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Review

Accessibility of the Built Environment for People with Sensory Disabilities—Review Quality and Representation of Evidence

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Abstract: People with sensory disabilities constitute a significant portion of society whose accessibility needs must be prioritized in the design of the built environment. Sensory disabilities cause a gap in the environmental information received, most commonly visual and/or auditory cues, that requires consideration to create equal opportunities and experiences for all. This paper evaluates the quality and representation of existing research on accessibility for people with sensory disabilities, aiming to identify gaps and inconsistencies in current studies. By considering variations in disability type, degree of impairment, and assistive aid usage, we seek to enhance the development of inclusive accessibility standards. Through this analysis, we aim to provide actionable insights for future research and contribute to the creation of more equitable built environments for all individuals.

Keywords: built environment; sensory disability; d/Deaf; visual; accessibility

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1. Introduction

Sensory disabilities, stemming from various neurological disorders affecting sensory information processing, encompass a spectrum of impairments, including visual impairments ranging from legal blindness to total blindness and hearing loss spanning mild to profound deafness [1–5]. Because of these disabilities, the individuals are missing key environmental information that makes navigating, communicating, and managing their daily chores and safety more difficult. According to the 2017 Canadian Survey on Disability (CSD), an estimated 1.5 million individuals have vision disabilities, while 1.3 million experience hearing impairments [6]. Consequently, ensuring equal opportunities in the built environment becomes imperative, necessitating the translation of environmental information into accessible formats [7].

People with visual disabilities encounter challenges in navigating spaces safely, relying heavily on wayfinding strategies and memorization of pathways and landmarks [8,9]. Designing for visual impairment requires nuanced consideration, acknowledging the varying degrees of blindness and corresponding assistive tools, such as guide dogs or white canes [10]. However, despite these challenges, there remains a dearth of systematic research investigating the specific barriers faced by individuals with visual impairments in orientation and navigation within built environments, highlighting a crucial gap in the literature [7,8,11–20].

People with hearing disabilities are presented with barriers to their communication, especially when considering the signing population, and much of the associated research focuses on the social aspect of accessibility within the interior environment. Communication through visual means is one of the key features to accommodate the hard-of-hearing community, regardless of whether the individual uses assistive hearing devices, lip-reading, or sign language [19,21–23].

Overall, many of these gaps are attributed to several factors, such as the wide spectrum of different disabilities leading to different perspectives on their needs [24]. Additionally, inadequate planning, a lack of enforcement of the available guidelines and policies by the relevant authorities [12,13], or a lack of awareness and training of the needs and behaviors of people with sensory disabilities result in overlooking them in several situations in the built environment [7,10,13,17,19,25–27]. Moreover, in many cases, the problem is due to the lack of involvement of these individuals and accounting for their perspective in the dialogues or during the planning and designing of the standards [15,28,29], or due to the limited representation of their experiences by using nonrepresentative, small, or non-random samples in the interviews or surveys [8,10,15,30,31].

This study aims to assess the quality, consistency, and completeness of research papers on accessibility for people with sensory disabilities in the built environment. The assessment methodology is adapted from CERQual (Confidence in Evidence from Reviews of Qualitative research) with the aim of establishing a degree of confidence in the evidence and the extent of its representation [32–35]. The methodology consists of the following steps. The first step was to conduct an extensive search of the literature, which includes refereed journal papers and conferences. Secondly, a representative sample of the papers published in refereed journals and conferences was selected for an in-depth review. The review focuses on the objectives and scope, methodology, assumptions, representativeness of the sample surveyed and/or included in the experiments, findings, deductive reasoning, conclusions, and recommendations. Thereafter, the quality and shortcomings of the relevant research were identified, and their impact on developing guidelines and standards for a barrier-free built environment for people with sensory disabilities was discussed. The reviewed papers were grouped based on the following built environments: pedestrian infrastructure, outdoor environments, and indoor environments.

2. People with Visual Disabilities and Accessibility of the Built Environment

The built environment has been designed by sighted people for sighted people to navigate and access, leaving people with visual impairments struggling to gather the sensory information needed to orient themselves properly within the environment [14,28,31]. Failing to consider the accessibility needs of the visually impaired, the built environment becomes hazardous and their daily activities difficult. The research pertaining to visual disabilities and the built environment was categorized into three main themes: pedestrian infrastructure, outdoor environments, and indoor environments.

2.1. Pedestrian Infrastructure

Pedestrian infrastructure refers to the built environment that surrounds walking environments, such as sidewalks, crosswalks, and curbs. For people with visual impairments, pedestrian infrastructure also includes accessibility features such as tactile paving, blister blocks, and orientation blocks. Pedestrian infrastructure and mobility are where much of the research is focused for the visually impaired, due to the complex environment that impacts the mobility, safety, and accessibility of these environments. One of the most important accessibility requirements of the pedestrian environment for the visually impaired is to facilitate their ability to orient themselves and reach a destination safely.

Atkin investigated the effect of degrees of sight loss on the navigation of urban environments and what improvements can be made for a safer and more comfortable experience [36]. The study included interviews with professionals and observed journeys for eight participants with visual impairments in and around London while sharing their wayfinding strategies on usual unaccompanied trips, using street features and landmarks, as well as their level of comfort throughout the journey. Among the participants, there were three long cane users, three residual sight users, and two guide dog users. Five of them had undergone formal mobility training. The recommendations for each group of participants were then developed based on these interviews. The study highlighted the similarities and differences between participants' needs based on the mental maps they created to predict their environment. Participants stressed the need for signal-controlled crossings, audible signals, or tactile control boxes/rotating cones, and to have smooth, obstacle-free streets to reduce the risk of collisions during their trips. On the other hand, due to variations in sight loss, assistive mobility aids, wayfinding techniques, training received, and personal preferences for streets' configurations, many discrepancies in the design requirements of the pedestrian infrastructure were underlined. For instance, while residual sight users have issues identifying the height of curbs, both long cane and guide dog users prefer the use of curbs to provide them with a more distinguishable difference between roadways and sidewalks. Also, long cane users prefer sidewalks that are not excessively wide, whereas wide sidewalks are best for guide dogs and residual sight users. These discrepancies confirm the necessity to improve the effectiveness of tactile paving guidance and provisions that account for the different grades of sight loss and assistive devices. In addition, it is important to make use of natural cues for a safer and more predictable environment with even unobstructed pathways. It is worth mentioning here that although this study focuses on understanding the differences between the different groups of the visually impaired, it was conducted on a small sample size; therefore, the accuracy of the recommendations should be further reviewed with larger groups.

A study conducted by Tennøy et al. aims to assess the quality of current Norwegian standards in the planning and design processes of tactile paving systems and their efficiency in the accessibility of the visually impaired community [37]. The review included a comprehensive review of 36 Norwegian and international standards, handbooks, and guidelines. Additionally, it featured in-depth interviews with 20 individuals representing governmental authorities, organizations associated with people with visual impairments, and practitioners playing a role in facilitating built environments. Furthermore, two seminars were held with 21–26 attendees representing stakeholders involved in or working with facilitation for people with visual impairments, and a case study was conducted examining the previous work in a preselected bus terminal. The results of the study showed that many of the standards prioritized natural lead lines over specialized tactile paving and only suggested their use where warning is required or when natural cues are not adequately available. Based on the literature, people with visual impairments usually tend to train themselves using the naturally available elements for better wayfinding and orientation. However, the standards did not provide details on how safe and accessible built environments should be designed using natural leading elements. Instead, specialized tactile paving was described in more detail, especially in complex situations. Additionally, the results looked at whether implementing universal design can be an adequate solution and pointed out several challenges due to the variability in understanding universal design requirements among stakeholders, in addition to discrepancies between projects that interfere with one another and the delays in consideration of universal design in the planning and design stages. The findings implied a significant gap in knowledge on how people with visual impairments navigate in complex pedestrian environments, utilize physical elements in the environment, and how the design of the built environment can make it more usable for them. The study provided recommendations such as involving more practitioners and institutions engaged in mobility training for people with visual impairments in the research and providing training for practitioners involved in planning, designing, constructing, operating, and maintaining built environments.

Havik et al. performed a comparative field study and interviews investigating the wayfinding performance of 25 people with visual impairments in two shared spaces compared to two traditional spaces [38]. Shared spaces are a new design concept, also known as complete streets, where the goal is to help integrate the motorized road with an inclusive pedestrian environment. The participants ranged in the degree of their impairment, with a spectrum covering complete blindness to low vision, their age ranging between 19 and 69 years, and their assistive mobility aids, with five dog and long cane guide users, 15 long cane users, and five without any mobility aid. The participants had to complete a route, each containing one crossing, one or two turns, and walking parallel to the road. The walking of the routes was observed from the opposite side of the road, which included a schematic map of the path taken by the person with visual impairment. The test leader walked approximately 1–2 m behind the participant to intervene if the person required assistance. Assistance was given in circumstances where a participant was unaware that they had begun walking into traffic. The comparative field study results showed that navigating in an unfamiliar shared-space area is more complicated for people with visual impairments than navigating in an unfamiliar conventional area, as orientation is the main challenge in such areas. In shared spaces, the person with visual impairment, on average, took more time to complete the route, had a lower preferred walking speed, and rated the shared space design more negatively. The fully blind participants also required assistance during the route in all the shared spaces tested, as there was no curb dividing the sidewalk from the roadway. Shared spaces were consistently rated as feeling less safe, and people with visual impairments would not want to complete the trip independently. This research highlights a need for the concept of shared spaces to be addressed from the point of view of a disability to promote the idea of true space. This study was limited to four spaces in total, whereas studies with a larger sample size representing the full spectrum are needed to determine the full extent of the effects on the visually impaired population.

A survey focusing on the outdoor travel experience and the mobility-related barriers that people with visual impairments experience was conducted by Zeng [39]. A focus was also placed on the role of mobile devices and GPS technology and their impact on aiding the visually impaired with outdoor travel. Ninety-seven participants took part in the survey with varying degrees of impairment, with 64 participants being blind and 33 participants with low vision. The survey questions focused on the outdoor travel experience and the use of assistive technologies. For barriers that people with visual impairments experienced within the city, the survey emphasized their experiences when they travelled independently. Most of the participants presented the issues of public transport stops lacking auditory information (82.4%) and traffic lights without an audio output (81.4%). Other common issues presented by the participants were the failure to find the entrance of a building (64.9%), ill-formed and irregular sidewalks (58.7%), falling from unknown stairs (47.4%), getting lost (45.3%), falling because of an unknown hole (44.3%), and complex pedestrian crossings (43.4%). One of the major findings of this study is that 36% of the blind and 21% of the low-vision individuals were not able to navigate and orient themselves independently and needed sighted companions to help. This highlights the need to improve the built area for pedestrian infrastructure via accessible facilities and assistive aids. This research was solely focused on understanding the mobility-related areas without providing recommendations on remediation, but it highlighted many areas of the built pedestrian environment that cause barriers to accessibility for the visually impaired. Additionally, the study revealed that the current GPS systems lack the up-to-date map and environmental accessibility data needed for people with visual impairments. This survey identifies areas that need to be addressed, but the sample size is a small representation biased toward the infrastructure available in developing countries. This may have influenced the results, as other issues may be more prominent in these areas in developed countries.

A study conducted by Inagaki et al. examined the installation of newly designed orientation blocks and the effectiveness of their placement to facilitate people with visual impairments at crosswalks [40]. These orientation blocks provide great guidance while crossing the roadway if they are placed in the proper position relative to the tactile walking surface indicators. The main problem is that tactile blocks are often not placed perpendicular to the crossing, which confuses the person with visual impairment when walking off the crossing. Using an experimental setup, 21 people who are totally blind examined the position of the orientation blocks relative to the blister tactile blocks. The participants were then video recorded to observe their walking trajectory. The orientation blocks were placed 8 cm, 12 cm, and 16 cm from the blister block, and then the deviation was measured at the 10 m mark. The results of the experiment showed that separating the orientation and blister tactile blocks by about 8–12 cm effectively limits the lateral deviation of 5 m from the start point of the crossing.

The physical attributes that affect the walkability of the environment were investigated by Bona Frazila and Zukhurf [41]. The research was conducted by interviewing blind and people with visual impairments and performing statistical modelling on the facilities required for walkability. Two surveys were conducted to thoroughly understand the perspective of blind pedestrians and the key physical elements that impact their walkability. To evaluate the effect of each physical attribute on walkability, a linear correlation between them was assumed, in addition to the perspective of the blind individuals about the importance of the facilities that needed to be provided. Walkability was found to be affected by the effective width of the sidewalk, pavement condition, including tactile guidance, crossing facilities, and sidewalk level, physical guidance such as tactile guidance and Braille information, and security and safety facilities. These physical attributes need to be carefully considered during the planning phase of the pedestrian facilities to serve walkers with visual disabilities.

2.2. Outdoor Environments

Outdoor environments such as city parks present unique challenges to the visually impaired, as there is less information available to them. These types of environments often bring out feelings of discomfort and a need to rely on a sighted guide to use these spaces. The overall area has not been researched as heavily as other areas of visual disabilities.

Siu performed a case study on the urban parks in Hong Kong with 12 people with visual impairments to determine the overall accessibility of the park and the key directions that lead to complete social inclusion for everyone [42]. The participants were interviewed to understand the overall accessibility of urban parks, and a combination of site studies and field observations were used during these interviews. Government officials and planners were also interviewed to understand the current standards. Six parks of various sizes in three different districts of Hong Kong were visited. The inaccessibility of urban parks for the visually impaired was found to be related to three main areas: identifying and approaching parks, the overall environmental setting, and the facilities inside the parks. The participants had accessibility issues identifying and approaching parks, as they experienced mental stress from trying to locate the park and often had to memorize the route to the park. They often had difficulty entering the park independently or without the help of a sighted guide. The overall environmental settings of the park were found to be inaccessible due to the lack of tactile information about direction and orientation, and little to no auditory information was available. Information about the facilities within the park and their accessibility was often not provided. Therefore, the study suggested providing further assistance by categorizing the information into in-advance and on-site. Although the research highlighted the problem of the limited and poor-quality support provided for people with visual impairments to navigate urban parks independently, it only considered a small sample size of 12 participants.

The barriers that limit the experience of people with visual impairments exploring the outdoor environment, in addition to the role of technology in improving these experiences, were investigated by Bandukda et al. [43]. After interviewing seven people with complete blindness and using thematic analysis, common threads and themes were identified. The participants varied in their location and age (20–60 years). The interviews, which were conducted over the phone and video calls, contained generic and specific questions about the participants' experiences. Three key themes were analyzed: independence, knowledge of the environment, and sensory experiences. The "independence" of a person with visual impairment is often negatively impacted by the lack of wayfinding information and landmarks, which makes the outdoor environment more physically and mentally demanding. The "knowledge of the environment" theme reflected the fact that a person with visual impairment will almost always need to be accompanied by a sighted companion. The need for the sighted guide stems not only from a need for help with orientation but also for a description of the visual environment. Finally, the "sensory experiences" theme helped people with visual impairments identify the environment around them. These sensory characteristics can be a change in tactile sensation from the ground, sounds of flowing water, and sounds from birds, which help indicate the presence of trees. The study revealed the gap between existing technology and human–computer interaction (HCI) research in outdoor environments, the need to provide an independent navigating experience for people with visual impairments in outdoor environments without the need for sighted companions, and the lack of natural landmarks and clues that force the people with visual impairments to use navigation apps that lack accessibility features. One of the interesting findings of the paper is the discrepancies between the perspectives of different individuals when describing their needs.

2.3. Indoor Environments

Navigating indoor environments represents the biggest challenge for people with visual impairments, especially when exploring unfamiliar spaces without clear guidance and the availability of assistive aids [16,44]. Jeamwatthanachai et al. performed a survey to understand the challenges, behaviors, and strategies used by the visually impaired when navigating an unfamiliar indoor environment [45]. The survey included 45 participants of whom 15 experts and 30 people with visual impairments commented on the accessibility of the indoor environments. Of the 30 people with visual impairments, 22 self-reported as blind/severely sight impaired, and eight participants were sighted impaired/partially sighted. Both the sighted and visually impaired completed 18 questions, which were split into five categories regarding indoor navigation by the visually impaired. Five types of buildings were examined, which were further broken down into four room types and analyzed based on the level of difficulty and confidence in using the space. Every person with a visual impairment was asked to rate the level of difficulty (easy, moderate, or hard) and their level of confidence in navigating space (no confidence or confidence). After rating the buildings and spaces, they were asked to give comments on their reasons for the level of difficulty or lack of confidence in navigating the space. The results of the study confirmed that the main challenge facing people with visual impairments is the fear of navigating unfamiliar indoor spaces independently and the time it takes them to become familiar with the space. Therefore, they need to have a sighted guide before building the confidence to explore these spaces with the help of assistive aids. The recommendations are to have different alternatives for navigation that help them to develop confidence and create a safer environment, in addition to providing information about the obstacles and barriers that might impede their accessibility with the help of landmarks and environmental cues such as light, noise, and smell. The study showed that certain types of buildings and sizes of rooms do cause a large difficulty in the accessibility of the indoor environment. While the deduced conclusions and recommendations are useful, they were based on a very small sample size that may not be representative of all people with visual impairments.

3. People with Hearing Disabilities and Accessibility of the Built Environment

The everyday built environment is not typically designed for auditory cues, even though they play a large role in the ability to communicate within space. As communication is often done verbally, those in the d/Deaf community may be unable to communicate if visual cues are unavailable. Our research revealed that much of the research related to sensory disabilities focuses on visual impairments, and fewer studies investigate the requirements of people with hearing impairments. Furthermore, indoor environments appear to cause more barriers for people in the d/Deaf community. Without actively creating a barrier-free space, the ability of people with hearing impairments to communicate with others when indoors will remain limited. The issues presented in indoor environments for people who are d/Deaf are largely related to communication and safety. Since most of the barriers to accessibility that the d/Deaf community experiences are related to social problems, most of the research related to the built environment is looking at how to improve barriers to social problems, such as improving communication.

As an attempt to cope with and improve the surrounding indoor environments for the d/Deaf community, DeafSpace was introduced in 2005 as a set of architectural design space principles that account for a correlation between the built environment and the senses [21,46]. The principles of DeafSpace were collaboratively developed by the hearing architect Hansel Bauman and students at Gallaudet University, an American university designed for the accommodation of students who are d/Deaf. The five concepts of the DeafSpace are "Sensory Reach" by utilizing visual cues to promote awareness of the surroundings, "Space and Proximity" by maintaining appropriate distance during conversations to accommodate the signing space, "Mobility and Proximity" through keeping an adequate signing space between individuals walking while talking, "Light and Color" through modulating natural light attuned to d/Deaf eyes, and finally "Acoustics" through minimizing sources of background noise. Edwards and Harold [21] discussed the principle of DeafSpace relative to the concept of Universal Design. While Universal Design focuses on providing standardized and universal barrier-free spaces for all types of people, it was criticized for failing to consider the particularities of the d/Deaf community. The study highlighted some of the criticisms of DeafSpace. Due to the limited number of buildings adopting the DeafSpace design, it may not meet the end goals of the users. An example is the implementation of curved corners, which are designed to allow the d/Deaf to see farther around them and avoid having people bump into each other, but in practice, people tend to hug the corner. Overall, DeafSpace emphasizes flexible and innovative designs that account for acoustic environments and that should not conflict with Universal Design, yet understanding their relationship together will require time. There are still uncertainties about the spaces DeafSpace can produce specifically for the d/Deaf community; otherwise, it will just remain a set of rules and principles.

The reliance on visual emphasis has been criticized in Western architecture as it alienates people with different needs. For that reason, Pérez Liebergesell et al. investigated the potential to connect people by exploring the experiences of George Balsley, an architect who is d/Deaf who utilized vision in his designs reflecting the interaction of visual and spatial dynamics in sign language [23]. The study was based on interviews and observations about the design of his building, the Sorenson Language and Communication Center (SLCC) in Washington, DC. The SLCC resides at Gallaudet University; therefore, its accessible design for the d/Deaf community is highly important. It is important to note that only the architect was included in the interview to understand his design. The goal of this study was to understand the designs that Balsley implemented to increase the accessibility of the building for the d/Deaf community. Balsley noted that one of the main concepts to consider when designing a space for the d/Deaf is the need for visual communication and the space required to implement it. To have the required space for visual communication, it is necessary to design elements such as open spaces, glass walls, rounded corners, and automatic closing doors. The d/Deaf community is reliant on visual cues to experience their environment, which leads to the design being focused on translating sounds into visual cues. The SLCC building shows this with the decision to move the elevator into the center of the atrium and make it clear so that individuals who are d/Deaf can see if the elevator is moving or not.

To further investigate the visual needs the d/Deaf community relies on when using sign language, Azalia et al. discussed the concept of spatial proximity and what space configurations can support their communication in public places like cafés [47]. Proxemic space considers not only the amount of space needed for sign language but also the preferred distance that the conversations take place at for the comfort of the individual. Anthropologist Edward Hall introduced the concept of interpersonal distances characterizing Western culture, where the proxemic zones are broken up into four categories: intimate, personal, social, and public space [48]. These proxemic zones stem from the tactile and visual reach needed to communicate. When designing layouts within buildings to accommodate the d/Deaf community, the target zones for design are the personal, social, and public spaces. Personal space is considered 46–120 cm of sensory reach, and it is the optimal space for sign language and lip reading with friends and family. Social Space is considered 120–370 cm, which is optimal space for sign language between acquaintances. Public space is considered any space above 370 cm. The results were used to analyze Kopi Tuli, a café for the d/Deaf community, and the observations showed that providing a variety of proxemic zones, with the arrangement of tables and furniture and the use of semi-reflective surfaces and transparent materials, allowed for a variety of the d/Deaf community to feel comfortable while still having easy communication. This is shown by the variety of social and public proxemic zones being available, allowing the d/Deaf community to pick the areas that feel comfortable and accessible to them. It is important to note that the experiment took place in a café considered a place for the d/Deaf community.

Another study was conducted by O'Brien, where five academics who are d/Deaf were interviewed to understand and experience how the academics who are d/Deaf navigate the physical environments of their workplaces at Higher Education Institutes (HEI) [22]. With the concept of DeafSpace expanding into how individuals who are d/Deaf change their environment, many individuals in HEI must adapt their workspace to fit their needs. The walking interviews provided the ability to see how sign language communication is affected by the built environment, or the DeafSpace concept of perceived space. Several of the hallways and pathways did not provide enough width for two signing individuals to walk side by side, as there was not enough space to comfortably articulate and see the whole signing space. Another barrier to the accessibility of pathways and hallways was the obstacles, which needed O'Brien or the participant to guide each other around during the conversation. Adaptation within the perceived space is also important for the safety and accessibility of people who are d/Deaf. Examples of these adaptations include fire alarms with flashing lights, flashing doorbells, or fire alarms that connect to the individual's phone. The DeafSpace principles often cause a conflict between d/Deaf and hearing values, such as the concept of tactile sensation from floorboards. While the tactile sensation helps the d/Deaf identify people around them, they also have a concern about the amount of noise the floor makes, as they do not want to disturb the hearing people around them. Other aspects of making the spaces 'deaf' are through the concept of the lived space, a sub-concept of DeafSpace. This is shown through adjustments that the people who are d/Deaf make the space more accessible to them. Within the context of O'Brien's conversation with individuals who are d/Deaf in HEI, moving desks to make the office more deaf-friendly was a common one. This consisted of moving the desk to face the door or strategically placing mirrors, so they were aware if someone wanted to enter the office. Another concept discussed was the conceived space, which identified issues with university planning. The main issue addressed was the lack of windows on doors, as without them, individuals who are d/Deaf cannot tell when someone is trying to enter their office. Overall, the study strongly emphasizes that even minor adjustments that account for individual spatial experiences can foster an inclusive environment for all while also maximizing the productivity of academics who are d/Deaf in their workplace.

4. Analysis and Discussion

This study aims not to review the state of knowledge but rather to analyze the soundness and completeness of the refereed papers that document the accessibility of the built environment for people with sensory disabilities, specifically the completeness of the experiments and confidence in the results, conclusions, and recommendations. Towards such objectives, qualitative and quantitative analyses were carried out, with the former focusing on the people with sensory disabilities and the diversity of the community, and on the different types of built environment, and the latter on whether the experimental results are a true representation of the population. It should be noted that the search revealed a much smaller number of papers on the accessibility of the built environment for people with sensory impairments compared to the total number of papers published on the accessibility of people with sensory disabilities.

Sensory disabilities require information perceived by one sense to be translated into another. When looking at sensory disabilities, general research often groups visual and hearing disabilities together, although their needs are different and at times contradictory. For visual impairments, visual cues are commonly translated into tactile or auditory cues within the environment [8,14,31,37,40,45]. Strong colour and tonal contrasts can be used as well to help residual sight users provide missing information [8,31,45]. Alternatively, people with auditory or hearing disabilities rely on clear visual cues to help provide the missing information from the lack of sound [19,21–23,47]. Therefore, due to the opposite types of sensory cues, the important distinctions between the two communities need to be properly addressed [24]. To illustrate, the use of glass walls represents a good example where, for the people who are d/Deaf, they help provide accessible levels of communication while providing a visual separation of spaces [23]. Then, again, for the visually impaired, glass walls are problematic for those who rely on residual vision as they cannot easily detect the glass. As such, the distinct needs of individuals with sensory disabilities should be treated separately and critically studied to ensure that the accessibility measures for one group do not limit the accessibility of the other groups [21].

Examination of the Deaf communities reveals that they are diverse, with people identifying as Deaf, DeafBlind, DeafDisabled, Hard of Hearing, and Late Deafened. Among them, there are variations in the level of hearing, age of onset, educational background, and communication methods [49]. Similarly, the visually impaired community includes people with different degrees of residual sight, such as light perception, severe vision impairment, or complete blindness [50]. Moreover, people in both the Deaf and Blind communities employ different assistive devices to enhance their accessibility when navigating the built environment. Therefore, it is important to understand the different needs created by the various assistive devices and the degree of impairment loss to properly design for their needs. For instance, long-cane users are far more reliant on tactile information to guide them [36]. Multiple studies have highlighted that there is little understanding of how the visually impaired community orient themselves within the built environment, especially when considering the pedestrian and outdoor environments [36,37,42,43]. The differences in needs among the visually impaired based on their degree of impairment highlight the need to better understand the best practices for the implementation of accessible features for the entire visually impaired community [36,38]. This implies that studies need to distinguish not only between the needs of the Deaf and Blind community but also the diversity of the individuals that form the community.

When dealing with the built environment, the research surrounding indoor environments for people with sensory disabilities shows that barriers to accessibility stem from different areas. Hearing impairment focuses on the visual aspect of the space and the space needed for communication, whereas visual impairment in general concentrates on the orientation ability of the individual. For the hearing impaired, one of the areas most addressed by DeafSpace is looking at the space required for the use of effective sign language, as the watcher needs a full view of the signing space. On the other hand, research on visual impairments focuses on the ability of people with visual impairments to orient themselves within an environment and the size of space that impacts their ability.

Quantitatively, the review revealed that the sample size used to conduct the experiment and deduce observations, conclusions, and recommendations is not representative of the population. Especially when recognizing the diversity of the groups and the uniqueness of the individuals' needs. Different methods exist to estimate the sample size, such as power analysis, random sampling, convenience sampling, or stratified sampling. Statistically, the sample size depends on the size of the population, the precision of the estimates, the confidence level in the results, the variation in the population, and to some extent the resources available to conduct the study; however, not all methods employ them [51–53]. When reviewing the published research, it is evident that they used the convenience sampling approach, which is the simplest and lowest-cost approach. However, the disadvantages of the convenience approach are sampling bias, selection bias, low external validity, and the fact that it is difficult, if not impossible, to generalize data or break it down into subcategories. Moreover, the size of the sample is far too small to be representative, even for convenience sampling, where a minimum of 100 and a maximum of 1000 are usually suggested. For reference, the sample size can be determined statistically using the following relationships when the population size is unknown [Equation (1)] or known [Equation (2)], respectively.

$$n = \frac{Z^2 * p(1-p)}{e^2} \tag{1}$$

$$n = \frac{Z^2 * p(1-p)}{e^2} \Bigg/ 1 + \left(\frac{Z^2 * p(1-p)}{Ne^2} \right) \tag{2}$$

where Z is the Z-Score and for 90% Z-score = 1.645, e is the margin of error taken as 10%, p is the standard deviation taken as 0.5, and P is the population size. According to Statistics Canada, there were 7.4% and 5.6% of Canadians with vision and hearing impairments in 2022, respectively [54]. The previous census on Deaf, Deafened, and Hard-of-Hearing reported a range of one out of every twenty-five Canadians (1:25) to one out of every eight Canadians (1:8) having impaired hearing. By assuming that Canada's population is comparative to the U.S. and that Canada has 1/10th the population of the U.S., the Canadian Association of the Deaf reported that there were approximately 357,000 profoundly deaf and deafened Canadians and possibly 3.21 million hard-of-hearing Canadians in 2015 [55]. The National Institute on Deafness and other Communication Disorders reported that approximately 15% of American adults aged 18 and over report some trouble hearing [56] and that one in eight people in the U.S. aged 12 or older has hearing loss in both ears, based on standard hearing examinations [57]. If one deduces that there are at least 350,000 Deaf and Deafened Canadians, then the sample size to conduct a scientific study according to Equations (1) and (2) is 96. However, to conduct a meaningful statistical analysis, studies need to account for the diversity of hearing impairments within the population by applying the stratification sampling approach. Accordingly, the sample size needs to be at least 96 people for each stratum.

In the province of Ontario in Canada, there are an estimated 189,000 people who are partially sighted or blind, which is slightly greater than the 7.4% reported by Statistics Canada. In 2015, 3.44% of the worldwide population had distance visual impairment, of whom 0.49% were blind and 2.95% had moderate-to-severe visual impairment [58]. For Canada, if one accepts that Ontario has 189,000 people with visual impairments, then the sample size to conduct a scientific study according to Equations (1) and (2) is 96. Similarly, if one considers the population of Toronto Central LHIN boundaries, which is estimated to be about 17,344 people that are partially sighted or blind [59], then the corresponding sample size is found to be equal to 96 persons per stratum to account for the diversity in impairment within the population and the different assistive devices.

From the reviewed literature, the ratio of papers studying hearing impairments compared to visual impairments on accessibility of built environments is 1 to 3. Closer examination reveals that most of the research surrounding visual impairment is directed towards pedestrian safety, specifically the interaction between pedestrians and the surrounding environment [14,20,30,39,41], as shown in Figure 1a, whereas the research in other areas of the built environment, such as the accessibility of public transportation and indoor environments, is limited [11,27,45]. Every environment presents unique challenges to people with visual impairments in the niche areas that they serve. Of significance is the observed gap in research due to the design environments not being actively understood with the visually impaired community in mind. Research should be directed towards understanding the wayfinding process and how to formalize it as a required component of the standards. Wayfinding includes the collective use of tactile paving, lead lines, and sounds in the environment that the visually impaired use to orient themselves [36,37,40,42,43].

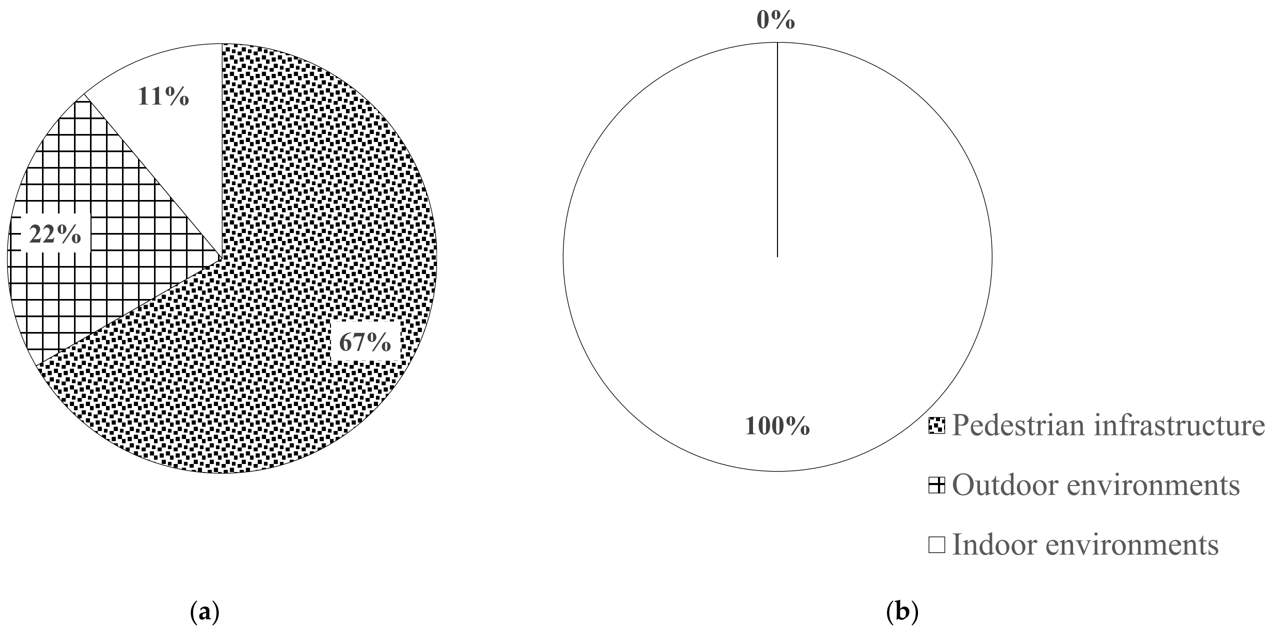


Figure 1. Distribution of research studies based on built environments for (**a**) visual impairments; (**b**) hearing impairments.

The reviewed research on the d/Deaf community is solely focused on the indoor environment, as shown in Figure 1b, specifically addressing safety and signing spatial considerations [22]. Further research on including d/Deaf design in building standards, such as defining the amount of space needed in hallways for proper signing, is an important step to ensuring that buildings become more accessible and comply with the standards. DeafSpace, which places a large focus on visual cues its effects on people with different disabilities need to be researched, especially when considering people with visual disabilities.

Published research on people with hearing disabilities is largely of a qualitative and interpretive nature. Focusing more on studies of a quantitative nature to determine the amount of space required in indoor environments for comfortable signing would be important for future research. Moreover, transportation is a key area to focus on when considering hearing disabilities. While the d/Deaf community can drive and does not need to rely on the public transportation system, research needs to study the barriers the d/Deaf community encounters when using public transportation systems. O'Brien deduced that the research surrounding the d/Deaf community focuses primarily on the social impacts of their disability [22], and research is needed to understand and address other key areas of the built environment to ensure that it is fully accessible.

The quantitative examination of the research on people with visual and hearing impairments, respectively reproduced in Tables 1 and 2, shows the diversity of the population, research methods, and assistive aids, as well as the low number of people participating in these studies. The results further indicate that the experimental programs are most likely biased toward the perceptions of the participants, who are not a representative sample of the population. This finding is evident in the current standards, which do not address the diverse needs of people with sensory disabilities. For illustration, 97% of the participants are people with visual impairments, and 3% represent the d/Deaf community. Moreover, the research on people with visual disabilities is greatly influenced by the perspective of sighted individuals, such as authorities, designers, and researchers, who represent 29% of the participants, according to Figure 2a. Sighted participants, designers, or authorities are not part of the population and do not necessarily reflect the needs of people with visual disabilities, as evident in the work of Jeamwatthanachai et al. [45]. Among the 71% of participants with visual impairment, 46% are identified as having complete blindness and 25% have residual sight or low vision. It should be noted that each group has unique accessibility that needs to be studied separately. For most, if not all, of the case studies, only one type of sensory disability was investigated with a very small sample size [8,15,30] that included but did not account for the diverse types of assistive mobility technology [10,31] as shown in Figure 2b,c. Moreover, the effects of participants' level of knowledge, previous experience, satisfaction, perception of safety, or perspectives that might influence the findings were not documented [10,24,25,29,31]. Additionally, there are always concerns with qualitative research that is of an interpretive nature using a small sample size that is not statistically representative, where personal judgements of participants can be influenced, and the questions can be subjective. Lastly, designing and performing any experimental program where people are the investigated subject poses complex challenges such as ethical issues, collaboration of people, diverse population, diverse built environment, etc.

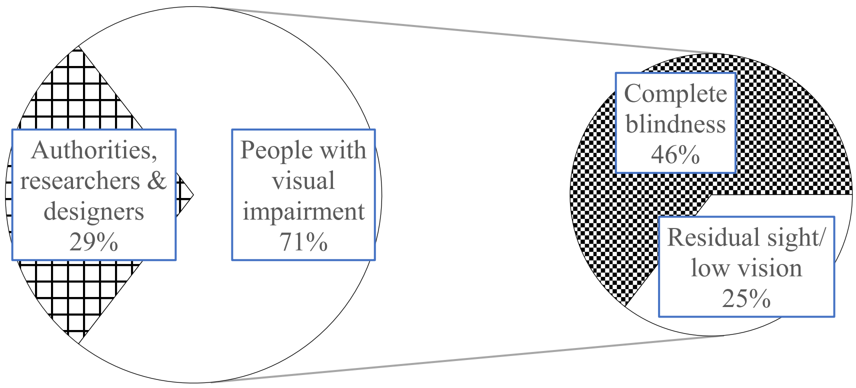
Table 1. Summary of research papers on visual impairments.

Built Environment	**Research Method Tools**							**Participants**										**Ref.**
									Visual Impairment									
									Complete Blindness					**Residual Sight/Low Vision**				
	Interviews (In Person, Telephone, or Video Calls)	**Seminars/Focus Group**	**Observed Journeys/ Walking Interviews**	**Literature/Documents Review**	**Case Studies**	**Survey**	**Statistical Modelling**	**Authorities, Researchers and Designers**	**Sighted Guide**	**White/Long Cane**	**Guide Dog**	**White Cane and Guide Dog**	**Tactile Maps**	**White/Long Cane**	**White Cane and Guide Dog**	**No Mobility Aids**	**Total Number of Participants**	
Pedestrian infrastructure	✓		✓			✓		?		3 *	2 *					3	>8	[36]
	✓	✓		✓	✓			67									67	[37]
			✓							10		4		5	1	5	25	[38]
						✓				61	3			12		21 *	97	[39]
			✓							21							21	[40]
	✓					✓	✓										?	[41]
Outdoor environments	✓	✓			✓			?								12 *	>12	[42]
	✓									3 *				4 *			7	[43]
Indoor environments						✓		15	12 *	5 *	1 *		4 *	8 *			45	[45]

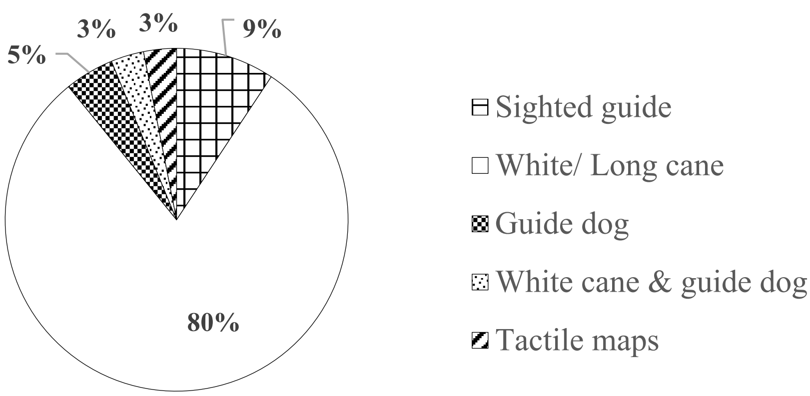
* The numbers are deduced based on the results reported in the research studies.

Table 2. Summary of research papers on hearing impairments.

Built Environment	Research Method Tools				Total Number of Participants with Hearing Impairment	Ref.
	Interviews (In Person, Telephone, or Video Calls)	Observed Journeys/ Walking Interviews	Literature/Documents Review	Case Studies		
Indoor environments	✓				1	[23]
		✓			5	[22]
	✓		✓	✓	?	[47]
			✓		-	[21]

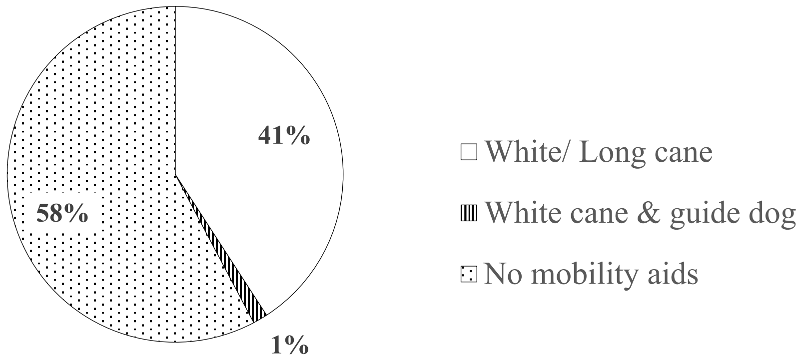


(**a**)



(**b**)

Figure 2. *Cont.*



(c)

Figure 2. Distribution of participants in research studies; (**a**) relevant to visual impairments, (**b**) with complete blindness based on the use of assistive aids, and (**c**) with residual sight/low vision based on the use of assistive aids.

5. Conclusions

From the review and analysis of the literature on accessibility of the built environment for people with sensory disabilities, the following conclusions pertaining to the status of research are deduced to facilitate the consolidation of efforts and resources of authorities involved in developing standards:

1. Statistical analyses of experimental data must account for the population size and diversity of the population for the findings to be accepted as representative of the population. Accordingly, for individuals with sensory disabilities, the representative sample needs to account for the diverse degree of impairment, personal and social preferences, and assistive aids leading to different needs for their accessibility in every specific built environment.
2. Ninety-seven percent of studies investigate the accessibility of the built environment for people with visual impairments, compared to only 3% for those with hearing impairments. Of significance is the lack of research that considers people with combined visual and hearing disabilities, or people with sensory and physical disabilities, which is necessary to ensure that the accessibility features of one group do not adversely impact the other groups.
3. Research on people with visual impairments mostly focuses on pedestrian environments. Research on their accessibility in public transportation and indoor environments is lacking. Moreover, research should focus on understanding and standardizing the wayfinding process to help them navigate independently. This involves using tactile paving, lead lines, and sounds as navigational aids.
4. Indoor-built environments for people with sensory disabilities pose accessibility challenges. Providing a space for effective sign language communication for the d/Deaf community is found to adversely affect the accessibility of people with visual impairments due to the impact of space size on orientation. Research needs to consider the physical barriers, such as the width of hallways and pathways, they face in the built environment and not only the social impact of their disabilities.
5. Designing and performing experiments on people in general pose complex challenges such as ethical issues, the collaboration of people, diverse populations, diverse built environments, etc. The analyses suggest that people with sensory or other disabilities are reluctant to participate in these research studies. Education, incentives, and a supportive environment have been shown to enhance participation.

In conclusion, the presented analyses and discussions reveal the significance, diversity, challenges, and importance of having an accessible built environment for people with sensory disabilities. The quality and representation of research evidence will help reveal the true barriers and facilitate the transfer of research findings to applications and standards.

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Glossary

Term	Explanation	Ref.
Access route	Any route in an internal or external environment, whether it is level, gently sloped, ramped, or stepped that is available and understandable for a person to use. In external environments, access routes comprise paths, pavements, and other pedestrian routes, such as a right of way through a public space.	[60]
Acoustics	Characteristics relating to sound	[60]
Assistive device	Any medical device, mobility aid, communication aid, or other aid that is specially designed to assist a person with a disability with a need related to their disability.	[61]
Blister blocks/Blister tactile blocks	A type of tactile attention indicator (TWSI)	[40]
Braille	A system where raised dots are used to represent letters and words. Unified English Braille (UEB) is the braille standard for Canada.	[62]
Crosswalk	A portion of a pedestrian crossing that is within the vehicular right-of-way.	[62]
Environmental cues	There are other auditory and tactile cues that someone with sight loss can use to navigate safely. For example, different ground types feel distinct when walking or sweeping a white cane over them, such as soft grass vs. the hard concrete of the sidewalk. The sound of voices or music can help someone locate a doorway, as can a change in temperature (such as a draft of cool air in summer or warm air in winter from an open door).	[63]
Guide dog	Bred and trained to guide people who are blind around their environment by avoiding obstacles, indicating hazards, and locating destinations. Working as a team, these incredible animals give their handlers independence and confidence.	[63]
Landmarks	People who are blind or partially sighted often navigate by landmarks. Someone may not be able to read the sign for “Baker St.” but will know it as the street with the tall hedge on the corner. They may not be able to read the house number, but they know that they want to turn in at the fourth driveway after the house with the wooden planter boxes.	[63]

Term	Explanation	Ref.
Long cane	Used as probes to sweep and scan the environment, detect objects in a person's path, changes in the walking surface, and potential hazards like steps and curbs.	[63]
Mobility aid	Any manual or electric wheelchair, scooter, boarding chair, walker, cane, crutch, prosthesis, or other aid that is specially designed to assist a person with a disability with a need related to mobility.	[61]
Orientation blocks	A new type of blocks, developed by Inagaki et al., installed at crosswalk entrances dedicated to indicating direction.	[40]
Pedestrian crossing	The combination of crosswalk segments, curb ramps/blended transitions, medians, and refuge islands that connect departure and arrival walkways across a vehicular right-of-way.	[62]
Sighted guide	There are times when people who are blind find guidance from a sighted person helpful. It is a great way to safely, and respectfully guide someone who is blind.	[63]
Tactile paving surface	A profiled paving or textured surface that provides guidance or warning to pedestrians with visual difficulties	[60]
Tactile walking surface indicator	A standardized surface, detectable underfoot or by a long white cane, to assist people with low vision or blindness by alerting or guiding them. **Tactile attention indicator:** a TWSI comprising truncated domes that signals a need for caution at a change in elevation, a vehicular route, train tracks, or other potential hazard. **Tactile direction indicator:** a TWSI that uses flat-topped elongated bars to facilitate wayfinding in open areas. **Note:** ISO 23599 refers to the tactile direction indicator as a "guiding pattern".	[62]
Wayfinding	A spatial problem-solving process based upon the consistent use and organization of definite sensory cues in the environment that individuals use to understand where they are, know where their desired location is, and know how to reach that destination from their present location.	[62]
White cane	One of the most common tools used by people who are blind to safely navigate their surroundings. Recognized around the world, it is also an important identification tool. It is a clear signal to others that the user is a person with sight loss.	[63]

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