires



Intra-conques



Intra-auriculaires/
Écouteurs insérés

*Ces images sont tirées de l'Union internationale des télécommunications (ITU-T P.57 2005).

☐ Circum-auriculaires

☐ Supra-auriculaires

☐ Intra-conques

☐ Intra-auriculaires

☐ Je ne sais pas

Est-ce que les casques ou systèmes de communication comprennaient les éléments suivants?

	Oui	Certains	Non	Je ne sais pas
Volume variable	○	○	○	○
Limiteur de volume/niveau sonore	○	○	○	○
Protection auditive intégrée	○	○	○	○

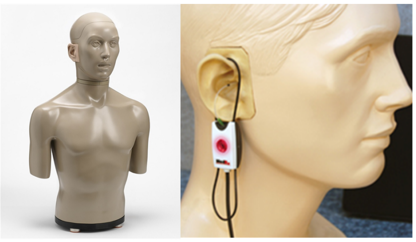
Autre - Veuillez préciser...

Casques de communication

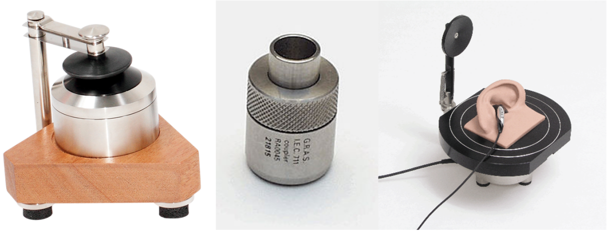
69%

L'utilisation en milieu de travail et la mesure d'exposition au bruit associée

Quel équipement avez-vous utilisé pour mesurer l'exposition au bruit sous les casques de communication?



Mannequin acoustique   Sonde microphonique dans l'oreille



Oreille artificielle Type 1   Simulateur d'oreille Type 2   Oreille artificielle Type 3.3

Sonomètre   Dosimètre

(Un exemple de chaque appareil)

☐ Mannequin acoustique: Préciser le type/fabricant/modèle:

☐ Oreille artificielle: Préciser le type/fabricant/modèle:

☐ Sonde microphonique dans l'oreille (MIRE): Préciser le type/fabricant/modèle:

☐ Sonomètre/dosimètre sous le casque d'écoute: Préciser le type/fabricant/modèle:

☐ Autre - Veuillez préciser...

Avez-vous corrigé les mesures obtenues pour avoir une représentation exacte de l’exposition du travailleur?

	Oui	Parfois	Non	Je ne sais pas
Corrections de champs diffus ou libre (ou de communication audio)	○	○	○	○
Durée de l'utilisation audio du casque de communication	○	○	○	○
Bruit environnant	○	○	○	○

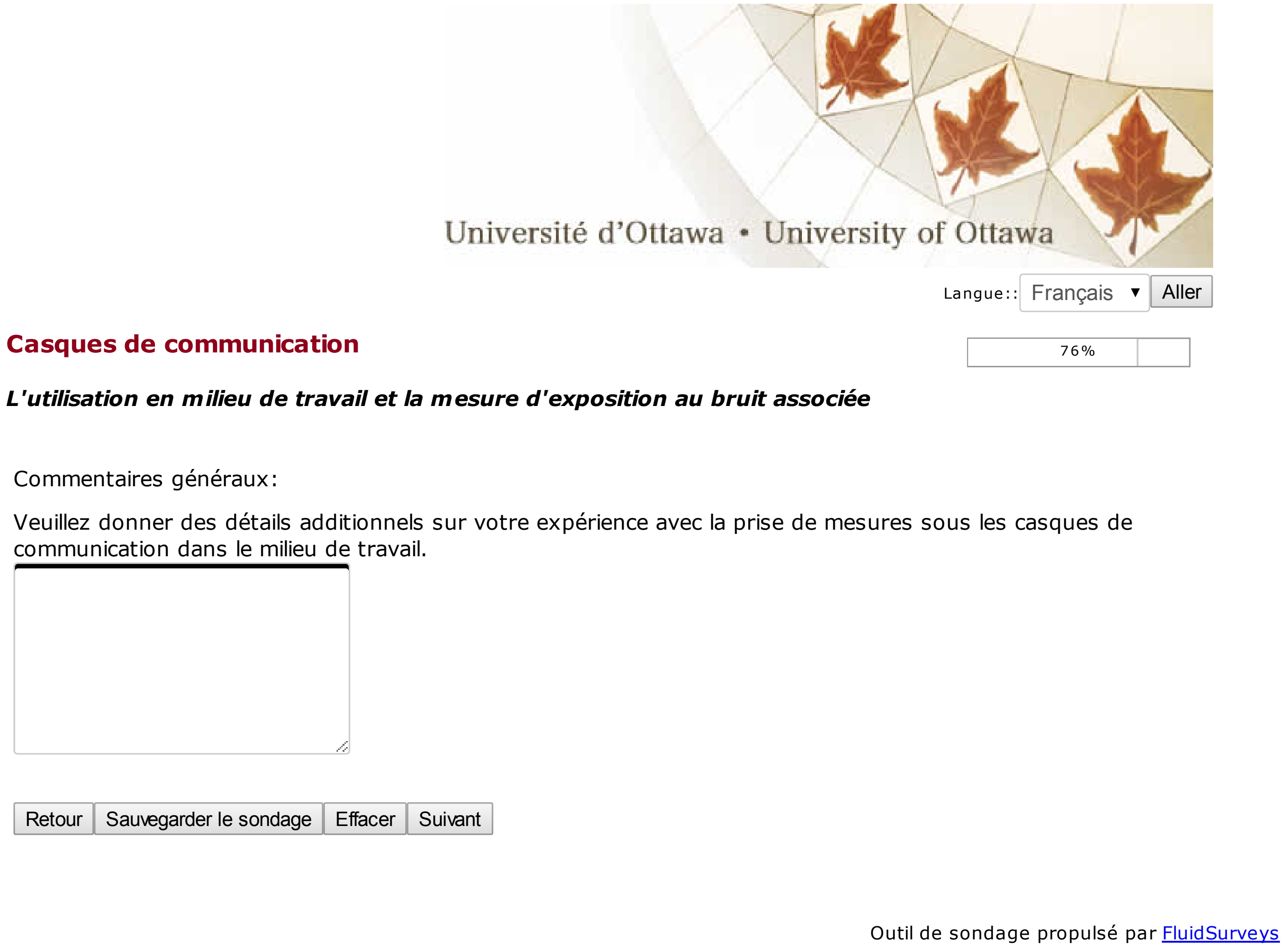
Est-ce que les résultats obtenus des mesures d'exposition au bruit ont démontré qu'un programme d'intervention devait être mis en place à ce(s) milieu(x) de travail?

	Oui	Parfois	Non	Je ne sais pas
Réduction du bruit environnant	○	○	○	○
Sélection d'un casque de communication avec une meilleure protection auditive	○	○	○	○
Réduction du volume d'écoute	○	○	○	○
Réduction de la durée d'exposition	○	○	○	○

Autre - Veuillez préciser...

Retour | Sauvegarder le sondage | Effacer | Suivant

Outil de sondage propulsé par FluidSurveys



Casques de communication

L'utilisation en milieu de travail et la mesure d'exposition au bruit associée

Commentaires généraux:

Veuillez donner des détails additionnels sur votre expérience avec la prise de mesures sous les casques de communication dans le milieu de travail.

Outil de sondage propulsé par FluidSurveys

Casques de communication

L'utilisation en milieu de travail et la mesure d'exposition au bruit associée

ACCÈS À L'INFORMATION SUR LES CASQUES DE COMMUNICATION EN MILIEU DE TRAVAIL

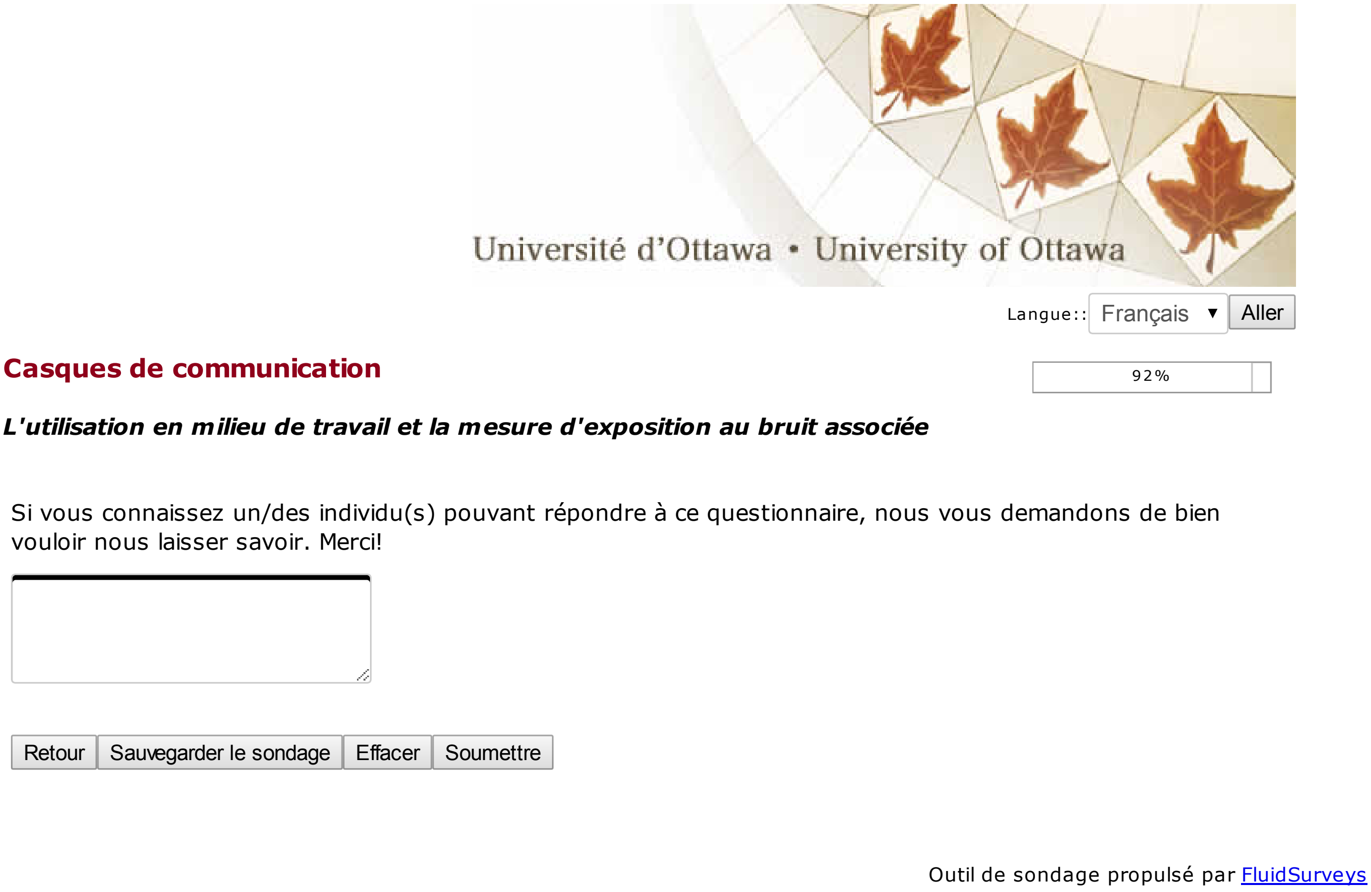
Voyez-vous l'utilité de diffuser davantage d'information aux intervenants en santé et sécurité au travail sur les casques de communication, les méthodes de mesure du bruit sous ces casques ainsi que sur leur utilisation sécuritaire?

○ Oui
○ Non

Expliquer:

D'après vous, quelle serait la meilleure façon de diffuser cette information aux intervenants? (p. ex., ateliers, dépliants). Expliquer:

Outil de sondage propulsé par FluidSurveys



Casques de communication

L'utilisation en milieu de travail et la mesure d'exposition au bruit associée

Si vous connaissez un/des individu(s) pouvant répondre à ce questionnaire, nous vous demandons de bien vouloir nous laisser savoir. Merci!

Outil de sondage propulsé par FluidSurveys

Appendix C

Comparison of Direct Measurement Methods - Participant Questionnaire

Measurement of occupation sound exposure from communication headsets: Cross-comparison of direct measurement methods

Entry Questionnaire

Participant #: ____________________

Date: ____________________________

What is your professional expertise (e.g., audiologist, engineer, etc.)?

What is your type of employment (e.g., clinical, research, acoustical consultant, health and safety officer, etc.)?

How frequently do you fit, give fitting instructions, or advise on the use of the following equipment to clients/subjects/individuals?

	Weekly	Bi-weekly	Monthly	Yearly	Other
Hearing Protectors	☐	☐	☐	☐	__________
Audiometric Earphones	☐	☐	☐	☐	__________
Hearing Aids	☐	☐	☐	☐	__________
Communication Headsets	☐	☐	☐	☐	__________
Portable Listening Devices	☐	☐	☐	☐	__________

How frequently do you use the following **basic** sound measuring equipment?

	Weekly	Bi-weekly	Monthly	Yearly	Other
Noise Dosimeter	☐	☐	☐	☐	__________
Sound Level Meter	☐	☐	☐	☐	__________

How frequently do you use the following **specialized** sound measuring equipment?

	Weekly	Monthly	Bi-weekly	Yearly	Other
Acoustic Manikin	☐	☐	☐	☐	__________
Artificial Ears	☐	☐	☐	☐	__________
Microphone in the Ear	☐	☐	☐	☐	__________
Hearing Aid Analyzer	☐	☐	☐	☐	__________

Comments: