Carleton University | Accessibility Institute

Informing Standards for Acoustics and the Built Environment

Final Research Report

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Carleton University | Faculty of Engineering and Design

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Sensors and Analytics for Monitoring Mobility and Memory
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1. Executive summary

The project *Informing Standards for Acoustics in the Built Environment* was carried out by a cross-functional team of researchers from the Accessibility Institute and the Faculty of Engineering and Design at Carleton University, with funding from Accessibility Standards Canada (ASC). The project goal was to investigate the role of the acoustic environment on persons living with disabilities and explore technologies that can contribute to the reduction and elimination of acoustic barriers. Sound and noise can impact the everyday activities and the experience of persons with disabilities, whether due to hearing loss, mental health conditions, autism spectrum, neurological injury, or aging. Identifying and understanding these effects can help improve comfort and functioning in the built environment.

The research objectives of the project were to:

- Identify key challenges and key accessibility barriers due to the acoustics in the built environment;
- Explore the role of existing and emerging technologies that can reduce barriers related to sound and acoustics;
- Advance the state of research and identify areas for future exploration to improve the acoustic experience of people with disabilities; and
- Identify key considerations and best practices relating to acoustics, and strategies for the use of technology to further acoustic accessibility in the built environment.

To meet these objectives, the team conducted a literature review, a co-design project, surveys and interviews of people with lived experience of disability, and engineering technology explorations. The interacting sub-projects focused on different areas of the problem space with both engineering and accessibility perspectives.

The literature review covered accessibility, engineering, and acoustic standards literature to produce a summary of the current state of acoustic accessibility. The review included the roles that sound and noise play in daily activities, the acoustic barriers created by the built environment for persons with disabilities, and how current standards and technologies try to reduce these barriers.

The review of standards was used to develop the co-design project, where persons with a variety of lived experiences of disability created stories to explore how the existing standards apply to their daily lives, and to identify gaps where barriers are not being addressed.

The role of assistive and personal technology in reducing acoustic barriers was explored through surveys and interviews with students with disabilities. The student feedback guided the engineering exploration of emerging technologies and their potential for reducing barriers.

Our research findings revealed a need for an increased awareness of the importance of acoustic accessibility, including a broader definition that goes beyond communication barriers associated with hearing loss. Participants and literature often mentioned challenges with the mental aspect of sound processing such as blocking out noise or listening to a single person in a group. Noise does not need to be loud to create a barrier and have negative impacts on focus, concentration, stress, and mental health. Group conversations or discussions in noisy environments can be difficult even for people who can hear well in quiet or one-on-one settings. These challenges exist for persons who are deaf and hard of hearing, including those who use hearing aids, as well as for persons with other, often invisible, disabilities. For these individuals, difficulties with sound processing may receive less attention because it is considered a side-effect of another condition. Some participants expressed frustration with this situation, and a feeling that they had no good strategies to manage the impacts of sound and noise. The participant concerns highlight the importance of echo and noise control, even in more spaces where it has not been traditionally seen as necessary, and the importance of access to quiet spaces to recover from noisy environments.

Our technology explorations showed the importance of a layered strategy for accessible spaces, such as amplifying sound with loudspeakers while also providing information in visual or alternative formats. These strategies complement one another and recognize the diversity of functioning and disability. Assistive technology is another layer that plays a role in overcoming barriers. Increasingly this role is being filled not by specialized assistive devices, but by consumer devices such as cellphones customized with assistive applications and accessories, and noise cancelling headphones used for personal sound control. This repurposing of technology for accessibility purposes is evolving rapidly, and more research is needed to maximize the benefits and understand the impacts.

This report translates these research findings into detailed recommendations for focus areas that should receive special consideration when designing acoustically accessible spaces, as well as some best practices for acoustic design. These recommendations can be summarized as:

- Design for diversity;
- Identify and support the roles of sound;
- Identify and reduce the effects of noise;
- Assess and re-assess acoustic accessibility; and
- Normalize and support the use of assistive technology.

The recommendations cover the lifecycle of a built space: from design, through construction, and ongoing use. They aim to help lead to the creation of a shared built environment where acoustics and accessibility are not just features, they are core properties of the space.

2. Project background

2.1. Project mandate and motivation

The purpose of the research project *Informing Standards for Acoustics in the Built Environment* was to investigate the impact of the acoustic environment on persons living with disabilities, to identify acoustic barriers within the built environment, and to explore technologies that can contribute to the reduction and elimination of these barriers.

There are specific interactions and impacts that sound can have on the experience of persons with disabilities. According to the 2018 Canadian Survey on Disability, over 20% of Canadians over the age of 15 report their daily activities are limited because of difficulties with their ability to hear (Government of Canada, 2018). Since age-related changes are the most significant contributor to hearing difficulties, this number is expected to grow as the Canadian population ages. Acoustic barriers also exist for people with other, often invisible, forms of disability, including learning disabilities, autism spectrum disorders, attention deficit disorders, mental health disabilities, and neurological injuries, though these have not received the same level of research or policy attention. This project aimed to broaden the scope of acoustic accessibility by investigating the diversity of relationships between sound, noise, and disability, with the aim of facilitating the creation of fully accessible acoustic environments.

The project was funded by Accessibility Standards Canada (ASC) for one year (2022 – 2023). Key outputs of this project for ASC include:

- Literature review of the current state of acoustic accessibility and relevant standards;
- Consultations with people with lived experience of disability about the acoustic barriers they face in the built environment;
- Development of a targeted yet widely adaptable set of best practices relating to acoustics in built environments; and
- Final research report to be made publicly available in an accessible format in both official languages.

The results of this project aim to give standards developers a simple and practical guide to incorporate acoustics considerations into the development of relevant accessibility standards under the *Accessible Canada Act* 2019.

2.2. Project team

The project was conducted through the Accessibility Institute at Carleton University and was driven by a cross functional research group. With backgrounds in engineering and electronics, linguistics and neuroscience and psychology, the project team goal was to address accessibility through both social science and engineering lenses.

The engineering side allows for deeper understanding of technical measures around assistive technology, the scientific properties of acoustics and sound behaviour in various environments. The social science lens brings focus to the real barriers encountered by individuals living with disabilities and brings forward the importance of exploring non-visible disabilities.

The project has partnerships with Inclusive Design Research Centre (IDRC) at the Ontario College of Arts and Design (OCAD) as well as the Rick Hansen Foundation and the Paul Menton Centre at Carleton University.

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2.3. Context

a) Language

This work references literature that relates to both the medical and social aspects of disability. These fields use different language to describe people with disabilities and their associated sensory impairments or functional limitations, and these differences are reflected in the words used in different sections. A discussion of the design of the built environment may refer to the barriers experienced by person who is deaf or hard-of-hearing, while a description of the mechanisms of hearing may refer specifically to a peripheral or binaural hearing impairment. Terminology for hearing-related topics comes from the American Speech-Language Hearing Association guidelines (American Speech-Language-Hearing Association, n.d.-c).

We use the terms disability and barrier as they are defined in the Accessible Canada Act (Naef & Perez-Leclerc, 2019):

> "Disability means any impairment, including a physical, mental, intellectual, cognitive, learning, communication or sensory impairment—or a functional limitation—whether permanent, temporary or episodic in nature, or evident or not, that, in interaction with a barrier, hinders a person's full and equal participation in society".
>
> "Barrier means anything—including anything physical, architectural, technological or attitudinal, anything that is based on information or communications or anything that is the result of a policy or a practice—that hinders the full and equal participation in society of persons with an impairment, including a physical, mental, intellectual, cognitive, learning, communication or sensory impairment or a functional limitation."

b) Functioning and disability

Models of disability influence how we view and study disability, including what standards are written and what they contain. Standards are both the product of, and a contributing factor to, the social environment.

This project considers the accessibility of the built environment through a biopsychosocial model, as used by the World Health Organization International Classification of Functioning, Disability and Health (WHO ICF) (World Health Organization, 2001). This model recognizes the roles of health conditions, personal experience, activities, and environmental factors, and how their interactions inform an individual's functioning and disability. The model also stresses aetiological neutrality and the significance of shifting from a binary classification of individuals based on health condition, to a view of disability existing on a continuum with functioning. Anyone can experience disability, and we cannot infer participation from diagnosis alone.

This model supports a systematic person-focused analysis of accessibility in the built environment. Such an analysis starts with the people who use the space, considers the activities associated with the space and assesses the ability to perform those activities in that space. . Based on the assessment of the space, changes to the environment can be made, repeating the assessment process. This leads to a design that treats accessibility as a core property rather than an addition.

c) Use of quotations

This report includes quotations from people with lived experience of disability who participated in our co-design project (see section 6.4). These quotes are included to provide some personal perspectives to accompany the discussions in the surrounding text. They are not intended to be representative of the views or experience of a population or group of people; they illustrate the specific experience of an individual. We gratefully acknowledge the participants for sharing their stories and allowing the use of these quotes.

2.4. Methods

> "*With this classification scheme … it may be possible to create instruments that **assess environments** in terms of their level of **facilitation or barrier-creation** for different kinds and levels of disability. … it will then be more practical to develop and implement **guidelines for universal design** and other environmental regulations that **extend the functioning levels of persons with disabilities** across the range of **life activities**." (ICF beginners guide)*

To address the project objective, the project team applied the ICF model described in section 2.3b to create interacting sub-projects that incorporated both engineering and social science perspectives. The sub projects included a literature review of accessibility, engineering, and acoustic standards literature; an assistive technology exploration; co design sessions with experts about the existing standards; and a survey and interviews around assistive technology used by students living with disabilities.

The literature review was used to identify the effects of sound and noise on people with disabilities, and to identify what standards exist, what they optimize for, and where there may be gaps. Using the findings from the literature review, surveys were designed to shape the co-design project, which examined the standards and their potential for gaps.

The findings in the literature review, combined with feedback from students, and others with lived experience, guided the exploration of technology. The technology exploration was used to evaluate the performance of emerging technologies and their potential for reducing barriers, from an objective perspective. Individual interviews and co-design story sessions were used to gather deeper, personal insight into the daily lives of persons living with disabilities, and their experiences with technology.

2.5. Organization of report

The remainder of this report focuses on the findings of the project. Sections 3 – 6 present summaries of our research activities along with relevant background and literature review; each section has a bullet-point summary written in plain language. The sections are divided into topics that can be roughly categorized using the ICF model:

- Section 3 focuses on people and activities in the built environment by providing a discussion of how sound and noise can affect people with certain disabilities;
- Section 4 focuses on the environmental factor of acoustics of built spaces, including what it means to create an accessible acoustic space;
- Section 5 discusses the personal and environmental factors of assistive technologies, and how they can be used to extend functioning in the space; and
- Section 6 looks at existing standards that deal with sound and acoustics, describing what is measured and what role accessibility and disability played in the development of the standards.
- Section 7 brings the findings together into a set of recommendations that can help with the creation of a fully accessible built environment.

3. Sound and disability

Hearing loss is a common and growing form of disability. According to the 2018 Canadian Survey on Disability, over 20% of Canadians over the age of 15 report their daily activities are limited because of difficulties with their ability to hear (Government of Canada, 2018). This number is expected to grow as the Canadian population ages. Age-related changes to physical and cognitive health are the leading causes of hearing loss; in the United States, about 15% of adults over 18 have some hearing loss, and for those over 75 the rate rises to nearly half. The World Health Organization estimates that 1 in 4 people globally will be living with some degree of hearing loss by 2050 (WHO, 2021). Communication difficulties from hearing loss impact a diverse range of everyday activities and can lead to reduced participation, poorer self-reported quality of life, and feelings of social isolation (Lind et al., 2016). While literature and discussions about sound and disability have typically focused on these communication barriers for people who are deaf and hard of hearing, auditory communication barriers exist for people with other, often invisible, forms of disability, such learning disabilities, autism spectrum disorders, attention deficit disorders, mental health disabilities, brain trauma, and others. There are multiple ways sound can play a role in disability, both through its absence when desired and through its presence when unwanted.

3.1. Hearing and listening

Conversations in noisy environments or with multiple participants are the most commonly reported functional and activity limitations for older adults, including those who use hearing aids (Picou, 2020). Difficulties listening in complex sound environments are commonly reported by individuals in groups as diverse as military Veterans (Gallun et al., 2017), stroke patients (Bamiou et al., 2012), individuals with Autism Spectrum Disorder (ASD) (Dunlop et al., 2016) and with multiple sclerosis (MS) (Gallun, 2021).

The paired tasks of hearing (perceiving sounds) and listening (attending to and extracting meaning from sounds) are composed of a chain of interacting physiological and cognitive processes. This section uses the task of listening in noise to provide an overview of these processes to inform the discussion of auditory barriers to everyday functioning.

Social conversation in a noisy environment is a common everyday activity that is accomplished transparently for many without disabilities but is often cited as a difficult situation for people with a range of seemingly unrelated disabilities. The familiarity of this task hides the complexity involved in extracting meaning from the incomplete fragments of sound isolated from the mixture of competing and overlapping signals received at our ears. This ability to selectively attend to a source of interest while filtering out competing ones, known as the cocktail-party effect, is thought to be accomplished by creating a mental model of the acoustic scene, with auditory objects playing the role of physical objects in a visual scene (Bregman, 1994; Bronkhorst, 2000; Shinn-Cunningham, 2008).

The ear collects incoming sound waves and converts them to electrical signals that are sent to the brain. The brain combines the signals from both ears (binaural listening) and builds up auditory objects using learned patterns about how sounds are produced and change through time. Low-level sound elements are formed by grouping together sound components that are joined in time and frequency, as well as components that are harmonically related (multiples of the same pitch) or have similar amplitude fluctuations. These short-term objects are linked through time using higher-level features like pitch continuity, the location of the sound source, and even learned concepts like language and grammar structure. The result is a background stream that is monitored with low priority, and a foreground auditory stream that can be actively focused on to extract meaning or to locate the source of the sound.

While this process is described as progressing bottom-up – from the ear, to low-level features, to high-level objects – there is a top-down path as well. Conscious attention and information that comes from understanding the situation can influence the low-level grouping, assignment of objects to streams, and even the frequency sensitivity in the perception stage. The information that can affect attention includes the location of the desired source, their pace of talking, and the pitch and frequency content of their voice.

With a single sound source in a quiet environment the acoustic cues are clear, and the foreground stream can often be extracted quickly and reliably without significant cognitive effort. As the scene becomes more complex and more sources are added their time, frequency, and spatial cues start to overlap with the desired source, and the cues become harder to separate. When this happens, auditory streams take longer to build up and stabilize, and may contain sound content from multiple objects, or may have gaps where the sound element was blocked by a competing object. Decoding these incomplete streams relies more on knowing what is being heard, which requires more cognitive effort and working memory. In group conversations the task is multiplied when the conversation flows through changing topics, interruptions, and multiple talkers, requiring rapid switches in attention. Focusing on a new talker means resetting the top-down attention pathways and restarting the stream formation process. Some information from the new stream is lost in the switch, so the recent input signal must be mentally replayed from auditory short-term memory to recover the content. Sources (Bregman, 1994; Bronkhorst, 2000; Buschman & Miller, 2007; Conway et al., 2001; Oxenham, 2018; Pichora-Fuller & Singh, 2006; Shinn-Cunningham, 2008; Shinn-Cunningham & Best, 2008)

3.2. Functional limitations due to auditory processing

Listening, especially listening in noise, requires the interaction of many body structures. Discussions of auditory disabilities often divide the auditory processes into peripheral and central systems, where the peripheral auditory system in the ears is responsible for converting sound waves into electrical signals (hearing), and the central auditory nervous system in the brain is responsible for interpreting those signals (listening). Impairments of the peripheral system have typically received more attention and research effort, in part because they can be understood in a physical way and can often be traced to a specific physiological origin.

a) Peripheral hearing loss

> *“I was inside my workspace, a restaurant, and the construction noise outside during streetcar track repair was the focus of my one good ear. I can only hear from one ear, and droning ambient noise makes it hard to focus on the sounds I need to.” – co-design participant*

Peripheral hearing loss is characterized by reduced sensitivity to sound. Auditory thresholds are increased so quiet sounds cannot be perceived at all, and other sounds may be unclear or muffled. Sound level is not the only feature that is impacted, time and frequency resolution are often reduced as well, which makes sounds unclear even if they are loud enough to be heard. Amplification by hearing aids, cochlear implants, or even loudspeakers can be used to raise signals up to audible levels, but this cannot restore the clarity of these spectro-temporal cues. Since the auditory processing stages build on one another, these distortions of the basic auditory information at the beginning of the hearing process have impacts on higher level processing stages (Shinn-Cunningham & Best, 2008).

Known causes of peripheral hearing loss are wide-ranging and include (American Speech-Language-Hearing Association, n.d.-b):

- genetic causes,
- noise exposure,
- tumours,
- infections,
- medication side-effects,
- physical trauma, and
- aging.

An individual’s hearing loss is often described in terms of type, degree, and configuration. This classification does not determine the impact on the individual, but can be used to describe the health condition and help predict the outcomes and benefits of potential treatments or assistive technologies.

The *type* of hearing loss is categorized by the part of the hearing system that is affected. Conductive hearing loss refers to problems with the passage of sound waves into or through the outer and middle ear, sensorineural hearing loss refers to the sensing or neural pathways of the inner ear, while mixed hearing loss refers to a combination of both. The *degree* of hearing loss describes the severity of the functional impairment as measured by the decrease in sensitivity relative to the "otologically normal" hearing levels. Degree is described on a scale that ranges from normal, to slight, mild, moderate, severe, and profound hearing loss (deafness). The *configuration* of hearing loss describes variations in the degree of hearing loss for different frequencies. High frequency sounds tend to carry less energy and are more easily absorbed and scattered, making a high frequency configuration common among people with age-related and noise induced hearing loss. (American Speech-Language-Hearing Association, n.d.-b)

The onset of hearing loss may be gradual or sudden, and the impacts may be permanent, temporary, or fluctuating. For example, middle ear infections are a leading cause of temporary and fluctuating hearing loss among school-aged children – given the frequency and duration of these infections, on any given week there can be expected to be multiple children in each classroom with this invisible disability (Nelson & Soli, 2000).

Hearing loss can impact everyday activities such as enjoying music or the sounds of nature, though the largest self-reported impact is on a person's ability to understand spoken communication, particularly in noisy environments. Difficulties communicating, and the associated real or perceived stigma, can limit their participation and performance in a broad range of activities such as learning, working, communicating with partners, and other forms of social interaction. Avoiding, or being excluded from, social situations can also lead to feelings of isolation, loneliness, and inadequacy (Bennett et al., 2021). This social isolation is one suggested mechanism to explain results showing that that hearing loss may be a contributor to, rather than strictly the result of, cognitive decline (Lin et al., 2013).

b) Central Auditory Processing Disorders

Central Auditory Processing Disorders (CAPD) refer to "difficulties in the processing of auditory information in the central nervous system"(American Speech-Language-Hearing Association, 2005). The complex interactions between the central auditory processes and confounding individual factors, such as neuroplasticity and compensation in the brain, mean that individuals with CAPD have a wide range and severity of symptoms.

While peripheral impairments can be characterized by audiometric tests using pure tones in a controlled listening environment, there are no standardized diagnostic criteria or descriptive classifications for CAPD. This, combined with the high co-occurrence and interaction with other conditions, has led to controversy in the auditory neuroscience community about whether CAPD is a distinct condition or a collection of related symptoms from different conditions (D. R. Moore, 2018).

This view has been a significant barrier for individuals with CAPD, contributing to reduced research, as well as a lack of diagnosis, dismissal of symptoms, and reduced access to treatment options. This barrier is now being acknowledged, even by those opposed to recognizing CAPD as a diagnostic entity (D. R. Moore, 2018).

The discussion of CAPD is less controversial among audiologists. Informed by their clinical encounters with patients, they place less emphasis on identifying the exact mechanism of impairment (a "site-oflesion" perspective) and consider CAPD as a distinct condition characterized by its impact on the individual. This perspective is reflected in position statements by national audiology organizations including Canada (Millett et al., 2012), the United Kingdom (D. Moore et al., 2018), and the United States (Musiek et al., 2010).

CAPD is described as a deficit in the central auditory nervous system, affecting the processes where low-level sound features are combined to form higher level objects in the acoustic scene. It is characterized by activity limitations in the temporal and binaural processing of sounds including: linking sounds through time, ordering sounds, identify gaps and changes in sounds, determining pitch, localizing sounds and identifying the source of a signal (Millett et al., 2012). Many of these activities are used to create and maintain auditory streams, so individuals with CAPD will often report difficulties listening, or understanding what they hear, especially in noisy situations or when faced with rapid or degraded speech (Bamiou et al., 2001). The reduced acuity of pitch perception can also lead to difficulty playing or enjoying music, and in understanding prosody changes used to relay social cues such as emotion or sarcasm (American Speech-Language-Hearing Association, n.d.-a).

The range of brain regions involved in auditory processing and the plasticity of the brain means that the symptoms collectively described as CAPD can develop unexpectedly, often as an overlooked side-effect of other conditions including:

- **Traumatic brain injury** – studies of military Veterans with a history of blast exposure (Gallun et al., 2016; Tepe et al., 2020), athletes with previous sport-related concussions (Turgeon et al., 2011), and other individuals with mild traumatic brain injury (mTBI) (Hoover et al., 2017) found that more than half displayed difficulty in speech in noise in real-world and controlled situations despite 'typical' auditory thresholds. These symptoms may persist for years after the original injury is considered healed.
- **Stroke** – studies of stroke patients have found a high proportion with persistent auditory processing deficits. In many cases the deficit was undiagnosed and unrecognized by the individuals (Bamiou et al., 2012; Koohi et al., 2017; Purdy et al., 2016).
- **Multiple Sclerosis** – MS is known to affect neural conduction pathways which can distort binaural cues. MS patients have reduced performance localizing sounds and communicating in complex acoustic environments (Iva et al., 2021; Levine et al., 1993).
- **Aging** – age-related changes in physical hearing structures make peripheral hearing loss very common in older adults, but peripheral effects do not fully account for measured hearing difficulties in complex environments (Murphy et al., 2006). The processes involved in understanding speech in noisy environments relies heavily on working memory to mentally replay and extract information from multiple sounds sources, and may be impaired by age-related reductions in memory capacity. Central auditory processing disorders may also arise as more general cognitive decline and neuroplasticity lead to reorganization and redistribution of cognitive resources. Peripheral and central auditory losses can also reinforce each other, as specialized auditory processes become less effective and therefore less relied-upon. (Peelle et al., 2010; Pichora-Fuller & Singh, 2006; Stach et al., 1990).

The symptoms of CAPD are also highly associated with conditions that impact memory, attention, and sensory processing:

- **ADHD** – the relationship between ADHD and CAPD is so strong that research has questioned if one condition is a manifestation of the other. Both are associated with sensory and attention processes, and their impacts are very similar especially for young learners and their performance in classroom listening, comprehension, and learning (Bamiou et al., 2001; Riccio et al., 1994).
- **ASD** – individuals with ASD often report difficulty distinguishing speech from background noise (Alcántara et al., 2004). Rather than being the result of reduced auditory functioning, this may be due to enhanced perception of low-level features (Mottron et al., 2006) and un-attended sounds (Remington & Fairnie, 2017). More detail is extracted from the auditory cues, and multiple auditory streams are maintained in parallel with the foreground, leading to sensory overload in complex environments.

Other known causes include tumours, genetic factors, prenatal and neonatal circumstances, and exposure to neurotoxins (American Speech-Language-Hearing Association, n.d.-a). The list presented here is intended to be illustrative rather than exhaustive. For many individuals there are multiple causes, or the cause is unknown, however, the inability to attribute a specific cause does not reduce the impact to the individual.

3.3. Response to sound and noise

We are immersed in sound, those who perceive sound cannot “look away” from it. The sound we experience is always a mixture of desired sounds and noise. Exposure to environmental noise, such as construction, industry or transportation noise, can have significant negative impacts to heart health, cognitive capability, sleep quality, and overall well-being (World Health Organization, 2011). Noise, especially fluctuating noise or sound that has meaningful content like speech, can disrupt language processing even when the information is presented in text form (Larsby et al., 2005). The presence of noise, or of any sounds with specific level, time, or frequency characteristics, can also provoke strong emotional and physical responses and act as a barrier to participation in everyday activities. Health conditions impacted or characterized by responses to sound and noise include:

- **ASD** – there is extensive evidence for atypical processing of auditory information in individuals with ASD from behavioral and neurophysiological literature (O’Connor, 2012). Besides CAPD, individuals may experience a reduced tolerance for loud sounds (‘hyperacusis’) (Rosenhall et al., 1999), and an increased perceptual intensity of certain sounds including sudden sounds (dog barking, coughing) or high-pitched continuous sounds (electrical appliances or lighting) (Grandin, 1992; O’Connor, 2012). These sounds can provoke intense emotional and physical responses, and can increase repetitive behaviors (M. Kanakri, 2017); design recommendations for autism-friendly spaces therefore emphasize the importance of noise control (Kanakri et al., 2017; Mostafa, 2008).
- **Hyperacusis and misophonia** – averse responses to loud (hyperacusis) or common (misophonia) sounds is not unique to people with ASD and can have pervasive effects on focus, concentration, sleep, and emotional well-being (Tyler et al., 2014; Vitoratou et al., 2023).
- **Mental health and anxiety** – the presence or anticipation of sudden, loud, or unpleasant sounds can trigger a negative reaction (Jüris et al., 2013) and can also reduce the ability of some people with mental health conditions to focus in a noisy environment (Pfleiderer et al., 2010). Chronic

noise has been shown to significantly increase the risk of certain mental health disorders, such as the demonstrated relationship between aircraft noise and depression (Hegewald et al., 2020).

- **Learning disabilities** – the relationship between auditory processing and learning disabilities has been strongly contested (Dawes & Bishop, 2009). Practitioners such as teachers and audiologists have observed highly correlated symptoms that have led to speculation of CAPD being the cause of certain learning disabilities. The research however has not been able to demonstrate this relationship. What is strongly established is that some types of language-based learning disabilities rely on accurate phonological processing of spoken and written language. Due to difficulties with processes such as sound blending, elision, or phoneme isolation, any external auditory barriers can exacerbate the functional limitations experienced as a learning disability.
- **ADHD** – sound can act both as a distraction or a stimulant depending on the situation and the type of sound. Distracting irrelevant sounds can impact performance of people with ADHD on both auditory (Freyaldenhoven et al., 2005) and non-auditory (Pelletier et al., 2016) tasks, while white or other random noise may increase arousal and cognitive performance (Söderlund et al., 2007).

> *"… Late at night, when I was either trying to study or sleep I often would hear noises coming from the staircase side of my room (doors opening and closing, footsteps going up and down the stairs) ... It made it incredibly difficult to focus, and made me increasingly irritable whenever it occurred. As a person with ADHD I struggle to focus, so whenever I finally was able to get "in the zone" to study I was broken out of it whenever I heard those sounds." – Co-design participant*

- **Vision impairment** – people who are blind often rely on acoustic information to perceive a sense of space, and to orient or navigate within a space (Ryhl, 2013). Sound information is given more salience and regions of the brain typically used for visual processing may be remapped to process auditory information (Bavelier & Neville, 2002; Kujala et al., 1997) with a resulting improved processing of auditory scenes and more accurate auditory streaming (Boroujeni et al., 2017).

> *"[I] was in a retail store; the sound was loud music over a PA system throughout the store; I am blind and navigate with the help of a guide dog; I must tell the dog left right straight etc. to reach areas in the store; I was trying to find the cashier lines; without music I would be able to hear the audible beeps of the scanning wands and would use this as a way finding tool; I could not hear the beeps over the loud music." – Co-design participant*

As with the discussion of CAPD, this list of conditions presented here is not exhaustive. Functional limitations due to auditory processing and sensory sensitivities share many underlying causes, and they can co-exist and interact in the same person.

3.4. Research – Impact of sound and noise on students with disabilities

Two studies were conducted to gather insight from students with disabilities regarding the impact of acoustics in their learning and campus environments. These studies were carried out with Carleton University researchers, and students registered at the Carleton University disability coordinating services known as the Paul Menton Centre (PMC). These two studies were comprised of an online survey and one-to-one interviews.

Study Goal

The principal goal of the two studies we conducted, the survey study and the interview study, was to investigate how sounds and noises impact daily campus activities for students who are registered at the PMC. Specifically, we aimed to better understand 1) the challenges created by sounds and/or noises in different environments on campus and 2) how these challenges may be overcome by the use of assistive technologies.

Methods

The online survey study:

An online survey asked students with disabilities about their assistive technology uses and experiences around their learning environment at Carleton University, with a specific aim to gather their insight on acoustic barriers and needs. This survey used multiple-choice question format. The survey was cleared by the Carleton University's Research Ethics Boards and was distributed via email among the students registered at PMC by the support staff. The survey was then sent, via email to all students registered at the PMC, and was active for over 2 months. This survey was anonymous and voluntary. To ensure full anonymity, participants were not offered an honorarium as this would identify them.

The one-to-one interview study:

Following the survey, to gather deeper understanding of the Survey participants' experiences and needs, we developed and administered one-to-one interview sessions. This study also required ethics clearance, which was granted. Each student took part in a 30–60-minute interview session via Zoom, scheduled at a time of their convenience. Zoom audio-recorded interview sessions and each session was later transcribed. Participants were provided with an honorarium as a gratitude for their time.

Findings

The following is a summary of the main findings of the survey study:

The survey was distributed, via email, to over 3000 students registered at the PMC. On the first day of the survey distribution, we received 100 responses. After approximately 3 months of data collection, 212 responses were received. The survey asked students to indicate potential challenges related to sounds and/or noises that may impact their activities in different environments on campus and how they may overcome those potential challenges by using technology or non-technological strategies.

- Approximately 90% of the students who participated in the survey study have at least one of the following: Attention-Deficit/Hyperactivity Disorder and General and/or Social Anxiety Disorder (about 50%), Autistic Spectrum Disorder (about 20%), auditory and/or sensory sensitivities and/or information processing difficulties (about 20%).

- About 70% of participants reported that they have multiple disabilities or health conditions that create challenges related to sounds and/or noises, which impact their activities on campus.
- Approximately 90% of participants use noise-cancelling or noise-reducing headphones, earplugs, or earbuds.
- More than 30% of participants listen to music to block out environmental noises and aid in concentration.
- More than 40% of participants think that there is no workable solution to the problems they face on campus, and therefore, avoid or leave campus environments which they cannot tolerate.
- Participants reported that less than 40% of their instructors use the microphones that are provided to them in large lecture halls.
- Many participants indicated that they rely on lecture slides and/or notes provided by instructors or volunteer note-takers.

This study revealed barriers around sound and assistive technology, while also highlighting the importance of non-visible disabilities. This illustrated the need for deeper exploration, leading to the development of the interview study, in which participants could share, more openly, their experiences. 27 participants from the same group of participants as in the survey study were asked the same types of questions as in the survey study via a 30-60-minute interview. The questions in the interview study were all open ended, rather than using multiple choice format, which made it possible for the interview participants to elaboration on their responses.

The following is a summary of the main findings of the interview study:

- Noise-cancelling or noise-reducing headphones are integral to some students' education. However, students face a number of anxieties when using their assistive technologies. These include fear of appearing rude to their professors and peers, fear of their disability being known to others, financial strain (as devices are expensive), and personal safety (as they are unable to hear potential danger in their surroundings).
- Instructors have failed to accommodate the needs of the students despite the students being registered at PMC and having prescribed or registered learning accommodations. For example, students reported that instructors have forgotten to use microphones, FM signal transmitters, or add captions to videos.
- Students requested that information about assistive technology be made widely available. Students expressed a desire to increase awareness of the importance of assistive technology as well as the importance of quiet and accessible campus environments.
- Students with disabilities hoped that those without disabilities would receive education or information about disabilities, which should help the entire Carleton community become more understanding of the students with disabilities and their needs.
- Students remarked on the financial strain of assistive technology. They wished that grants or bursaries were made available to them to help ease the financial burden of paying for their assistive technologies.

3.5. Section summary

- Listening in noise is a complex task that requires cooperation between the hearing structures in the ears that collect sound energy, and the sound and language processing regions of the brain that decode and extract meaning from the sound signals.
- Hearing loss is a common form of disability that is becoming more common as the Canadian population ages. Hearing loss can make some quiet sounds harder to hear and can make other sounds unclear. Hearing aids can make sounds louder but can not make all sounds clearer.
- There is increasing recognition that people with brain injuries, autism spectrum, anxiety, attention deficit, and some auditory cognitive impairments can have difficulties understanding speech, especially in noisy spaces. Differences in sound processing in the brain can make it harder to focus on a single sound when there are noises or echoes. Many of these people may not be aware that they have difficulty hearing.
- Sound and noise can do more than make it hard to understand speech. Noise can make it harder to focus, learn, and work. It can also increase mental health problems, decrease sleep, and trigger anxiety.
- Better technology is needed to reduce noise without removing the sounds we want to hear. Currently, people with sound sensitivities often have to choose between living with noise or blocking everything out.
- Overcoming negative attitudes about the assistive technologies used to reduce noise requires more education, awareness, and understanding of how harmful unwanted sound can be.

4. Acoustics of the built environment

The acoustic built environment refers to the sounds we experience in the human-created spaces where we live and work. Sounds are shaped by the space they fill, and our experience of those spaces is shaped by the sounds. The location of, and activities within, a space determines which sounds exist in it. The shape of the space and the materials used in its construction control what sounds can enter and how they behave.

4.1. Sound and noise

Some sounds are used to intentionally convey information; speech is an important example, also sirens, alarms, and music. Other sounds have information as a side-effect; the sound of an arriving train, or of footsteps can tell us not only that there is motion, but the direction as well. Any sound we do not want to hear is noise; the division between what is sound and what is noise is subjective and depends on where we are and what we’re doing.

Since any sound can be a noise, we often try to put noises into categories based on their pitch or tone, how long they last, and how predictable they are. The drone of a distant highway is constant, predictable, and low frequency; the hum of a refrigerator or a misbehaving light fixture is intermittent and mid to high frequency; a dog barking or a door slamming is unexpected, transient, and contains a mixture of frequencies.

Noises within a space can be characterized by their source (“where they come from”) and their mode of transmission (“how they got here”):

- *Environmental noise* is any noise from human activities that originates outside the building (World Health Organization, 2011). While this can include community noise from playgrounds and music, it usually means noise from construction and industry, or transportation sources such as car, rail, and air traffic. These mechanical noises are transmitted to built spaces through the air, and their low frequency means they are not readily absorbed and can be heard over long distances. Their frequency content does not change very much, and the level is usually constant over short time intervals but can change during the day (e.g., during rush hour). Environmental noise is controlled by choosing a quiet site, using large scale sound-blocking features like berms, and through sound insulation and other design features of the building exterior.
- *Mechanical noise* is from mechanical systems within the building, most often heating, ventilation, and air conditioning (HVAC). Like the environmental noises that come from machines, these mechanical noises are also low frequency which means they can transmit over long distances, especially through ductwork and structural vibration. The frequency content is consistently low, but the level may change with the operating mode of the system. Mechanical noise is controlled through HVAC system design, duct insulation, and sound insulation between spaces.
- *Activity-related noise* is sound from activities within the building, either the same space or adjacent spaces. This can include a wide range of sounds from voices, music, or equipment such as fans and computers. These sounds can be variable in time and frequency, and this makes them more difficult for human listeners to filter out. Transmission of sound from adjacent spaces can be airborne (e.g., voices), or structure-borne (e.g., footsteps) and is controlled by structural design and sound insulation.

4.2. Reflection and echoes

The behaviour of a sound wave when it hits a surface depends on the acoustic properties of the surface (Long, 2005):

- Soft and porous materials, such as foam, fiberglass, carpet, and acoustic panels used in suspended ceilings, absorb sound, converting its energy into heat and reducing its intensity.
- Hard and smooth surfaces, such as concrete, metal, or glass, reflect sound without decreasing its energy significantly, resulting in distinct reflections and audible echoes.
- Irregular reflecting surfaces scatter sound waves in multiple directions, creating a diffuse sound field that has no apparent source, rather than clear echoes.

Reflections that arrive at the ear shortly after the main sound are merged with the original by our auditory systems, making the sound louder and easier to hear. Later reflections are heard as echoes, and collections of echoes become reverberation that masks or blurs the original signal, turning the desired signal into noise. Reverberant spaces can also multiply the effects of noise by allowing noise to build up instead of dying down. These increased noise levels cause people to unconsciously raise their voices in conversations through a process called the Lombard effect (Garber et al., 1976), which further increases the sound level.

Echoes and reverberation are not always accidental or undesirable. Reflections from nearby walls, or lack of reflections in doorways or stairwells, provide non-visual information about the structure of a space and its features. In concert halls reflections are carefully controlled and sculpted to create the rich layered mixture of musical instruments in a symphony performance, and in places of worship they are directed to reinforce the speaker without the need for amplification (Kahn, 2021).

> *Echoes in a hallway help me locate the washroom. Sounds from outside help me find the doors. Sounds on the floor help me track the movements of people. – Co-design participant*

4.3. Acoustic design and education

The shape of a space and the acoustic properties of its surface materials determine its response to sound, or it's "acoustic character". Architectural acoustics is the art and science of creating spaces with "good" acoustic character. Good in this case is subjective, and the perceived key metrics will vary depending on the type of space, for example:

- Work environments require acoustic privacy between workstations, high speech intelligibility for collaborative work, and low noise levels of distracting noise for focus work.
- Educational spaces require good sound transmission and high speech intelligibility for instruction, and low levels of distracting noise for focus work.
- Restaurants value acoustic privacy between tables, high speech intelligibility between patrons at the same table, and a diffuse noise field to promote feelings of liveliness and anonymity (Roy, 2019).

Historically, acoustic design was based on patterns and principles that evolved from experience and experimentation; good designs were scaled, replicated, and iterated on. Successful examples of such designs remain, such as Greek and Roman theatres where performers without amplification could be heard by thousands of spectators (Long, 2005; Sheridan & Van Lengen, 2003). The acoustic character of these structures continues to impress listeners; however, this iterative design process does not lend itself to arbitrary shapes and sizes. Modern architectural acoustics based on a scientific understanding of sound and materials science dates only to the 20th century (Long, 2005).

The study of architectural acoustics was motivated by the need to improve performance spaces such as theatres and concert halls (Milo, 2020); for everyday spaces it remains a largely overlooked aspect of architectural design. Architecture is seen as a largely visual art and appreciation of architecture is most often described by its visual appeal (Sheridan & Van Lengen, 2003). The visual sense is easier to capture and reproduce – a sketch, model, or photograph can convey the visual aspects of a design, but the response of a space to sound is dynamic and needs to be experienced.

Researchers of architectural acoustics who interviewed practicing architects found that acoustics is seen as a specialized area of study that is typically handled by outside experts (Harvey, 2021). Even in cases where the architects feel a design would benefit from acoustic expertise, they are hesitant to propose the additional cost to clients who feel it should already be covered. In most cases they rely on manufacturers’ technical data to meet code requirements for acoustic performance.

The view of acoustics as a distinct branch of architecture is also reflected in the software used for acoustic design. Computational advances have allowed the introduction of acoustic simulation tooling that can “auralize” a design by placing virtual sound sources within the space and listening to the simulated response at different locations, but these tools are not well integrated with the architecture design flow (Harvey, 2021; Peters, 2015). Surveys found that use of these tools is limited to larger architectural practices and acoustic specialists (Milo, 2020).

A review of acoustics teaching in architecture programs in Canada revealed that architecture students consider acoustics to be more closely aligned with engineering than with architecture. This was reflected in program course offerings; mechanical and civil engineering offered multiple courses in acoustics, vibration and noise control, while architecture programs often had none, or a single course combining lighting and acoustics (Berardi, 2017). Instructors are trying increase architecture students’ understanding of sound and how it influences our participation in spaces using novel tools such as smaller-scale acoustic simulations and field measurements with smartphone audio recorders (Berardi, 2017; Milo, 2020; Sheridan & Van Lengen, 2003).

Classifying acoustics as a construction detail rather than design feature leads to a lack of consideration of the acoustic consequences of fundamental choices such as the room shapes, layout, and design finishes; acoustic issues are often considered only after the fact, or when problems arise (Sheridan & Van Lengen, 2003). This is common in everyday structures, and even in spaces designed for sound, as in the case of the recent renovations to the home theatre of the New York Philharmonic. Drastic modifications were needed to improve the sound, as prior attempts could not address the "fatal flaw built into the shape of the room" (Nathoo, 2019; Reyes, 2023).

4.4. Accessible and inclusive acoustics

> *Thought should be considered at the design stage of new builds to ensure that spaces with service provisions allow for noise dampening within the built environment in order to allow for maximum communication in the absence of technology. Enhancement technology disappears in the event of power failure, and attitudinal failures, but the built environment can be a constant in accommodating. – Co-design participant*

Acoustically accessible spaces minimize distracting and harmful noises, and shape the flow of sound to facilitate communication and wayfinding. In recent decades, research with young learners has highlighted the role of good acoustics in promoting a healthy learning environment and has demonstrated how poor acoustics can degrade the experience for students and educators and create significant barriers for those with auditory disabilities. Updated school design guides, such as those in from the United States (Acoustical Society of America, 2010) and the United Kingdom (Daniels, 2015) provide acoustic performance standards that primarily aim to limit noise and reverberation to facilitate auditory communication.

Acoustic accessibility outside the classroom has received less research attention, an important exception is Camila Ryhl, a Danish architect, accessibility researcher, and professor of universal design who has studied sensory accessibility from the perspectives of users and designers. Ryhl has found that acoustic accessibility is hindered by a view of accessibility not as a design concept, but a legislative concept associated with requirements for specific design features to accommodate users with disabilities, especially physical disabilities (Ryhl, 2013, 2016b). This perspective leads to targeted accommodations that are grafted on to an existing design, rather than a true universal design approach where consideration for user diversity is integrated into the design.

The difference between these approaches is highlighted in a case study of the design of the headquarters of Danish disability organizations. Accessibility was a central aspect of the design, yet “the few specifications on sound were primarily related to induction loop and other assistive technology” (Ryhl, 2016a), as a result acoustic performance varied within the building:

- The specification for the meeting rooms had a target reverberation time of 0.6 seconds and called for the installation of hearing loops. Meeting rooms are conventional spaces and were therefore designed with standard approaches and materials. The reverberation time in the completed rooms was measured to be around 1 second; interviews with users found communication in the rooms to be challenging, with the performance of the hearing loops to be mixed. Interviews with the construction team showed that they did not consider the acoustic performance to be an important quality factor as the induction loop was present as a solution to accommodate hearing impairment.
- The specification for the five-story central atrium had a maximum reverberation time of 1.6 seconds. The scale of the space meant this could not be achieved using standard designs, so the acoustic quality became a central design consideration. The space features irregular surfaces and plants to scatter and absorb sound; the resulting reverberation time was measured to be 1.3 seconds and users of all abilities emphasize the positive acoustic experience of the space.

In the case of the atrium, designers were able to balance the desire to create an open and welcoming space with the need to control noise and reverberation. When design objectives conflict, acoustics and acoustic accessibility may be seen as a “nice to have” features rather than key performance indicators, so they are sacrificed to meet other goals.

Effective noise and reverberation control requires surface treatments made from sound absorbing materials and that are typically soft and textured. This desire frequently conflicts with the requirement to have cleanable and hygienic surfaces that are non-porous, hard, and smooth. In sanitary

> *I have not experienced any indirect sounds in the building that made it easier for me to accomplish my goal. Normally, indirect sounds are environmental noises that interfere my concentration.*
> *– Co-design participant*

environments the hygiene requirement is paramount, leading to the use of materials like stainless steel and tile, and producing spaces that are very acoustically reflective, with long reverberation times and noise accumulation.

> *I find that the right type of ambient music will generally lower the stress of heavy focus. – Co-design participant*

In addition to hygiene concerns, the activities or equipment of certain spaces may challenge the goals of acoustic comfort and accessibility:

a) Medical spaces

Emergency rooms and intensive care units have a complex sound environment with a background noise level created by mechanical systems and multiple conversations, punctuated by sporadic bursts from public address systems and medical monitoring equipment. Noise and overall sound level are common sources of complaint and are known to be detrimental to patient sleep and recovery, and to the health, wellbeing, and performance of medical staff (Mackrill et al., 2014; Salandin et al., 2011). Alarm fatigue is one specific example of a concern, as alarms are intended to be loud and difficult to ignore, yet the majority of alarms result in no action being taken (Lawson et al., 2010). The sounds are reinforced by the open spaces and long halls made of reflective materials that facilitate movement, but also transmit and retain sound; the material choice is dictated by infection control, wear, and cost (Busch-Vishniac et al., 2005).

b) Long term care homes

These spaces face design challenges owing to their dual roles as spaces for both everyday living and healthcare delivery. Since a large proportion of residents have some form of auditory disability, acoustics plays an outsized role in many day-to-day activities. Research highlights the importance of access to natural and desirable sounds for creating welcoming and home-like environment (Graham, 2020), this “sense of place” improves quality of life and medical outcomes for residents (Janus et al., 2021). Unfortunately, these acoustic needs of residents are balanced against sanitary and infection-control concerns, as well as the practical and economic realities of staffing and service delivery. Long term care spaces tend to be closer in design to hospitals than houses, with the same hard surfaces, long reverberation times, and lack of natural sounds (Graham, 2020). For illustration, the 2015 Ontario Long-Term Care Home Design Manual has only one mention of acoustics and noise, listing noise minimization as a design objective of the dining area (Ontario, 2015).

c) Restaurants

Restaurants rely on sound levels to create an ambience that is both lively and private. Some research shows that increasing the level creates a more positive impression for many patrons, and encourages them to spend more time and money (Tarlao et al., 2021). This can foster the misguided view that “louder is better”, leading to spaces that are excessively loud for patrons and employees (Bottalico et al., 2020; Roy, 2019).

d) Schools

School design guides have noise level recommendations for unoccupied spaces including classrooms and support spaces (Acoustical Society of America, 2010; Daniels, 2015). These recommendations do not consider equipment and activities within the classroom such as computers, projectors, and fans, though these may interact with the baseline noise and reverberant spaces to become barriers to communication and focus (Brill et al., 2018). Similarly, restroom fixtures such as powerful automated flushing toilets and hand dryers create sounds with levels and characteristics that can be distressing, especially for those with sensory sensitivities (Drever, 2017).

Some apparent conflicts can be managed by recognizing that acoustic quality is not only a concern for individuals with auditory disabilities, so what may be seen as accommodations should be re-classified as design features. As Ryhl notes, people with disabilities “due to their increased sensitivity can inform us of details in the acoustic environment we are all exposed to, and as a result contribute with important information of the role of our acoustic experiences” (Ryhl, 2016a).

In other cases, the acoustics goals for different user groups may be fundamentally opposed, however, a compromise may be found in embracing this diversity. The Government of Canada GCWorkplace Design Guide recognizes that individuals have different functional needs and personal preferences, and recommends workspaces with varying levels of auditory and visual stimulation (PSPC, 2022). Creating a mix of common and private spaces, including quiet refuges within common workspaces, allows individuals some control in tailoring their environments.

When inclusive and diversity aware design cannot mitigate design conflicts, providing awareness of the acoustic environment can support individuals’ personal agency related to how they interact with the space. Examples of this in practice include:

- Restaurant reviews and apps that measure and report the sound levels during mealtimes, allowing patrons to choose their preferred noise level and provide feedback to restaurant owners (Roy, 2019).
- A “sonic story” visual representation of a theatre presentation that highlights loud or sudden sound events, allowing patrons with sensory sensitivities to prepare themselves (Renel, 2019).

In most cases, accessible acoustics simply means good acoustics. The negative impact of poor acoustics is universal: loud sounds are uncomfortable and distressing; distorted audio is unpleasant; communicating in crowded acoustic environments with noise and reverberation increases cognitive effort. For some these impacts are annoyances or inconveniences, for others they can be barriers that exclude them from full participation. (Acoustical Society of America, 2010).

4.5. Research – Soundscape of Carleton University

The term soundscape is used for the acoustic environment as it is perceived by humans. The soundscapes of the built environment describe the sounds we experience in the human-created spaces where we live and work; they are a mixture of sounds from outside the space, sounds from the infrastructure itself, and sounds of activities in the space. These sounds interact with the space itself to create the acoustic environment we experience. The accounts and descriptions provided by respondents of the student assistive technology survey, described in Section 3.4, powerfully illustrate how our experience of sound in a built environment is entirely subjective, and it can range on a spectrum from fully enjoyable to harmful. To better understand the responses and the factors that contribute to them, we conducted an informal soundscape investigation of the spaces on Carleton campus described by the student survey participants. The investigation consists of the following elements:

- A description of the physical environment, including any acoustic treatments or considerations, as well as the activities in the space.
- Sound level measurements from an ANSI S1.4 Type II compliant sound level meter (EXTECH Instruments, #407764). The "slow" setting was used to capture the average background sound level from sources such as ventilation machine noise, and the "fast" setting was used for faster changing sounds like nearby speech and the sound of movement. These levels are compared against the standards in section **Error! Reference source not found.**.
- Audio recordings captured with and omni-directional electret measurement microphone (Dayton Audio EMM-6) and a USB audio interface (Focusrite Scarlett 4i4). These recordings were used to qualitatively describe the time and frequency characteristics of the sounds.

The following sections highlight the key findings from the soundscape as they relate to the student survey responses.

a) Lecture and teaching areas

Teaching spaces are difficult to manage acoustically because they are typically large, open areas with many people. Communication and focus are both essential, so the design must balance the conflicting needs of transmitting the speaker's voice and controlling noise and reverberation.

According to the survey respondents, the most significant barrier in this environment is noise, with over two-thirds reporting difficulty concentrating on the speaker due to other conversations, and an even larger proportion facing issues with other sources of noise. Respondents commented how the heightened attention of a lecture and the stress of being in a crowded public space can make sound intrusions more difficult to filter out. Speech intelligibility was another barrier, with over two-thirds of respondents reporting challenges due to the speaker being too quiet or unclear. Amplification alone does not seem sufficient to overcome this barrier, as some reported challenges even when the speaker uses a microphone.

We considered two teaching spaces, the first is a large classroom with room for approximately 100 people. The room has standard surface treatments: vinyl flooring, painted drywall, and acoustic tiles on the ceiling. Seating is rows of long desks with laminate surfaces and attached chairs with cushioned backs and seats. This room was chosen in part because lecturers commented on the distracting effect of the squeaking of these attached chairs. The lecturer used a microphone, and the speakers for the system were at the front of the room pointing towards the audience. The following table presents the sound levels measured during different points of the lecture:

Situation	**Sound level (dBA)**
ambient (video projector + HVAC)	39
murmur	45 – 60
closing of classroom door	68
chair squeaking	65 – 70

lecturing (with microphone)	50 – 65

The second space is a small classroom with seating for approximately 40 people. The surface treatments are similar to the large room: vinyl flooring, stone walls, and acoustic sound tiles on the ceiling. The desks are also laminate, but unlike the large room the chairs have metal legs and are not attached to the table. There was a microphone system, but it was not used by the lecturer. The following table presents the sound levels measured during different points of the lecture:

Situation	**Sound level (dBA)**
murmur (before prof enters)	50 – 65
shuffling + murmur (after prof enters)	45 – 50
chair scraping	85
lecturing (no mic)	50 – 60
lecturing at the board	55

The measurements show that the baseline noise level in the rooms is low enough to meet the ASA-ANSI S12.60 guidelines for primary school teaching spaces (Acoustical Society of America, 2010). This is important because high baseline noise can mask the desired speech, reducing speech intelligibility. The measurements and recordings also show that the door slams and chair noises are louder than the speaker and they occur suddenly and unpredictably, making them more distressing and disruptive. The chair noises have a lot of tonal content and much of the energy is at high frequencies, both factors that can increase sound annoyance.

The measurements also appear to show that the level of the speaker with no microphone in the small classroom is comparable to level of the microphone-assisted speaker in the large classroom, but frequency analysis of the recordings shows that this does not give the full picture. While the overall signal level remains consistent, there is a sharp drop in the high frequency speech content when the lecturer turns to face the board. This has a potential impact on intelligibility because the high frequency region contains most of the energy for English consonants, this is used to distinguish words such as “sit”, “fit” and “hit”. Furthermore, with the lecturer facing the board, the audience would not benefit from speech (lip) reading or other visual cues. As the survey results illustrated, there are limits to what microphone amplification can do in noisy environments. However, compared to an unaided voice, a well-designed amplification system can provide an audible signal across a longer distance and can also provide more consistent level as the talker moves through the room.

b) Study spaces

On-campus study spaces are areas of focus and concentration. They are communal spaces where social etiquette, and sometimes regulations, dictate that sounds should be minimized. This expectation means that, unlike most spaces, acoustics are often a primary design consideration. The library study spaces we investigated have sound absorbing features such as carpet, ceiling tiles, and wall partitions, as well as sound diffusing features such as textured wooden panels. Sound absorbing surfaces minimize sound levels, while diffusing surfaces blur the location of sounds so they blend more easily into the background. Combining these features creates a soundscape of uniform featureless background sound.

The measured noise levels ranged from 42 dBA in the most secluded space to 50 dBA in the space closest to a service desk; conversation murmur from nearby study groups brought the levels of all spaces up to approximately 55 dBA. These levels are aligned with the recommended noise levels for open office spaces dedicated to focused individual work (48 dBA) and for collaborative between small groups (52 dBA) respectively (ISO, 2021). Despite these design features and noise levels, many survey respondents reported facing challenges in campus study spaces, and their responses illustrate the diversity of experiences to sound.

The responses illustrated the range of preferences for auditory stimulation. Some respondents were hyposensitive and described an inability to focus due to the extreme quiet of libraries and dedicated study spaces. Others reported feeling sensory overload, even in quiet environments. For some the challenge was due to the level or unpredictability of a sound, for example loud noises punctuating a quiet space. For others it was the type of sound that caused it to hinder focus even if the level was low, this is especially true of information-bearing sounds. Participants described how sounds of human activity such as nearby talking, chewing, or shuffling papers interrupted focus and concentration. To manage these situations many respondents reported using noise-reducing headphones or headphones with music to create a more controlled acoustic environment for focus and concentration. Unfortunately, most respondents reported that their main strategy was to avoid common spaces, leading some to express concerns about social isolation.

c) Service counter

The food court in the University Centre (Nideyinàn) has a contactless ordering area; customers order on tablets, receipts are printed by businesses, and customers wait for their order to be called out. All food stands are open concept with visible stainless steel kitchen equipment. During the mealtime rush the soundscape consists of the human sounds of activity from ordering, cooking, eating, and socializing, also the artificial humming, buzzing, and beeping sounds of machines and cash registers. The complexity of the acoustic scene creates communication barriers as sounds overlap and compete for attention.

The acoustic investigation took place during the exam period, so the food court was not fully occupied. During a busy time (noon) there were approximately 15 people (including employees) in the area and the noise level was measured to be 70 dbA. During a quiet time (3:30 pm), there were approximately eight people (including employees) and the sound level dropped to 65 dBA. Normal conversation level in quiet, measured at a distance of 1 m, is around 55 dBA, and talkers start to raise their voices involuntarily at noise levels around 45 dBA; communicating at a distance in noise at 70 dBA requires speech levels that are rated to be rated loud (72 dBA) to very loud (78 dBA) (Lazarus, 1986).

Respondents reported on this situation from the perspective of patrons and employees. Some reported experiencing negative reactions to the high frequency and tonal sounds of the machinery, and many commented on the difficulty of hearing and being heard, as well as focusing and understanding what is being said. Several participants remarked on the increased challenges brought by the Covid precautions of plexiglass screens and masks. To overcome these barriers, most respondents rely on non-technological solutions such as asking the person to repeat themselves or mentally rehearsing a prepared “script” for the interactions. However, multiple participants shared that they often skip spoken communication and instead type messages on their phone and show the screen to the other person.

d) Other spaces

We also investigated some spaces that were not covered by the survey scenarios but were mentioned by participants in comments or open questions.

Bathroom

The bathroom we investigated is a universal bathroom with ceramic tiled floor and porcelain tiled walls. A porcelain toilet and sink are located across from an automatic hand dryer. There is an audible ceiling vent producing rattling noise located above the toilet, creating a 45 dbA ambient noise level.

The hard tile and stainless surfaces in the bathroom are chosen for sanitary reasons, but they also create a highly reverberant enclosed space that contains sound. The effect is especially noticeable when the high-powered "jet" style hand-dryer is operating. The baseline level of the hand dryer was measured to be 90 dBA and the sound is a combination of the "whooshing" of moving air, and the hum of the powerful motor. When hands are placed under the jet of air, the turbulence adds chaotic hiss that varies in time and frequency as hands are moved; the level of this sound was measured at 97 dBA, equivalent to a noisy intersection. The remarkably high sound level of these devices and their potential effect on people with sensory sensitivities has previously been reported (Drever, 2017).

Tunnels

Buildings at Carleton are linked by a network of pedestrian tunnels. The tunnels have concrete walls and floors, and ceilings with exposed HVAC systems. Recordings and measurements were taken at the intersection of two tunnels, adjacent to a concrete staircase leading up to a building. The typical soundscape consists of a relatively high ambient noise level of 60 dBA from mechanical and ventilation noise, rising to 70 dBA when groups of people pass by, and punctuated by occasional beeps from maintenance carts. The reverberant effect of the concrete surfaces is clear in the audio. Sounds take a long time to decay and sound energy builds up during periods of activity when there are groups of people or carts passing. The carts stop and sound their horn at every tunnel intersection, and different carts have horns with varying intensities and durations. Several respondents commented on negative experiences of sound in the reverberant space of the tunnels, especially the sounds of the carts which were described as loud and anxiety-inducing.

Analysis of the recordings showed that the cart sounds have the tonal and high-pitched characteristics known to provoke negative responses for people with sensory sensitivities. The sound of the cart motor and rotating wheels is dominated by harmonic tones that rise and fall in frequency as the carts accelerate and decelerate. Two different cart horns were recorded, both were both short bursts of harmonically related tones, but their frequency content differed. For one cart the energy decayed slowly in frequency, which created a high-pitched "beep" sound. For the other cart the decay in frequency was more rapid, there was no energy above the noise floor for frequencies higher than 5 kHz, which created a more low-pitched "honk" sound.

The sound of the cart horns, and the conditions of their use, illustrate the challenges of shared acoustic spaces. The horns' purpose is to notify pedestrians and other cart operators of their approach, so they are used repeatedly, and the sound is distinct and loud enough to be heard above the ambient sounds. Unfortunately, these same properties are what makes the sounds more likely to trigger feelings of anxiety and other negative responses.

Minto Centre Piano

The piano in the Engineering building (Minto Centre) was the subject of opposing comments; some student survey respondents described the difficulty focusing on conversation when the piano is playing, a participant in the co-design sessions discussed in Section 6.4 described it as beneficial to their focus:

> *"For a period of time, there was a piano in the engineering building at Carleton university. It was always noisy in that building (open concept, a lot of metal surfaces) so I rarely studied there. However there was this one time when I was waiting for someone and decided to pull a book out to read/review some concepts for a class, and someone started to play the piano. And it actually made it easier to read … in this case the music actually allowed me to read with a higher level of comprehension. It was not long lived (maybe at most they played for 6 minutes) but it was a pleasant experience." – co-design participant*

As the co-design participant noted, the interior building surfaces are primarily concrete and metal and there is an open atrium that extends two stories above the ground floor. The piano is in a concrete and glass alcove on the ground floor. The level of the playing piano was measured to be 65 – 80 dBA in the atrium directly adjacent the piano. Two stories above the piano, in a study space, the piano was still clearly audible and the level was measured to be 65 – 70 dbA.

This example highlights the concept of acoustic diversity and the need for sound control. The live piano can create a shared sensory experience that is a positive addition to an otherwise dull soundscape. However, the reflective and reverberant character of the building allows the piano sound to carry throughout the space and linger in time, turning it into a noise that is difficult to avoid and disruptive to other activities.

Conclusions

The combination of the survey responses and the soundscape investigation highlight the challenges faced in designing and using the acoustic built environment. The lecture and teaching spaces show how sound and noise levels that many consider acceptable may still pose challenges for people with sound-related disabilities, and underscore how assistive technologies can reduce those barriers. The shared spaces show the importance of acoustic diversity. When there is no single soundscape that is perfect for all, diversity enables individuals to seek out their preferred environment. Finally, the bathrooms and tunnels show the consequences of acoustic considerations being given lower priority compared to other design requirements.

4.6. Section Summary

- Sounds we hear in a room can come from activities and equipment in the room, in other rooms, and outside the building.
- Architectural acoustics involves designing spaces to control: how much sound is allowed to enter the space, how sound is reflected or absorbed to create echoes and reverberation, and how long it takes for sounds to die down.
- Many people, including architects and designers, put more importance on how a building or a room looks than how it sounds. Acoustics are a primary concern only for spaces like concert halls where sound is the main function. Often, acoustics are considered only when there are issues with noise or echoes, but these problems can be hard to fix after a building is built.

- Accessible acoustics usually means good acoustics. Spaces that have too much noise or are too reverberant can make it difficult for anyone to talk, live, and work. People with disabilities can be more sensitive to the effects of noise, so they may notice and experience impacts before they are felt by people without disabilities.
- Accessible acoustics sometimes conflicts with other design goals of a space. For example, hard tile bathrooms are easy to clean, but they also create echoes and make noise seem louder. These design conflicts can often be solved by recognizing that acoustic accessibility is a feature that should be built into the design, not something that can be added later. Spaces can also be made more accessible by embracing diversity and creating different acoustic environments that people can choose from.

5. Role of technology

Truly accessible spaces facilitate maximum participation in their passive state; the onus should not be on individuals to “fix themselves” with technology to fully access the space. However, communication and noise tolerance challenges persist even in spaces that have been designed for good acoustics:

- speech may be difficult to perceive because of a talker’s speech disability, or because of low levels caused by necessary distance between the talker and the listeners,
- noise in a space may be from uncontrolled external sources, or may arise from the activities of the space itself, such as sporting events,
- reverberation times may be long because of the size of the space or the need for sanitary surfaces.

In these cases, technology can be used to reduce barriers, increase participation, and extend functioning in the space. The technology may be something built into the space, it may be an individual’s personal assistive technology, or it may be public or personal technology that has been repurposed for use as an assistive technology.

5.1. Personal hearing devices

Hearing aids and cochlear implants are the assistive devices most associated with auditory disability. Hearing aids amplify incoming sounds to improve audibility for people with mild to moderate hearing loss. Cochlear implants bypass the peripheral auditory system and electrically stimulate the auditory nerve directly to provide some sound sensation to people with severe to profound hearing loss. The processing and aims of the devices are similar, but the amount of sound information relayed by cochlear implants is more limited. Both types of devices can provide substantial benefit in many situations and rates of user-reported satisfaction with modern devices are quite high (Picou, 2020).

Digital hearing aids do more than simply make the signal louder. Gain is applied differently across frequencies to match the hearing profile of the user, and the amount of gain is dynamically controlled so quiet sounds can receive large boosts while loud sounds are not painful. Digital noise reduction and directional microphones are used to reduce background noise and avoid the situation where “everything just gets louder”. Many devices are equipped with multiple microphones, which allows the directionality to be changed adaptively or via buttons on the device or a companion smartphone app. Typically, there is a “conversation mode” that provides a boost to sounds coming from in front and suppresses sounds coming from the sides and behind, and an “omni mode” where sounds from all directions are treated equally. (Wagener et al., 2018)

These sound level increase and spatial processing features provide communication benefits in quiet or moderately noisy situations, but complex acoustic environments are still challenging. Hearing aids increase the amount of sound energy that is perceived, but they cannot improve the quality and resolution of the time and frequency details of the sounds, or the higher-level cognitive processes required to focus in noise (Murphy et al., 2006). Likewise, people with central hearing loss, who do not have elevated hearing thresholds, may not benefit from amplification provided by hearing aids.

Barriers to hearing aid adoption include the cost of devices, the need for a prescription, and the stigma of needing and using an assistive device. Recent regulatory changes in the United States aim to increase access to hearing aids and lower device costs by allowing retailers and online merchants to sell them over-the-counter to people with mild to moderate hearing loss, without the need for a prescription. A similar change in Canada is expected, but the rollout would require coordination between federal and provincial health agencies (Crawley, 2022).

5.2. Assistive listening

> *I think transmitting to portable devices is fantastic! As many people discovered when the world became in plexiglass and masks, many people can benefit from accommodations that we typically associate as being for the Deaf/hard of hearing even if they do not identify as such. – Co-design participant*

> *I am blind and often use the audio described headsets at theatres; 90% of the time they are out of batteries, are broken etc. – Co-design participant*

Users of personal hearing devices can extend their functionality with accessories such as remote microphones, telephones, televisions, or assistive listening systems (ALS). The accessory wirelessly broadcasts a signal that is picked up by the device using a miniature electromagnetic receiver called a telecoil or, more recently, a Bluetooth receiver. Bluetooth is more familiar to smartphone users, but most Bluetooth systems only allow a transmitter to be connected to a single receiver, limiting it to personal accessories. The wireless signal replaces, or is mixed with, the microphone signal that is played to the listener, passing the transmitted audio directly to listener. This direct transmission means the signal from the accessory does not collect additional competing sounds, reverberation, and other distortions as it travels the acoustic path from the source to the listener.

Personal listening accessories such as remote microphones use Bluetooth, but ALS in public spaces broadcast signals using a small FM radio transmitter or an induction loop built-in to the room. FM signals are picked up by neck-worn receivers (neckloops) and relayed to the device via Bluetooth or telecoil, loop signals can be directly picked up by anyone in the room with a telecoil-equipped device or receiver. This seamless integration with a listener's own device, without the need to rely on borrowed equipment or even to disclose their disability, make hearing loops the preferred ALS choice (Audiology, 2019). Additional benefits of hearing loop-based ALS include:

- power consumption, telecoil mode does not increase the power consumption of hearing devices; and
- latency, telecoil mode does not add any delay to the signal, ensuring that audio for live performances is synchronized with the talker's speech.

Simplicity of an analog system means induction loops also have disadvantages, including:

- interference, transmission through electromagnetic waves is less sensitive to acoustic noise but more sensitive to electromagnetic signals such as those coming from loop systems in adjacent rooms, or from electrical wiring and lighting systems; and
- lack of stereo, hearing loops can only receive a mono signal, so the same sound is played to both ears and direction information is lost making movies, stage presentations, and multi-participant conversations more difficult to follow.

The biggest challenge with hearing loops is not their performance, but their availability. On the infrastructure side, groups such as the Canadian Hard of Hearing Association are working to increase awareness and get loops installed in more locations. On the device side, telecoils are analog and their sensitivity is a function of physical size, so they have not benefited from the miniaturization advances of other hearing aid components. Competing with other features for cost and space, the share of new hearing aids with telecoils has reduced from 30% in 1999 (Bakke et al., 1999), down to 20% in 2020 (Picou, 2020).

Digital wireless streaming is seen as the natural next step for assistive listening. In 2020 54% of hearing aid users reported their devices had wireless capabilities up from 43% in 2015 (Picou, 2020). Unfortunately, the Bluetooth Classic technology in current hearing aids can only be used to connect devices 1:1, not in broadcast, and the power consumption and delay of the audio streaming profiles are too high for use in hearing devices. In the absence of a unifying standard, mobile phone manufacturers have proposed competing proprietary streaming solutions, such as Apple's "Made for iPhone" hearing aid certification and Google's "Android LE-ASHA" mode (Audiology, 2019). This fragmentation is expected to be resolved by the new Bluetooth LE Audio Standard which was released in 2022 and includes "Auracast", a digital broadcast mode designed specifically for assistive listening applications (Bluetooth, 2022).

A digital wireless streaming solution using standardized commodity hardware has the potential to bring significant benefits:

- digital audio can support multiple audio streams for stereo or multiple languages
- digital signals are more robust to electromagnetic interference
- wireless transmitters use standard mass-consumer technology and can be integrated into existing spaces without infrastructure modifications
- wireless receivers are available in a wider range of devices than telecoils, including hearing devices, smartphones, headphones, and smart earbuds. This extends the benefits of assistive listening to people who do not use hearing aids, and to those who are not hard-of-hearing but have auditory processing or other sound-related disabilities.

The current state of assistive listening is summarized in a policy statement on digital audio streaming and hearing loop obsolescence released by the International Hearing Access Committee, a group consisting of hearing device manufacturers and disability advocacy organizations. The group expressed excitement for the potential benefits of streaming but also concern that overly optimistic timeframes for adoption will lead to a slow down or reversal in hearing loop adoption before there is a workable replacement. They estimate that there will be a transition period of 10-15 years (ending in 2029 – 2034) where hearing loops will coexist with streaming solutions (IHAC, 2019).

While an ALS can greatly reduce communication barriers, a listening system is not a replacement for good acoustics. In challenging environments the listening system microphone can capture and transmit the noise and reverberation, reducing the benefit of the ALS (Heylighen et al., 2008). Also, when the ALS replaces the microphone signal with the wireless signal, devices users can become acoustically isolated from their immediate surroundings.

> *I recalled the isolation I felt sitting in my psychometrics class while hooked up to an FM system. I could hear only the professor and his answers to student questions. I was not available to hear her response so I could not ask the student next to me to clarify the language of the questioner or their intent … All sanctioned discussion (ie distinct from background ambient mumbling) was lost to me at the expense of hearing the prof clearly. Ultimately I chose not to continue to use an FM system for this reason. My innate sense of personal accommodation that would best serve me in that situation was undone by the equipment to "fix the problem." – Co-design participant*

5.3. Captioning

Captions are text versions of speech and non-speech audio such as applause or sound effects that are displayed on-screen with the media or on separate caption viewers. Captioning has been growing in popularity owing to a combination of availability, increased awareness, and shifts in societal attitudes. Recent surveys have shown that captioning is being embraced by people across a range of listening abilities, with the youngest demographic showing the highest rates of usage (BBC News, 2021).

Captions for pre-recorded movies and television episodes are generated ahead of time (offline) and are accurate and well-synchronized with the images. Captions for live events must be generated in real-time, so there is always a lag between the audio and the caption. Traditionally live captioning required a professional operator using a stenotype machine to perform Communication Access Realtime Translation (CART). Recent rapid advances in neural network research has produced powerful automated speech recognition (ASR) models that can achieve human-level transcription performance across multiple languages (Radford et al., 2022). Smaller models that can run in real-time have enabled automated transcription to spread across streaming video platforms, social media applications, and home and office video conference applications such as Zoom and Microsoft Teams. Co-design participants in our research discussed the use of smartphone-based live transcription apps to reduce communication barriers, researchers have documented other novel uses including speaking through COVID prevention plexiglass screens (Loizides et al., 2020).

Captioning is not an auditory assistive technology; it does not improve the ability of anyone to hear the full acoustic signal with the richness and complexity of music or the nuance and emotion of spoken language. It has however been shown to improve comprehension of spoken information for people with a broad range of auditory and cognitive processing disabilities, and even for people without identified disabilities (Gernsbacher, 2015). Decoupling the message from the audio allows it to be presented in visual forms and in multiple languages and allows individuals to process the information at different speeds and even review the content. When open captions are used, this benefit is widely accessible and does not require individuals to have a specific diagnosis or specialized hardware to access.

5.4. Sound control

While assistive technology for people with disabilities that relate to sound typically focuses on reducing communication barriers, an emerging application is technology to reduce the emotional and physiological impacts of unwanted noise and chaotic sound environments. Assistive technology in this case refers not to a specific device designed to meet an accessibility need but to a broad range of repurposed devices that allow people to control their experience of sound and create a “personal soundscape”; this can include purely passive devices like the earplugs and hearing protectors, as well as standard and noise cancelling headphones. Despite a lack of medical guidance, these devices have become common accommodations in schools and open offices where shared spaces with uncontrolled sound create barriers to focus and concentration.

In school environments, hearing protectors or earmuffs can be used to reduce sensory input and are a common recommendation for students with sensory sensitivities, especially those associated with ASD. Headphones with no sound playing, sometimes combined with earplugs, are a less conspicuous form of passive sound reduction, while headphones playing noise or pleasing music can provide an additional level of sound masking to block out unwanted noise. Experiments have shown headphones with white noise can similarly increase focus for persons with ADHD (Cook et al., 2014; Söderlund et al., 2007), and research has found that hearing protectors or headphones can increase participation for children with ASD in school, and also in the community and at home (Pfeiffer et al., 2019).

In open office environments noise cancelling headphones with or without noise or music can provide even more sound isolation and are popular method to reduce distraction from nearby talkers. A study on their use found that while noise cancelling headphones did not improve performance on cognitive tasks, there was a significant decrease in user-reported annoyance with background noise, and an increase in perceived ability to concentrate; the study did not report on the disability status of the participants (Mueller et al., 2022).

For situations where complete isolation is not wanted, many noise cancelling headphones now have a transparency mode that mixes in some level of the outside world. This sort of adaptive transparency and personal soundscape control were the main objectives of early generations of “hearables”, though this dedicated device segment has largely been absorbed into the larger headphone and earbud space. The evolution of devices to improve their secondary purposes illustrates how this assistive technology category is being driven largely by user recommendations and online communities rather than medical research (Boxall, 2021). The dearth of research into these devices creates challenges for stakeholders such as organizations, caregivers and individuals with disabilities who may benefit, but lack specific guidelines on their use (Neave et al., 2021).

5.5. Research – Residual noise characteristics of noise cancelling headphones

Active noise cancelling (ANC) headphones can reduce the amount of noise heard by the wearer. While the ear cups or plugs of standard headphones provide some passive sound isolation, the performance is poor for low-frequency noise such as that from transportation and industrial sources. ANC works by creating an anti-noise signal that destructively interferes with the waves of the unwanted sound. This process works best at frequencies below 1 kHz, making it a useful complement to the passive isolation of the headphone (Liebich et al., 2018). Early ANC headphones aimed to reduce the negative cognitive and communication impacts of continuous occupational noise exposure in fields such as aviation (Molesworth et al., 2013). Recent advances in consumer headphone technology and the introduction of ANC-specific integrated circuits have enabled the introduction of ANC features to into smaller and lower-cost devices, resulting in the use of ANC in more diverse noise environments (Ang et al., 2017).

One area where ANC headphones are seeing increased use is among workers in open office environments. Noise levels have long been a primary source of workplace dissatisfaction (Navai & Veitch, 2003), and pandemic-era shifts to hybrid and remote working styles have made audio and video conferences standard, leading to increased levels of distracting speech (Cutter & Bobrowsky, 2023). The lack of surfaces for sound absorption makes controlling noise in open offices very difficult, and significant design effort is needed to get speech privacy to an acceptable level (Bradley, 2003). Functioning in these environments is more challenging for people with disabilities. Noisy office environments have been found to increase stress and cognitive fatigue among people who are hard of hearing (Jahncke & Halin, 2012), and can impair focus and performance of people with cognitive or attention-related disabilities (Larsby et al., 2005) (Freyaldenhoven et al., 2005).

ANC headphones are also used in schools to reduce distraction for students with attention deficit hyperactivity disorder (ADHD), and to increase engagement and decrease distress for students with auditory sensitivities, especially students with autism spectrum disorder (ASD) (Kulawiak, 2021).

While ANC headphones are a common tool used by individuals with and without disabilities, there is limited research into their benefits or potential drawbacks. One small study with office workers reported a slight negative impact on workplace satisfaction when using in-ear ANC headphones, though this may have been due to the discomfort and fit issues with the selected headphones (Kari et al., 2017). Another study that used over-ear (circumaural) headphones found no cognitive benefit, but wearers reported improvements in their subjective impressions of noise and privacy (Mueller et al., 2022). A small study found that hearing protectors or headphones can increase participation for children with ASD not only in schools, but also in the community and at home (Pfeiffer et al., 2019). The dearth of research relative to the widespread use of the devices has led to concern among some users and stakeholders about the lack for guidance regarding when and how they should be used (Neave et al., 2021).

In typical usage, ANC is used to reduce the masking effects of noise so music or audio can be heard at a lower volume. The main goal is to maximize the amount of noise reduction; the quality of the remaining noise is of less concern because it is masked by the desired sound. When ANC headphones are used as an accommodation to reduce noise-induced distraction and anxiety, there is often no music or audio, so the quality of the residual signal becomes important. Users are typically not seeking total sound isolation, but more control over their sound environment. If the noise character is unnatural, or if the level fluctuates with time, the signal may become more distracting even as the level is reduced. Also, in many situations, such as workplaces, schools, or in public spaces, it may be important to maintain some situational awareness. In this case the clarity of the signal is important for comprehension, and the consistency of the inter-ear time and level differences (binaural cues) is necessary for the listener to be able to locate the sound source (Bregman, 1994).

For situations where complete isolation is not wanted, many noise cancelling headphones have a "hear-through" or "transparency" mode that mixes in some level of the outside world. Evaluations of the technical (Denk et al., 2020) and perceptual (Schepker et al., 2020) characteristics of these features in wireless in-ear hearables revealed mixed performance. Ratings of the perceptual quality for consumer-grade devices ranged from bad to medium as the character of the mixed-in sound did not match the sound from the open ear. The technical evaluation showed the binaural cues were distorted for some devices, though the impacts on quality or localization were not assessed.

We ran experiments to investigate the characteristics of the uncancelled remaining sound in two sets of over-ear wireless ANC headphones: a low-cost set, Anker Soundcore Life Q30; and a premium set, Bose QuietComfort 35 II. We chose over ear headphones because they offer high levels of passive attenuation and are comfortable enough for extended wear, making them well-suited for noise control accommodation.

The headphones were characterized by playing test signals of speech, pink noise, and logarithmic swept tones though a high-quality loudspeaker, and recording the signals inside the headphone with the synthetic ears of a binaural headphone test fixture (miniDSP EARS). Recordings were made with the headphones turned off to capture their passive performance, and in their different processing modes – the Anker headphones had noise cancelling and transparency modes, while the Bose headphones had high and low cancellation modes. Recordings from the test fixture without any headphones were used as an open-ear reference. The binaural performance was investigated by rotating the test fixture relative to the loudspeaker to create sound source locations to the left, front, and right of the listener.

We found the character of the audio to be subjectively good in all noise reduction modes for both sets of headphones: there were no audible processing artifacts, the level and frequency content of the signal did not vary over time, and the swept sine signal showed no signs of non-linear distortion. The transparency mode on Anker device also lacked artifacts and distortion, but frequency analysis of the signals showed that the level of the signal below 500 Hz was up to 10 dB higher than the open ear, creating an unnatural-sounding low frequency boost. This is consistent with a previous evaluation of the perceptual quality of transparency features that found implementations exhibited similar distortions of the frequency response relative to the open ear (Schepker et al., 2020).

We used frequency analysis to compare the level of sound reduction the headphones provided with the ANC feature on and off. With ANC turned off, at frequencies above 1 kHz the headphones provided passive attenuation of approximately 20 – 30 dB compared to the open ear measurements. The signal level increased as frequency decreased below 1 kHz, and below approximately 200 Hz there was no difference in level compared to the open ear measurement. This uneven attenuation created a low frequency emphasis that could be heard in the output. Enabling ANC added 25 – 30 dB of attenuation at

100 Hz but the benefit rolled off at frequencies higher than 500 Hz, and there was no gain over the passive attenuation for frequencies above 1 kHz. In other words, ANC worked best at low frequencies where passive attenuation was poor, and ANC worked poorly at high frequencies where passive attenuation was best. This complementary behavior meant that when ANC was enabled the devices provided relatively uniform attenuation of 20 – 30 dB across the entire frequency range and a more natural sound than the passive isolation alone. Neither device was affected by the type of noise, both showed consistent cancellation performance for the stationary broadband pink noise and the time-varying speech signal. Comparing the devices, the Bose provided slightly higher levels of cancellation, and the cancellation extended across a wider range of frequencies on the low and high ends.

Since the ANC is only effective below 1 kHz we analyzed the binaural separately in the bands below and above 1 kHz, to isolate the effects of the processing. At high frequencies, where passive attenuation dominates, the binaural cues for both devices largely matched the open ear across all processing modes. There was an offset in level difference for the Anker device that was consistent across operating modes, even when the headphones were turned off. This consistency means it was likely caused by variations in fit or placement on the ear. At low frequencies, the Bose device showed some distortion of the binaural information in the “high cancellation” processing mode that indicated some directional dependency on the amount of cancellation. This effect was not observed in “low cancellation” mode, which had level differences that matched the passive mode. It is not clear if the mismatch of low and high frequency binaural cues observed for the “high cancellation” mode would have a perceptual impact.

Conclusions

In summary, our experiments showed that both the low cost and premium devices are effective at reducing sound while preserving its time, frequency, and spatial characteristics. In noise cancelling mode both devices supply over 20 dB of attenuation across the entire frequency range. This offers protection from disruptive and intrusive noise but raises the concern of users being isolated from their immediate surroundings. The configurable cancellation offered by the Bose device provides some control over the attenuation of low frequencies but cannot restore the high frequency content lost to passive attenuation. The transparency mode on the Anker device is intended to provide situational awareness, but its boosting of low frequency noise negates the purpose of wearing the headphones for noise control. More research is needed to develop processing strategies that can balance sound level and situational awareness, to provide individuals with more control over their personal sound environment.

5.6. Section summary

- Technology should not be needed to participate in activities in a space, but it can help increase participation by making it easier to hear the sounds we want and to reduce the noise we do not want.
- Assistive technology for hearing usually refers to personal hearing devices like hearing aids and cochlear implants, but it can also refer to assistive listening systems built into spaces. Assistive listening systems send the sound wirelessly to the listener, making it easier to hear from far away or in noisy environments. They can work with personal hearing devices, or with a separate receiver and headphones.
- Audio information can be made available in alternative formats like captions, or visual alerts and alarms. These alternative formats do not replace good acoustics or audio assistive technology,

but they can be used together to make it easier for people with a range of hearing abilities to access information without any additional devices.

- Many people use hearing protectors and noise cancelling headphones to help them control their sound environment, especially at school and at work. More work is needed to understand how these devices can be designed to allow people wearing them to block out noise, but still communicate with and be aware of others around them.
- People with disabilities are using personal technology like cellphones and smart headphones as informal assistive technology devices for captioning and sound control. Using devices they own and are familiar with can give them a feeling of comfort and control.

6. Standards landscape

6.1. Objective measures

Regulatory standards need objective performance measures that can be used as targets in the design process and in compliance verification. Ideal acoustic metrics would quantify the quality of sound, the acoustic comfort in a space, and the ease of communicating in that space. Unfortunately, the experience of sound is subjective, and there is no accepted view of acoustic comfort (Roy, 2019). The subjective and perceptual nature of hearing also means that even commonly described characteristics such as clarity, reverberance and sense of space do not have agreed-upon objective measures, and some measures such as early decay time are defined but do not have accepted computational definitions (Bradley, 2011).

Part of the challenge of using static numbers to capture acoustic characteristics is that sound is a dynamic property of the space that is affected by factors including its size and shape, surface materials, and furnishings, as well as the people in the space and their activities. If the activities are known, specialized measures can be developed, such as the concept of “acoustical capacity” to estimate the number of people that can comfortably be supported in a restaurant (Rindel, 2012).

Considering these challenges, the metrics that are most used are those that are well understood and easy to measure, so acoustic specifications are typically based on single-number measures for noise level, reverberation time, and sound insulation.

a) Noise level (dBA)

Noise level is most often expressed as the A-weighted sound pressure level. The A-weighting attenuates low frequency sounds and emphasizes the speech band to approximate the frequency sensitivity of the human ear at normal speech volumes. The level is most often expressed in decibels, with the symbol dBA or dB(A) (Acoustical Society of America, 2010). Alternative weighting curves exist, such as the flatter C-weighting. In situations where low-frequency noise is a concern, a specification may include both C-weighting and A-weighting.

Despite its widespread usage, the A-weighting has been criticized for using a level-independent weighting and for underestimating the role of low-frequency noise (Nilsson, 2007). The low-frequency mismatch is of particular concern as many common sources of noise, including road noise and HVAC noise, are low-frequency dominant. The UK school performance guidelines specify noise levels in dBA, though the associated design guide acknowledges the shortcomings and notes “[f]or many people with special hearing requirements, low frequency noise can have a substantial impact on speech recognition, masking important speech sounds in a manner that cannot be appreciated by those with normal hearing” (Canning et al., 2015).

A limitation of any noise level measurement is that the average level is not enough to characterize the disturbance caused by the noise. The amount of distress or distraction a noise can provoke depends on the individual, and is influenced by factors including the tonal content – the frequencies present and whether they are pure tones or more broadband and noise-like – as well as the temporal properties, whether the sound is continuous, impulsive, or intermittent. The Norwegian standard NS 8175:2019 accounts for this perceptual impact by adding 5 dB to the noise level measurement before comparing it to the limit if the noise contains audible pure tones or has impulse sound characteristics.

b) Reverberation time (T60)

Reverberation time is the time it takes for a sound in a closed space to decay until it is inaudible, defined to be 60 dB below its initial level. The time is referred to as T_{60}, $R_{t,60}$ or simply R_t. Since reverberation is frequency dependent (e.g. higher frequencies are absorbed more easily) T_{60} may be computed for the entire frequency range, a single band of frequencies, or the average across a set of frequency bands. Reverberation is also dependent on the locations of the sound sources and the listeners, so the reported value is often an average of multiple measurements from different locations in a room. This spatial averaging is seen as a weakness of reverberation time as a metric since it can mask variation within a room. Other criticisms of reverberation time are that it does not account for the direction of the reflections or how different frequencies are treated within the space (Ovans, 1996).

For rooms with simple geometries and uniform finishes, reverberation time is closely related to the average properties of the room, especially the sound absorption of the surface treatments. Since long reverberation times are known to be harmful to communication it is often assumed that shorter reverberation times are always better, however this is not the case. In the human auditory system early reflections are merged with the direct path sound to create a louder signal, so they should be preserved to maximize intelligibility (Bradley, 2009). Reverberation time should also reflect the proportions of the space to facilitate orientation and wayfinding for people with vision loss, since overly absorbent surfaces can make it difficult to estimate distances to walls and doorways (Ryhl, 2013).

Reverberation time and noise level from activities in the space are both related to the sound absorption of exposed surfaces, since higher absorption reduces reverberation time and prevents noise build up. Taking this into account, a review of European standards found some countries moving away from specifications for reverberation time, instead providing targets for average absorption (Bergmark & Janssen, 2008).

c) Sound insulation

Sound insulation is the ability of a construction assembly to insulate against sound transmission. Sound insulation is essential for privacy and acoustic comfort, preventing activity sounds from one space from becoming noise in another space. Since airborne and structure-borne (impact) noises are transmitted in different ways, they are typically measured separately and have different performance targets. For both noise types, insulation is described as the difference in sound level of a source in the transmission room (sound source for airborne noise, tapping machine for impact noise) compared to the receiving room. A single-number value is computed by weighting and summing the contributions of different frequency regions. Different ways of measuring, weighting, and evaluating the performance have led to multiple insulation measures and variations being used by different standards. For example, ISO 22955:2021 uses the weighted standardized level difference, while NS 8175:2019 uses the closely related weighted apparent sound reduction index and also includes a spectrum adaptation term that is not used in ISO 22955:2021. Research found this term was necessary to properly account for the annoyance of impact noise, and the low-frequency content of airborne road and rail traffic noise (Turunen-Rindel, 2018).

d) Building material ratings

The noise level, reverberation time, and insulation specifications characterize a space after it is constructed. Designing spaces to meet these specifications can be challenging and acoustic specialists are often required for large or customized spaces. For more standard spaces the performance is often predicted using a “sum of the parts” approach based on material and assembly properties like the sound absorption coefficient, sound reduction index, and sound transmission class (Harvey, 2021). Extensive discussion of these and other material performance measures is found in (Mahn, 2021).

6.2. Existing standards

In North America, guidance on acoustic accessibility can be found in accessibility standards such as:

- ISO 21542 Building Construction – Accessibility and usability of the built environment,
- 2010 ADA Standards for Accessible Design,
- ICC/ANSI A117.1-2017: Standard for Accessible and Usable Buildings and Facilities, and
- ICC G2-2010 Guideline for Acoustics,

as well as building standards such as:

- ISO 22955 Acoustics – Acoustic quality of open office spaces, and
- ANSI/ASA S12.60-2010 Part 1: American National Standard Acoustical Performance Criteria Design Requirements, and Guidelines for Schools.

These standards, especially ISO 21542 and the 2010 ADA Standards for Accessible Design, form the basis of most of the sound and acoustics clauses in the accessible design guides reviewed from municipalities including Ottawa, Calgary, Winnipeg, and Mississauga.

The acoustic clauses in the accessibility standards emphasize the importance of echo and noise control and provide *general* guidance for acoustic design features as well as specific requirements for assistive listening systems, while the acoustic sections in the building standards provide *specific* performance targets for noise and reverberation in certain spaces. This division between accessibility and building standards creates a risk of accessible acoustics falling into a gap in coverage: building acoustics are too variable for accessibility standards to provide universal guidance, while building standards may view accessibility as external to the core design. For example, the noise level recommendations in ISO 22955 are derived from studies of speech intelligibility for people without auditory disabilities and accessibility and special needs are covered in a separate section that focuses largely on accommodations such as assistive technologies and accessible emergency alerts. In contrast, ANSI S12.60 was introduced specifically to reduce learning barriers for students who are deaf and hard of hearing.

Norway provides an example of a more integrated approach to accessible acoustic building regulations. Prior to the drafting of the 2012 Norwegian acoustic criteria for universal design, Standards Norway conducted a socio-acoustic survey of people with hearing or vision disabilities to measure their degree of annoyance in different spaces. Questions focused on ease of communication as well as noise disturbance impacting performance in work and learning, and the responses were used to determine which types of buildings should be regulated and what the limits should be. The resulting acoustic classification standard NS 8175:2019 (Standards Norway, 2019) rates buildings on a scale from A to D, where A is the highest performing, C is typically the minimum level for new builds and renovations, and D is used to describe existing buildings (Turunen-Rindel & Brynn, 2014). Rather than providing different standards for different building types, the standard covers a wide range of spaces in a unified and consistent way based on their function; for example, workplace cafeterias have the same acoustic considerations as restaurants.

The goal of the multi-tiered classification system was to provide choice related to the implementation of universal design principles as they relate to acoustics; the results in practice are mixed. Practitioners report that buildings are almost always designed to meet the lowest legal requirements (Bradette, 2019); spaces with acoustic classifications are designed to the class C rating, and spaces without explicit requirements (e.g., washrooms) are assumed to be free from acoustic concerns. Acoustic designers seeking to exceed the minimum face opposition from clients wishing to reduce costs. This aligns with research that found universal design is frequently viewed as a legislative concept rather than a design concept and, as a result, accessibility legislation and design requirements are often regarded as boxes to be checked, rather than as guidelines for designing for diversity (Ryhl, 2016b).

Treating accessibility as a legislative concept can still produce usable spaces if the standards are aligned with needs, but better solutions are achieved when designers recognize the motivation underlying the regulation and optimize for experience rather than compliance. This is illustrated by a case study describing the design of the Munch museum in Oslo (Olshausen, 2019). Proper viewing of large paintings requires large open spaces which leads to long reverberation times and noise accumulation, but the paintings themselves limit the amount of wall available for sound absorbing treatments. Acoustic modelling showed that designers could not achieve the reverberation requirements, so they used creative strategies to minimize the harm of the imperfect acoustics, including:

- mobile walls with sound absorbing edges for temporary exhibits,
- traffic flow guided through sound absorbing sluices, and
- personal and mobile phone based audio guides.

To further guard against excess noise, designers computed the acoustical capacity (Rindel, 2012) of the halls, which can be used to limit the number of visitors in a space. Since opening in 2019, the acoustics of the main halls have been recognized as a defining feature.

6.3. Research – Room acoustic characterization with smartphone-based automated speech recognition

Acoustic design affects the usability and accessibility of the built environment, especially spaces such as conference or meeting rooms that are primarily used for spoken communication. Noise masks the speech signal that a listener is trying to understand and can also act as a distractor, making it more difficult to focus on the speech. Early reflections can reinforce the signal and improve audibility, but long reverberation times blur the signal making it more difficult to decode individual words. Accessible spaces facilitate full participation in activities by individuals regardless of their level of ability or disability. Characterizing and monitoring the acoustic quality of a room is important to ensure spaces are accessible.

The pandemic-era shift to remote work models has made virtual and hybrid meetings standard. Since most conferencing software lacks stereo capabilities, the sounds from all participants are mixed, layered, and filtered by the room to form the single transmitted signal. This magnifies the impact of poor acoustics as remote participants cannot benefit from the visual and spatial cues that are typically used to identify, separate, and focus on individual talkers (Kidd et al., 2005; Kitterick et al., 2010).

The growth of hybrid meetings has also brought increased attention to the accessibility of video conferencing platforms. Supported by very recent rapid advances in neural network-based automated speech recognition (ASR), real-time transcription and captioning is now a common accessibility feature used by both in-person and remote participants. These state-of-the-art ASR models leveraging network structures popularized in language models have approached human-level transcription error rates (Radford et al., 2022) while smaller models running in real-time on mobile devices have been used as portable ad-hoc assistive listening devices (Loizides et al., 2020).

We conducted experiments to determine if these smartphone-based ASR systems could be used as a proxy for speech intelligibility to assess room acoustics. Reverberation time and noise level are common performance measures, but these are static measures and can be difficult for non-specialists to measure and interpret. The effect of reverberation depends on the location of the speaker and listener relative to each other and within the room, the reported measurement is often a spatial average from multiple locations. Similarly, the noise level targets are temporal averages over a minimum of 4 hours, which can hide the impact of fluctuating or impulsive noise.

Counting the number of errors made by an ASR system is an appealing proxy for intelligibility. It is easy to interpret as it directly measures understandability of speech, and its computation only requires the speech transcript rather than the original undistorted speech signal. ASR systems have been used to estimate speech intelligibility (Karbasi & Kolossa, 2022) and classical ASR systems were found to be accurate predictors of speech intelligibility for both normal-hearing and hearing-impaired listeners, though the correspondence broke down in low SNR conditions (Fontan et al., 2017). The ubiquity of smartphones combined with the large suite of acoustic sensors supported by powerful mobile computing resources makes them a useful platform for ad-hoc portable sensing.

For our experiments we measured the error rate of Google's LiveTranscribe running on a smartphone in realistic meeting situations in a newly constructed (2020) conference room on Carleton University campus. Real human speech was played from a loudspeaker at the head of the table to represent the talker, and the sound was recorded with an omnidirectional microphone to represent a remote participant, and a beamforming microphone array to represent a local participant with binaural hearing.

- To test the best-case performance, audio was recorded at each of the seating locations along one side of the conference room table, covering speaker-microphone distances from 50 cm to 5 m in 50 cm steps. In this environment the signal is only degraded by attenuation, ventilation noise, and natural room reverberation.
- To model listening in noise, the listener microphone was kept at the location 200 cm from the speaker, and a diffuse noise field was approximated by playing noise through stereo speakers. The baseline ambient noise in the rooms was 35 – 40 dBA and the added noise was varied from

40 – 65 dBA in 5 dB steps, covering the range of target noise levels for office spaces in ISO 22955:2021 (ISO, 2021).

- To model a competing conversation, two speakers were placed facing one another at the opposite end of the table and played a sequence of alternating time-reversed speech segments. The time-reversal created a nonsense signal that behaved like speech but would not be interpretable by the ASR.

Conclusions

We found that in a quiet room with a nearby microphone the ASR systems achieve near-perfect recognition rates, and performance degrades gradually as noise level or microphone distance are increased. When the listener is very distant from the talker, or when the noise is too loud, the main signal is overwhelmed, and the ASR performance quickly decreases. These challenges, which are also faced by human listeners, illustrate that the error rate of ASR systems can act as a proxy for acoustic quality. The array processing improves robustness allowing it to achieve better performance under noisier conditions, similar to the spatial benefits of human listeners. This work shows that a smartphone ASR app such as Live Transcribe can provide a convenient and readily available real-time assessment of the effects of noise and reverberation on remote listeners, even when those distortions may not be apparent to local listeners.

The results of this work are described in more detail in the paper “Room Acoustic Characterization with Smartphone-based Automated Speech Recognition” which was accepted through peer review for presentation at the 2023 IEEE Sensors Application Symposium.

6.4. Research – Gaps and limitations of acoustic standards

To further understand and grasp the impact acoustics have on persons with disabilities, we worked alongside the Inclusive Design Research Centre (IDRC) and with experts with lived experience of disability, often referred to as experts. This was done with a survey and two co-design sessions with the experts. The online priming survey asked the experts to consider scenarios in the built environment and through a co-creation approach, experts were asked to share through stories, their lives and the impact of acoustics in their environments.

The IRDC recruited 25 experts within the community, who were asked to complete a short survey and join two 2-hour co-design sessions. The survey was used a priming tool from the researchers to provide study context for the experts. The survey collected information about experts' experiences with sound and barriers to sound in public spaces. The survey was utilized to capture input on how existing standards are impacting those living with disabilities, while also identifying areas where the standards are not supportive to their needs.

The co-design sessions took a co-creation approach where the seat of expertise resides with the individuals with lived experience of disability. The first of the two co-design sessions was used to introduce the experts to one another and discuss a theme for the story they wish to create, as a group, in their second session. The second session was used to draft, create, and finalize the story they group wished to share. The 25 members were divided into 4 groups of 4 to 6 participants, each with a member of the IRDC to lead and facilitate the sessions. The goal of these sessions was to listen and learn from the experts’ reflection on their lived experience and acoustics in the built environment.

The story creation method allowed the experts to use their own life experiences to illustrate the real-world impact of acoustics on their day-to-day functioning.

> *"As someone who can't see, I rely on the way that sound. Bounces off of different items in my environment to determine where I am. For example, I can hear when there is an open door in a hallway. And can find the 4th door on the Right by walking along and counting openings. In a gym environment, it is super wide open. There's no way to tell where you are except by feeling." – Co-Design Participant*

Story Summaries

Story 1: Out of the head and into the body
This story was done as a podcast, illustrating the gym experience for those living with a disability. The story tellers express how the gym can be a place of discomfort as the noises are loud and does not bring them feelings of restoration but more requires energy to simply be there. Another storyteller shared that the noises around a gym where to sudden and loud for their support animal, that it was a place they could not attend.

Story 2: Aurel is no stranger to barriers
This story takes a narrative approach on how a day in the life of a person living with a disability unfolds. This story highlights the use of assistive technologies and the importance, as well as nuance, of having these technologies in their day to day. There is emphasis on the new work environment as workers are brough back to the office, and how the noise levels are a concern for this individual, especially in a space that does not seem to highlight acoustic inclusion.

Story 3: The Senses: Acoustic Co-Design and Beyond
This story follows a hard of hearing individual who is providing training to people and organizations who wish to better understand the needs of people who are hearing impaired. This training takes place at a convention centre, a place that was not acoustically designed to dampen noise, resulting in an echo-y environment, which, for this individual, makes socialization with colleagues near impossible. His story emphasizes how the space alienates the individual living with a disability, making them feel unable to contribute to conversation and overall, useless.

Story 4: A community space built for the community
This story is about an individual, Trevor, who recently lost their hearing and is navigating the challenges around being hearing impaired while attending social events with their friends. This group of friends go to a movie theater. Trevor feels confident in this experience as they will have friends to help navigate through the theater as they cannot hear for themselves, however the friends arrived early and went inside alone. This left Trevor feeling very anxious and stress about the interactions with the gate agent as they struggle to hear, which will impact the ability to communicate. The gate agent improvises a text screen, which leaves Trevor feeling very comfortable and confident in this movie experience.

> *"When a genuine effort is made, even if the experience wasn't great, the intentions for inclusion can still make it better." – Co-Design Participant*

Discussion

The story telling method highlighted the importance of acoustics for those living with various types of disabilities. Those with hearing impairments are not the only ones who are impacted by the acoustics in their environment. Many of the participants highlighted the negative impacts around making sounds louder for all to hear. Common themes and emotion experienced in the stories are feelings of anxiety, depression around the individuals and their disabilities. Stories also referenced feelings of incompetence as these individuals could not contribute in their social settings, leading them towards feelings of depression.

The co-design participants in the study appeared engaged with the topic and excited to share their views and experiences. After the second co-design session, a few of the groups even requested more time to develop and finish their story, wanting to ensure it was correctly representing their experiences. This additional time was time they would not be compensated for but highlights their passion around sharing this information.

This approach allowed individuals with disabilities, both including and outside of hearing impairments, to share their experiences and highlight the importance of an acoustically inclusive environment.

Summary and Analysis

Through deeper analysis of the stories, suggestions can be made based on specific categories commonly mentioned from the experts.

- Individual control of sounds
    - Ability to individually control, cancel and avoid noise in environments
- Systems and design to support accessibility
    - Fixture for captions
    - Hearing loops
    - Wayfinding alarms and support
        - Image representation of the auditory alarm
- Structural
    - Open spaces: open spaces may need to consider physical of technological means to support sound-navigation.
    - Accessible quiet spaces to balance noise
        - Closed offices or cubicles
    - Noise Reduction measures
        - Reducing hard surfaces to improve acoustics
        - Acoustically optimized walls, ceilings and flooring to control room reverberation, sound transfer and background noise

Ethics clearance for the project was obtained from Carleton University and all experts provided their informed consent. Experts were also asked to sign a contributor license agreement that indicates that the work of the group will be licenced under Creative Commons (CC By 4.0) licensing. Further analysis and recommendations can be found in the full report provided by the IDRC, titled "Acoustic Project: Co-creating experience stories".

6.5. Section summary

- Standards for acoustic accessibility aim to create a built environment that is usable and comfortable for people with disabilities. Usability and comfort cannot be measured directly, so standards use measures like noise level, reverberation time, and insulating ratings to predict how people will function in a space. These measures are useful, but do not fully describe a space.
- Acoustic accessibility is discussed in the acoustic section of accessible building standards, and in the accessibility section of acoustic building standards. These different types of standards have different views of accessibility. The Norwegian standard for acoustic classification of buildings is an example of a building standard that was written with accessibility as a main concern.
- Good acoustic standards do not guarantee good acoustics in buildings. The success of accessibility standards depends on the people implementing them understanding and appreciating the reasons for the recommendations. Accessibility works best when it is treated as a core design feature, rather than something that must be added-on.

7. Recommendations and considerations

In this section we provide strategies to reduce barriers and create a more accessible acoustic built environment. The barriers were identified from reviews of literature and directly from people with lived experience of disability who participated in our co-design, survey, and interview sessions. Many of the barriers stem from a lack of understanding of the impact of sound and noise on the functioning of people with a range of disabilities. The invisibility of sound makes acoustics easy to overlook; even people with hearing loss may not be aware of it and may not be able to identify what it is about a space that makes it difficult for them to function. Acoustic accessibility is often treated as an add-on feature focused on the most visible forms of disability, such as peripheral hearing loss, and the most visible barriers, such as communication challenges.

The following guidelines provide best practices and recommendations for focus areas that should receive special consideration in the design and creation of a built environment where acoustics and accessibility are not just features, they are core properties of the space.

a) Design for diversity

Accessible design is human-centred design. Spaces can be made more accessible by acknowledging and designing for the diversity of people and the different ways they access those spaces:

1. **Diversity in functioning** – Many health conditions can impact an individual's response to sound. Accessibility plans for built spaces cannot assume a disability will be visible or that it will follow an expected profile.

2. **Diversity in use of technology** – Use of assistive technology is influenced by personal factors including diagnosis, access to devices, and familiarity and comfort with technology. The use of a space should not assume or require the use of a specific assistive technology.
3. **Diversity in sensory sensitivity** – There is a wide variety of preferences and levels of tolerance for sound stimulation, this range is wider among people with sensory related disabilities. The ability to select a preferred level of stimulation, or to use technology to control the sound environment can support personal agency.
4. **Diversity of spaces** – Quiet areas are an important accessibility feature in spaces with loud and complex acoustic environments. They provide a refuge where people with sensory sensitivities can recover, they can be used for quiet conversations away from noise and competing sounds, and they enable the use of assistive technology such as screen readers and text to speech software.

b) Identify and support the roles of sound

Sounds play multiple roles in the built environment; these roles come with different challenges and considerations:

1. **Sound for communication** – Spoken communication requires a speech signal to reach the listener with sufficient volume and clarity, and minimal competing noise and reverberation. Account for speech and hearing disabilities in both speakers and listeners, while also considering the nature of the communication – personal conversation, presentations to an audience, or a meeting with local and remote participants.
2. **Sound as a source of information** – Sound is often used to broadcast information through announcements, alarms, and notifications. These broadcasts should be clear and audible. In complex environments sound amplification is not sufficient to ensure the message can be understood; consider separating the information from the audio and presenting in an alternative format, such as visual alerts.
3. **Sound for wayfinding** - Sound cues can provide wayfinding and navigation information to people with vision loss. These cues should accurately reflect the physical space. Alternative wayfinding methods are needed in large open spaces or in complex acoustic environments where the acoustic cues can become lost or distorted.
4. **Sound for enjoyment** – Sound is integral to the experience of certain activities such as music and performances. Use preferred seating and assistive technology to provide equitable access to these activities.

c) Identify and reduce the effects of noise

Effectively controlling noise requires an understanding of noise properties, and how these contribute to the effects of noise on functioning for people with disabilities:

1. **Noise as a barrier to communication** – Noise can interfere with both the hearing and sound processing needed for spoken communication. Any high-level noise can overpower portions of speech and make it difficult to hear or understand what is being said, in complex acoustic scenes multiple noise sources or talkers make it harder to focus on a single sound, even if each of the competing sounds are not loud enough to block out the sound.
2. **Noise as a barrier to focus and concentration** – The ability of noise to distract depends more on its characteristics than its level. A loud steady noise, such as a fan, may be easier to filter out

than a quiet sound with fluctuating level or frequency content. Speech and other signals with information tend to be the most distracting, and can be a barrier to focus even at low levels.

3. **Noise as a barrier to emotional wellbeing** – The impacts of noise on emotional state are often related to its lack of predictability and the inability to control the noise. Loud and sudden sounds, or the anticipation of them, can trigger negative responses especially for people who experience anxiety and stress or who have sensory sensitivities. Chronic noise exposure, even if it is steady and low level, can worsen mental health conditions.

d) Assess and re-assess acoustic accessibility

Designing with acoustics and accessibility as core principles means considering and evaluating the acoustic quality in all phases of the building lifecycle:

1. **Plan** – Select a site and building orientation that accounts for environmental noise considerations. Allocate and layout space in a way that considers the activities and sounds associated with each space, as well as the sounds of entry, exit, and movement through and between spaces.
2. **Design** – Identify the acoustic needs of a space. Determine the room shape, volume, and acoustic features to control sound transmission and reflection to meet these needs. Design connecting spaces like hallways to meet the needs of sound conduction and isolation between spaces.
3. **Build** – Select surface finishes and construction methods that meet the design objectives. Ensure the space includes or is compatible with assistive technology. Measure the performance after construction to verify that the objectives are met.
4. **Use** – Assess the acoustic performance of the finished and furnished space to ensure it meets the needs of the activities in the space. Spaces change over time; monitor the acoustic performance and re-asses it when there are changes in activities, equipment, and furnishing.

Performance measures for sound insulation, noise level, and reverberation time can be useful tools for assessing and verifying a design or a built space; however, these measures on their own are not sufficient to define a fully accessible space.

e) Normalize and support the use of assistive technology

While assistive technologies are not substitutes for good acoustic design, they can expand opportunities for people to fully participate in the activities of a space. Our research identified barriers to the access and use of assistive technology. The following sub-recommendations can help individuals, organizations and institutions increase adoption, understanding, and acceptance of assistive technologies in the built environment:

1. **Make accessible features universal** – Use of devices and features labeled as accessible or assistive technology often requires an unwanted disclosure of disability. The success of technologies such as captioning and automated speech recognition show that this labeling is often unnecessary. Treat accessibility features as another form of customization. Technology that is necessary for some may be useful for all, and increased use of accessibility features by people with and without disabilities can lead to reduced stigma and improved performance of these features.

2. **Reduce access barriers to assistive technology** – Accommodations for the use of assistive technology in workplaces and schools are often based on a specific diagnosis and require a disclosure of disability. Purchasing specialized assistive technology for personal use can impose a large financial burden. Make access easier and more equitable by providing devices based on benefit rather than diagnosis and offering financial support to offset the cost of personal purchase.
3. **Provide ongoing support for assistive technology** – Assistive technology often goes unused due to lack of maintenance or employee awareness. Extend plans for assistive technology beyond the initial purchase and include ongoing support and training for their proper use.
4. **Integrate with personal technology** – When evaluating assistive technology, favour solutions that integrate with personal devices such as mobile phones or personal hearing devices, rather than solutions that require specialized hardware. Mobile phones are ubiquitous and versatile and are commonly repurposed as informal assistive devices such as remote microphones, assistive listening receivers, or portable captioning systems. Use of a personal device provides familiarity and offers users more control over their use of the technology.
5. **Support low-tech solutions** – Strategies for assistive technology should not omit traditional low-tech accessibility solutions. These solutions are often the most universal and reliable. Examples include signage for wayfinding, writing materials for non-verbal communication, course notes and handouts as alternative formats for learning, and policies for behaviour and etiquette to help control noise and disturbance.

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