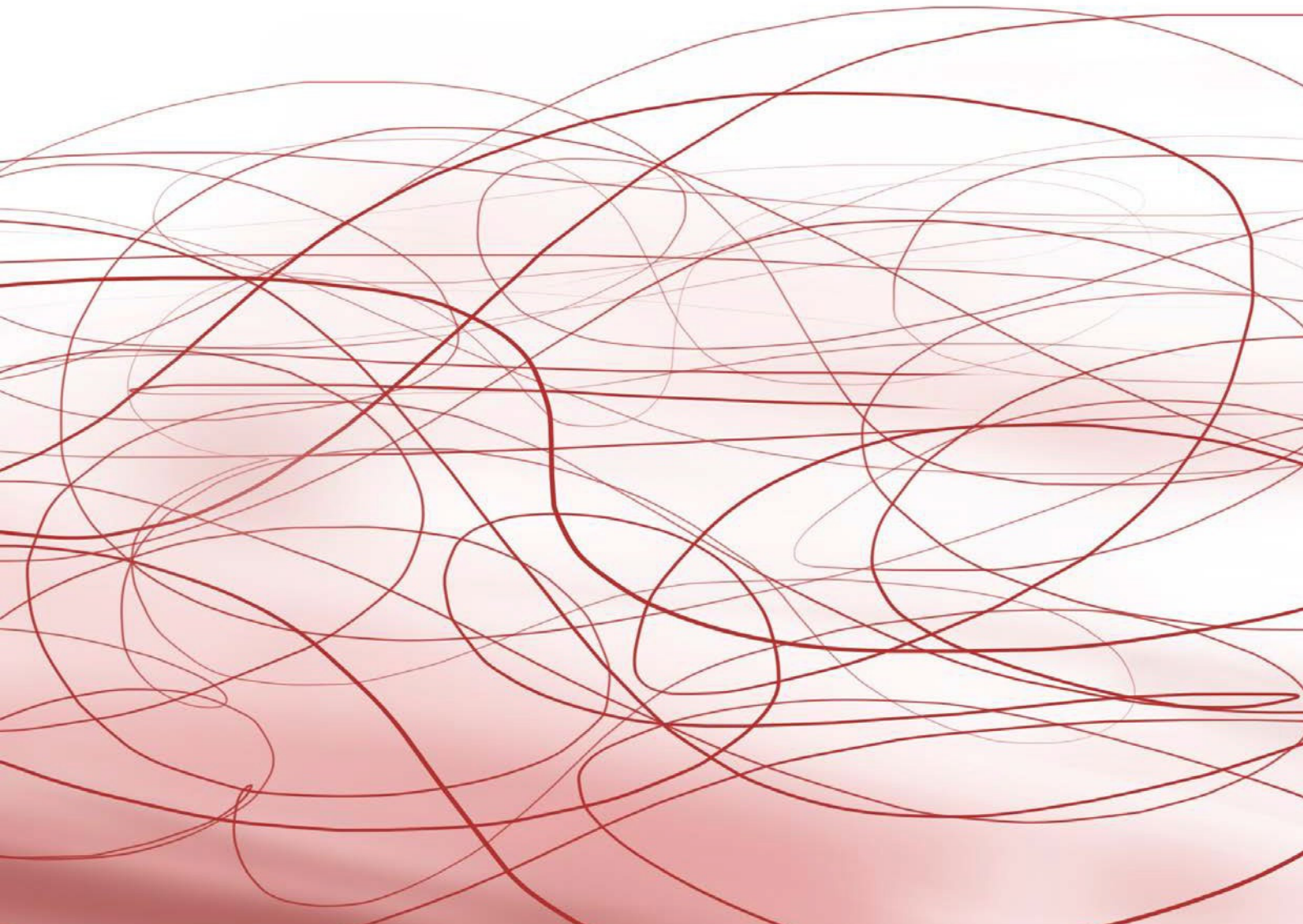
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Driving inclusivity: design needs in autonomous vehicles for people with epilepsy

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Abstract: In this study, the transportation needs of people with epilepsy are considered, specifically in regard to the development of autonomous vehicles. People with epilepsy who are unable to achieve control of their seizures are not typically able to safely operate a motor vehicle, and are unable to be licenced drivers, and it is logical to believe that autonomous vehicles would be a benefit to them. However, the specific needs that people with epilepsy may have with respect to autonomous vehicles have not been examined. In this work, interviews with people with epilepsy and medical professionals involved in the treatment of epilepsy were conducted, with the goal of understanding the ways in which lower levels of autonomy might allow people with epilepsy to safely operate a motor vehicle as well as what design features might be needed in fully autonomous (Level 4 or Level 5, those which do not require human intervention) vehicles. As a result of this work, a roadmap of possible technological innovations and research directions is presented, with the intention of providing solutions to various challenges faced by people with epilepsy in their access to transportation.

Keywords: autonomous vehicles, epilepsy, transportation accessibility, mobility independence, inclusive design

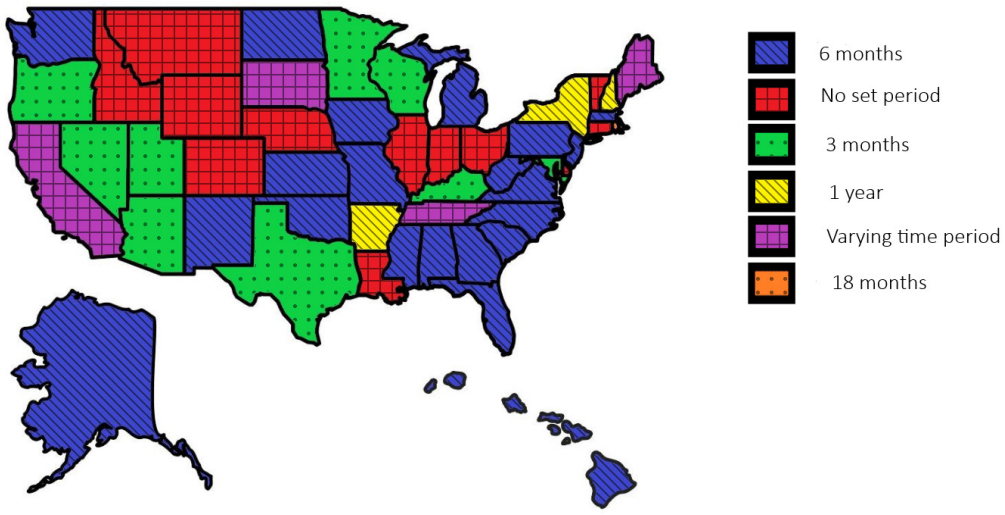
1. Introduction

One of the benefits of developing autonomous vehicles is that they have the potential to expand access to transportation to those who currently are unable to drive. This inability to drive may stem from a number of different causes, including disability status. Many disabilities can impact a person's ability to safely operate a vehicle; in this study, the needs of people with epilepsy are considered. People with epilepsy who are actively having seizures are typically unable to get a driver's licence, and it is acknowledged that they are not able to drive safely due to the risks of a seizure happening while they are driving. There are variations in how long someone must be seizure-free in order to be licenced to drive; data taken from the Epilepsy Foundation website (epilepsy.com/lifestyle/driving-and-transportation/laws) indicates that while some states have no set time period, those that do typically require six months without seizures. Some require as little as three months, while others require a year or more, with Rhode Island as the outlier with a requirement of 18 months. Figure 1 shows the variations in state requirements.

A number of studies have been conducted relative to epilepsy and driving, with the goal of understanding some of the associated risks; some of these studies also included other medical issues as well, as in a study in 1991 where it was found that drivers with either epilepsy or diabetes have an increased risk of traffic accidents (Hansotia & Broste, 1991). Similarly, a study by Hasegawa, Kumagai, and Kaji found that of 72 drivers with epilepsy, 18 of them experienced one

or more automobile accidents (Hasegawa, Kumagai, & Kaji, 1991). Later work conducted in 1996 looked at the risks of accidents for people with epilepsy behind the wheel, and discussed the risk of injury related to policies on how long someone must be seizure free in order to drive (Taylor, Chadwick, & Johnson, 1996). Another study in 1996, conducted in the United Arab Emirates where there were no rules on epilepsy and driving at the time, found that there was a significantly higher risk of property damage for accidents that occurred due to drivers having epileptic seizures (Bener, Murdoch, Achan, Karama, & Sztriha, 1996). Further studies continue to examine the risk of seizure-related accidents, e.g., (Tomson, Beghi, Sundqvist, & Johannessen, 2004), but not all showed the same results; work by Kwon et al. in 2011 found that people with epilepsy were not more likely to have motor vehicle accidents than the general population of drivers (Kwon, et al., 2011). Further work, conducted in 2019, found that of 658 drivers with epilepsy, 19 had seizures while driving, and 16 of those seizures resulted in accidents (Inamasu, Nakatsukasa, & Tomiyasu, 2019).

Figure 1: State Requirements: Seizure-Free Periods to Drive



Note: Map Outline from https://gisgeography.com/wp-content/uploads/2023/12/United-States-Country-Outline.jpg

Work by Sultan and Thomas presented results of a small study, in which eight people with epilepsy or their carers participated in semi-structured focus groups (Sultan & Thomas, 2020). This work, while closely aligned with the study reported in this paper, focused exclusively on the possibility of fully autonomous vehicles. Some of its findings included the devastating impacts of being unable to drive, concerns over the technology, the stigma associated with epilepsy, and the possible improvements in disease management if the concern over driving eligibility were removed. Another recent work by Ziyad and Ziyad specifically focused on the integration of emergency rapid response technology into vehicles to provide a response to epileptic seizures (Ziyad & Ziyad, 2021). This work focused on wearable medical devices that would communicate with a car's control system.

It is noted that the overwhelming majority of the literature on epilepsy and driving has been published in journals related to the medical field, not in the automotive literature. Much of it is descriptive, yielding useful information on the risks of driving for people with epilepsy and the impact of not being able to drive. Some studies, such as the work by Ziyad and Ziyad, propose technological solutions to some of the problems that are identified in other work. However, no comprehensive set of research directions or design concepts has been set forth to provide an agenda for researchers, engineers, and automotive designers.

In addressing this gap, this work is grounded in the broader context of accessibility and inclusive design. The Universal Design principles articulated by Connell et al. (Connell, et al., n.d.) emphasize equitable use, perceptible information, and tolerance for error, offering a structured framework for understanding how autonomous vehicles can support people with diverse abilities, including those with epilepsy. Furthermore, the focus on social participation and equity, as established by Tauke (Tauke, 2019), aligns with the objective of this study, which is to ultimately promote the full inclusion of people with epilepsy in society through ensuring that they have access to reliable transportation. By situating the findings of this study within these established frameworks, this work highlights not only the technical but also the inclusive-design significance of developing autonomous vehicles that expand mobility options for people with epilepsy.

2. Methodology

Data was gathered through semi-structured interviews and focus groups with people with epilepsy and health care professionals involved in the treatment of epilepsy. The study protocol and consent form were approved by the Kettering University Institutional Review Board (IRB). At the beginning of each interview or focus group, participants were asked if they had any questions or concerns about the consent form or the study in general.

For people with epilepsy, the following questions were used to frame the discussion:

- Tell me about how you handle transportation. Are you able to drive, or do you have someone else drive you? Is public transit an option?
- How accessible do you feel transportation is to you? Do you sometimes have to forego going places you want to because of transportation?
- In what ways, specifically, does epilepsy impact your ability to drive or use other forms of transportation?
- What would an ideal transportation solution look like to you?
- (Optional question for parents of children with epilepsy) What concerns do you have about the safety of your child/children with epilepsy in the car?

For health care professionals, the following questions were used to frame the discussion:

- Thinking about your patients with epilepsy, how much of a problem is transportation for them? What challenges do they face due to epilepsy with either driving or public transportation?
- What kinds of transportation solutions would work with the average patient? What would be necessary for the worst case scenario?
- What types of actions should an autonomous vehicle take if someone in it has an epileptic seizure? Are there actions an autonomous vehicle might take that would trigger seizures in some patients?
- If a vehicle was to have a system to detect a driver or passenger who had a seizure, how might this work? What could it detect that would indicate a seizure was taking place?

In discussing levels of autonomy and vehicle capabilities, the framework developed by SAE International was used, in which there are five levels of autonomy, in addition to a “Level 0”, which indicates no autonomy at all. These five levels of autonomy are (SAE International, 2021):

- Level 1: The driver must be constantly supervising the car, but may engage driver support for either steering or speed control.
- Level 2: The driver must be constantly supervising the car, but more than one driver support feature may be used, such as lane centring and adaptive cruise control.
- Level 3: The car can drive itself in some circumstances, but when the driver assistance features request to return control to the driver, the driver must take control.
- Level 4: The car can drive itself and the driver does not need to take control, but the vehicle may have a limited operational domain, outside of which it cannot operate autonomously.
- Level 5: The car can drive itself and the driver does not need to take control, without restrictions on where and when the vehicle can operate autonomously.

The levels of autonomy were familiar to some participants in the study; the health care professionals participating in the study were generally familiar with them, while some of the people with epilepsy were familiar and some were not.

Participants were recruited by the Epilepsy Foundation of Michigan, which publicised the research study to their contacts. The Foundation sent an email invitation to all community members who had reached out in the past two years looking for information or assistance related to transportation. The Foundation also invited members who participated with their Call & Connect groups, placed information on the Foundation website, and posted on social media. The Foundation ensured that all participants received a link to the electronic consent form prior to interviews and focus groups and set up the Zoom sessions. A staff member from the Foundation was present on the Zoom sessions in order to introduce the participants to the researcher, provide technical support if needed, and take notes to supplement the researcher's notes. Participants were placed in a focus group or individual interview based on their individual preference.

A total of 25 people participated in the study. Four were health care professionals, one was a parent of a child with epilepsy, and the remaining 20 were people with epilepsy. The criterion used to determine when sufficient participants had been recruited was saturation, which is a well-accepted criterion for qualitative work (Kielmann, 2012). The population was split almost equally between men and women. Due to the sensitivity of discussing medical issues, the need for respecting participants' privacy, and the specifics of the approved Institutional Review Board (IRB) protocol, detailed demographic data was not collected. Out of the 20 people with epilepsy, two of them currently were able to drive; the remaining participants among those 20 either did not drive, or did not disclose whether they were able to drive. Three of those participants reported that they had their first known seizure while driving, resulting in an accident. The participants came from multiple areas of the state of Michigan, and therefore while the geographic range was relatively small, it covered both urban and rural areas. Given the prevailing climate of the state, difficulties due to the typical weather in different seasons were inherent in the participants' experiences.

Of the 25 participants in the study, seven participated in two different focus groups, with one group of five and one of two, and the remaining 18 opted for individual interviews. Additionally, five participants confirmed attendance but did not attend their scheduled interviews; follow-up to see if they wished to reschedule was handled by the Epilepsy Foundation of Michigan staff.

Interview time slots were scheduled for one hour, although very few interviews took the full hour. Typical interviews lasted between 30 and 45 minutes. Focus groups were scheduled for a time slot of an hour and a half, and took approximately one hour in both cases.

The data was analysed using standard methods for qualitative data analysis. Specifically, techniques of descriptive coding (also known as topic coding) were used to identify the key topics that were brought up in the interviews and focus groups (Saldaña, 2021). Thematic analysis was conducted to identify the key recurring elements in participants' experiences (DeJonckheere, Vaughn, James, & Schondelmeyer, 2024).

3. Results

Analysis of the interview and focus-group data identified several major themes: (1) transportation constraints and vulnerability; (2) impacts of transportation barriers on daily life; (3) perceptions of autonomous and semi-autonomous vehicles; (4) desired features for accessible vehicle design; and (5) expectations and preferences for seizure-response and detection systems. These themes reflect consistent patterns that emerged across participants' accounts and align with established approaches to qualitative descriptive and thematic analysis. In addition to these key themes, participants were interested in the technical question of how seizures could be detected by vehicles, as well as the effects of surgery to prevent seizures; this has been grouped into a section on technical and medical considerations.

3.1. Theme 1: Transportation Constraints and Vulnerability

Participants described substantial limitations in their ability to travel independently, citing barriers across public transit, ride-share services, bicycling, and informal support networks. For most participants, public transit was not always a feasible option due to its availability, schedule, and consistency; however, some participants also reported concerns over how a bus driver or other passengers might react to a seizure. In addition, one health care professional reported that he knew of a case where someone having a seizure had been burned on the electric rail of a commuter train, as well as cases of robbery or sexual assault when someone was unconscious due to a seizure. Another participant reported an unfriendly ride-share driver, possibly due to their epilepsy, as there is a noted stigma attached to the disorder, as reported by the health care professionals in the study and in the literature (Jacoby & Austin, 2007); (Çamcı, Yakar, Oğuz, & Erdoğan, 2025). Other forms of transportation, aside from personal vehicles and public transit, that people with epilepsy reported using are shown in Table 1. It was noted, however, that using Uber alone could be an issue for some people, due to the possibility of having a seizure in the vehicle and the driver not knowing what to do, and that using a bicycle is not necessarily an option during the winter, and could be dangerous for some, due to the nature and frequency of seizures.

Table 1. Forms of Transportation Used Aside from Personal Driving or Public Transportation

Type of Transportation	Frequency
Depend on family or friends	8
Ride-share such as Uber or Lyft	4
Bicycle	3

Taken together, these findings illustrate the ongoing dependence many participants experience on others for essential mobility, and they underscore the importance of transportation accessibility as a prerequisite for participation in employment, education, medical care, and social activities.

3.2. Theme 2: Impacts of Transportation Barriers on Daily Life

Participants with epilepsy reported significant issues with transportation to a variety of places and events, and health care professionals reported seeing the same issues among their patients. One health care professional reported that transportation was the single biggest social problem caused by their patients' epilepsy. Lack of transportation impacted the ability to access medical treatment, maintain stable employment, spend time with family and friends, and participate in ordinary activities of daily living, such as going to the store. The most commonly cited transportation issues concerned employment, followed by medical appointments, shopping, recreation, and social activities with friends. One participant reported being ``medically retired'', in part due to transportation issues; another stated that she would like to join a writers' group, but had no way to get there. Yet another worked as a disk jockey (DJ), and spent much of his income from gigs on transportation; he also was unable to take jobs that came up at the last minute, due to the need to plan transportation in advance. Another participant wanted to attend college, and was concerned both with a residential experience, due to the possibility of having seizures without their existing support structure, and with commuting to school due to the difficulties of transportation. One health care professional also noted that the Epilepsy Foundation has many programmes to provide support for the community, but some members of that community are only able to participate in virtual events due to transportation needs.

These accounts collectively highlight the substantial equity gap created when transportation systems are not designed for users with conditions such as epilepsy, reinforcing the relevance of inclusive-design approaches that emphasize equitable use and flexibility.

3.3. Theme 3: Perceptions of Autonomous and Semi-Autonomous Vehicles

Participants were generally enthusiastic about the idea of autonomous vehicles; however, some had safety concerns and one participant in particular was strongly opposed to autonomous vehicles, feeling that their ability to operate safely is far in the future; this aligned with results seen by Sultan and Thomas (Sultan & Thomas, 2020). The idea of a semi-autonomous vehicle, which would take over from the driver in the event of a medical emergency, was seen as a more immediately attainable option. The safety concerns raised by the participants were typical of those that most people seem to have about autonomous vehicles, including how it would recognize pedestrians, whether it would follow traffic rules, and how it would be tested to ensure safety. Some participants in the study were engineers themselves, and they talked extensively about the design decisions involved in autonomous vehicles, testing protocols, and related issues. Several expressed the wish to participate in future work that might result in vehicles that would be appropriate for people with epilepsy. These responses point to a complex intersection of trust, perceived risk, and desired control, elements that are central to accessibility-focused human-autonomy teaming and inclusive technology adoption.

3.4. Theme 4: Desired Features for Accessible Vehicle Design

When participants were asked what their ideal transportation scenario would look like, several issues were raised, beginning with the cost of transportation. Even when options like Uber and

Lyft were feasible in other ways, the cost could at times be prohibitive, particularly given challenges maintaining stable employment. Participants emphasized features consistent with Universal Design principles, such as perceptible information, flexibility in use, and low physical or cognitive effort.

Most participants would find a shared vehicle to be an acceptable option, but one did specifically say that they wanted to own their own vehicle, with whatever level of autonomy would allow them to operate it independently. This might be connected to another concern, that of the hours of availability. Participants felt that something that was available with a reasonably short notice over a wide range of hours, including outside of business hours, was essential. The ability to interact with a vehicle via app or by calling for it from a home phone was also desirable. Other concerns included carseats, for those with children, and the ability to safely accommodate dogs, including service dogs. The ability to have the vehicle monitored by a dispatcher, as with some autonomous vehicles currently being tested was discussed; one such example is Waymo (Cummings, Li, Seth, & Seong, 2021). This was seen as a positive feature by some people, particularly if they were to have a seizure in the vehicle. Some of the other issues that were raised in regard to ideal transportation solutions were a secure place to keep medication, addressing sensitivity to noise, and the ability to block flashing lights for someone with photo-sensitive epilepsy. It was also noted that stress may trigger seizures in some people, and therefore having a level of trust in the vehicle is crucial.

In their interactions with a vehicle, participants generally felt that some kind of a display similar to those that now exist would be desirable. In most cases, they wanted a touch-screen interface, although some people would prefer a voice-activated system. It was also felt that communications should be customisable, depending on individual preferences for type and frequency of communications. These desired features reflect common inclusive-design considerations related to sensory accessibility, cognitive load, and compatibility with diverse user needs.

3.5. Theme 5: Vehicle Actions in the Event of a Seizure

There were extensive discussions on what a vehicle - whether fully autonomous or with the limited autonomy of taking control in an emergency - should do if a seizure occurred in the vehicle. Some participants had definite opinions on what should happen, while others could foresee different scenarios where different actions might be desirable; in some cases, participants thought a hierarchy of actions might be best, depending on factors such as how long a seizure was going on. This aligns with the views reported by Sultan and Thomas, wherein it was stated that "Participants could not agree on whether they would like the car to continue its journey or come to a safe stop in the event of the seizure." (Sultan & Thomas, 2020) The various actions mentioned by participants in this study are shown in Table 2; due to these different scenarios, the total number of responses is greater than the number of participants.

The most frequent action desired was to pull over and summon medical assistance; however, some participants definitely did not want this, unless a seizure was unusual in some way. There was also a debate over the desirability of locking doors; the discussion centred on whether that was more likely to keep a person safe, in the event that they were disoriented by the seizure and attempted to leave the vehicle and walk away, or whether it would be a hazard since it would prevent emergency personnel from reaching the person. The consensus was that some form of a profile should be created, which the vehicle would have access to, and which would contain critical information for that particular person. This aligns with the accessibility-driven approach

of emphasizing flexible, adaptable design that allows the system to match user needs, rather than imposing a one-size-fits-all architecture.

Table 2. Desired Vehicle Actions in the Event of a Seizure

Vehicle Action	Frequency
Pull over to the side of the road	18
Call a doctor, hospital, or EMTs	8
Call a designated friend or family member	7
Just wait for the seizure to end	3
It depends on the seizure type	3
Lock the vehicle doors	2

3.6. Technical and Medical Considerations: Seizure Detection and Effects of Surgery

Another topic of discussion was the question of how a vehicle could detect that a seizure was taking place. This presents a number of challenges, given the range of different types of seizures that could occur. Some of the ideas that were suggested included some form of helmet or device in the car's headrest that could detect brain wave activity and thereby send a signal to the car, devices to check a person's heart rate and pulse, or devices to detect violent muscle contractions or unexpected actions such as sudden braking or acceleration commands. There were also extensive discussions on the range of medical devices such as various types of vagus nerve stimulation devices (VNS) and responsive neurostimulation systems (RNS). One specific implantable device, the NeuroPace system, was mentioned (Kumar, Jandial, & Levy, 2025). Wearable devices to warn of seizures were also called out, with Empatica specifically being mentioned (Rukasha, Woolley, & Collins, 2020). There were many suggestions for ways to interface these devices with a vehicle, with the natural concern that privacy could be an issue and that HIPAA regulations could be a complication. Overall, participants enthusiastically offered ideas for how various types of seizures might be detected. In the case of people with epilepsy, these were generally based on their own personal experiences; health care professionals considered the question more broadly, as they saw a wide range of different types of seizures. These ideas reflect an intuitive recognition of the need for multimodal detection systems grounded in perceptible information and tolerance-for-error principles, critical to ensuring safety without overburdening the user.

An additional topic that emerged was the impact of surgery, which can stop seizures in some people, on the ability to drive safely. One person with epilepsy reported that after having surgery to stop their seizures, they experienced slowed reactions and some forms of cognitive issues, which impacted driving. Furthermore, one of the health care professionals mentioned that in some cases, if a person has surgery to stop seizures, their visual field of view is impacted, which makes it difficult or impossible to drive safely due to the inability to see enough of the surrounding environment. These findings suggest that autonomous and semi-autonomous vehicles may support not only those with active seizures but also individuals with postoperative impairments, expanding the scope of accessibility considerations in vehicle design.

4. Discussion

The results of this study highlight several interconnected challenges faced by people with epilepsy in accessing transportation. These challenges add to the existing literature on epilepsy and transportation. Prior work has discussed both real and perceived risks that can arise from people with epilepsy driving vehicles, as well as the impact of transportation limitations on quality of life (Hansotia & Broste, 1991; Hasegawa, Kumagai, & Kaji, 1991; Inamasu, Nakatsukasa, & Tomiyasu, 2019). The findings of this study reinforce those observations, but also provide additional insight into the cumulative impact of limited transportation access, including employment barriers, reduced independence, and difficulty participating in ordinary activities.

The experiences reported by participants also align with previous research on stigma and safety concerns beyond those of a possible vehicle accident. As seen in earlier work (Çamcı, Yakar, Oğuz, & Erdoğan, 2025; Jacoby & Austin, 2007), stigma associated with epilepsy continues to impact people's interactions with others, including transportation providers, and contributes to feelings of vulnerability in transportation as well as other settings, and is reflected in broader discussions of inclusive design (Tauke, 2019). The perspectives from health care professionals further affirm that transportation is a central life issue for people with epilepsy.

In discussing autonomous and semi-autonomous vehicles, participants expressed a range of views similar to those identified by Sultan and Thomas (Sultan & Thomas, 2020), including optimism about future benefits and hesitation regarding safety, technological reliability, and trust. However, this study adds further insight by showing how participants conceptualize autonomy through the lens of their own seizure types, support networks, medical histories, and comfort with technology. The emphasis on personalized action plans, flexible system behaviours, and multimodal detection reflects a more detailed set of expectations than what has been previously reported. These concerns enrich the discussion of human-autonomy teaming and system behaviour that is found in other areas of the autonomous vehicle literature (Cummings, Li, Seth, & Seong, 2021; Mai, Daveron, Julius, & Mishra, 2025), and align with accessibility-focused autonomous vehicle work showing how different populations think about trust and usability (Brinkley, Posadas, Woodward, & Gilbert, 2017).

These findings also connect directly to broader principles of accessibility and inclusive design, particularly Universal Design. Participants' desires for customisable communication, reduced sensory overload, safe emergency protocols, and flexible interaction modes align closely with principles such as perceptible information, flexibility in use, and tolerance for error. This connection suggests that autonomous vehicle development should not treat accessibility as an accommodation added late in the process but rather as a foundational design criterion.

The discussions surrounding seizure detection highlight an emerging and relatively under-addressed area in the literature. While prior work (Ziyad & Ziyad, 2021) has explored IoT-based seizure response systems, participants in this study went beyond existing proposals by envisioning multimodal, individualized detection frameworks integrated directly into vehicles and interoperable with medical devices, personal preferences, and privacy requirements. This also intersects with research on implantable devices such as the NeuroPace RNS (Kumar, Jandial, & Levy, 2025), which was mentioned by several participants. Their suggestions point toward future

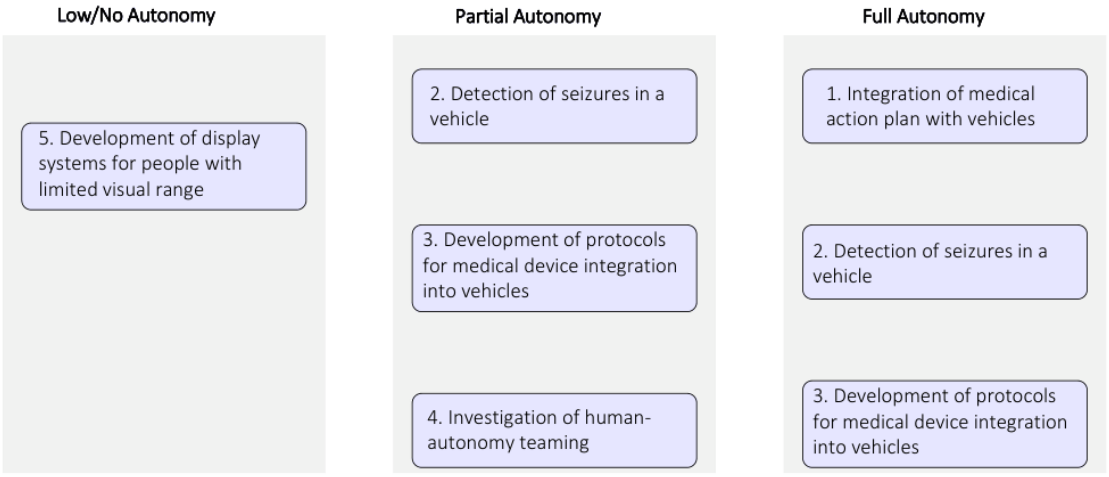
research on technical feasibility, safety thresholds, false-positive and false-negative tolerances, and regulatory considerations.

Finally, this study contributes new insight into how factors such as postoperative visual limitations or cognitive aftereffects influence driving ability and may create additional accessibility needs beyond seizure control alone. This expands the conversation about epilepsy and driving to include those whose seizures are medically managed but who still face significant barriers to safe vehicle operation. The results of this study, therefore, point to the urgent need to pursue a technical research agenda that centers the human experience, respects the varying needs of people with epilepsy, and focuses on both long-range and short-range research and development projects that can improve lives. Such an agenda is set forth in the Roadmap of Future Work, in the hopes that it will serve as a call to action to researchers working on the development of autonomous vehicles.

5. Roadmap of Future Work

The primary purpose of this study was not to itself advance autonomous vehicle technology, but to identify research and development challenges that could lead to vehicles that could provide mobility to people with epilepsy. Based on the results of the study, several avenues for future research are set forth here. The basic areas covered in this roadmap are shown in Figure 2. Each of the five areas is categorised by whether it applies to full autonomy, partial autonomy, or low/no autonomy. In addition, all areas of the roadmap should incorporate safety and system vulnerability; a full discussion of these issues is beyond the scope of this paper, but should be the subject of extensive future work.

Figure 2: Conceptual Framework: Research Roadmap by Level of Vehicle Autonomy



5.1. Integration of Medical Action Plan with Vehicles

The actions that vehicles should take when a driver or passenger has an epileptic seizure vary depending on the person and the circumstances. Therefore, one promising avenue for development is the creation of a vehicle system that would incorporate a medical action plan. Such a system would need to include input to determine whether a seizure was taking place, incorporate data to determine whether it was a ``typical" seizure for the person or not, and implement a hierarchy of actions based on the medical action plan. This plan could include escalation based on the length of the seizure, and have contingencies based on the inability to

reach primary contacts. Such a system could be expanded beyond the scope of people with epilepsy to include a variety of other medical conditions or disorders. The plan could also evolve or vary as vehicles gain increasing levels of autonomy.

5.2. Detection of Seizures in the Vehicle

In order to trigger a vehicle to take over from a driver and/or to execute a medical action plan, the vehicle must be able to reliably detect seizures. One key question to ask in this overall area of research is the proper balance between false positives and false negatives. Given the relative consequences, reducing false negatives at the expense of accepting more false positives is likely to be desirable. In this case, the vehicle could prompt the person to respond; if they did not respond, or indicated that there was a seizure occurring, then the vehicle could take appropriate action.

One key question that arises is the amount of time required in order to determine that a seizure is taking place. If the time period between a seizure's start and its detection is too long, an accident may have already occurred, particularly if the seizure involves sudden jerking movements that cause unexpected hard braking or high acceleration. The specific conditions in which such a system might be safe and feasible need to be investigated, in order to determine the operational design domain of a vehicle designed to operate safely when a driver has a seizure.

5.3. Development of Protocols for Medical Device Integration

Many discussions of seizure detection included existing medical devices used by some people with epilepsy. This also aligns with the work reported by Ziyad and Ziyad, which made use of these devices (Ziyad & Ziyad, 2021). Therefore, one promising avenue for development would be the creation of standard software protocols for communication between medical devices and vehicles. Such a protocol would need to implement robust cybersecurity that would also be HIPAA-compliant. Standards would need to be developed and adopted, and given the global reach of both the medical device and automotive industries, these standards would need to be agreed upon by multiple international organizations. Therefore, while there is a definite technical component to this work, it will also involve multiple standard-setting organizations and has public policy implications that must be considered.

5.4. Investigation of Human-Autonomy Teaming

If a vehicle is being actively driven by a human and needs to take over in the event of a medical incident, this takeover should be done in such a way that it does not produce dangerous or abrupt behaviour. Furthermore, if there is a false positive and the vehicle begins to take over when it should not, the conflict between the human driver and the autonomous system should be such that it does not cause the vehicle to take actions that would be hazardous. There are already efforts to study human-autonomy teaming, some involving vehicle steering such as work by Mai (Mai, Daveron, Julius, & Mishra, 2025); there is also literature on human-autonomy teaming in a wide variety of other environments, including collaborative robots (Vincentini, 2021) and in the field of psychology (Lappi & Mole, 2018); (Lyons, Sycara, Lew, & Capiola, 2021).

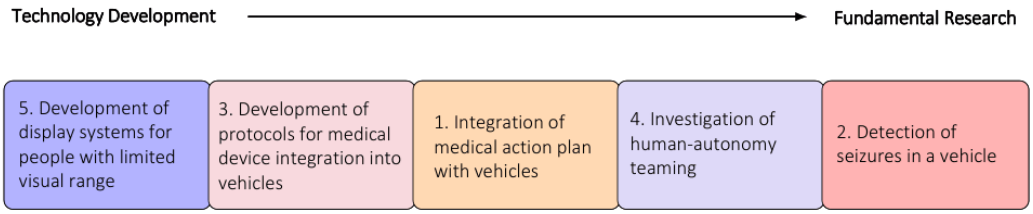
5.5. Development of Display Systems for Limited Visual Range

The potential for autonomous vehicles to benefit people with blindness or limited vision is well known (Brinkley, Posadas, Woodward, & Gilbert, 2017). The situation for people who have had

surgery to stop seizure activity, however, is slightly different from typical cases of blindness, as the person in question may have normal vision within a range. In particular, a system incorporating multiple cameras and a suitable display on the dashboard may provide sufficient information for a person to be able to safely drive using that display. The design of such a system is much more an issue of development than of research, as a wide variety of cameras and displays are readily available. However, researchers in human-machine interaction or cognitive psychology may find that there is significant scope for research projects.

These five areas vary in their level of technology readiness, with some being primarily development projects and others requiring more fundamental research, as shown in Figure 3.

Figure 3: Continuum of Research Needs: From Technology Development to Fundamental Research



6. Conclusions

The work conducted in this study has identified a number of ways in which vehicles can be designed in order to better accommodate people with epilepsy, who typically experience significant challenges with transportation. Future work can and should be done, in order to gather more data on these challenges and their solutions, and to refine the roadmap. This work can include additional interviews and focus groups as well as surveys focusing on specific options and their benefits.

It is noted that the challenges of mobility for people with epilepsy are not purely technical; there are also issues of public policy, economics, insurance, and legal aspects that need to be considered. Such considerations are beyond the scope of this specific paper, but should also be pursued as part of future work. Finally, future work should include development of these and other technologies which would provide options for people with epilepsy, in order for them to fully participate in work, education, social activities, and other activities of daily life that are currently challenging to access.

The broader significance of this research is that it begins to articulate a design agenda for autonomous vehicles that responds directly to the lived experiences of people with epilepsy and supports their full participation in mobility systems. As autonomous vehicle technologies continue to evolve, grounding their development in inclusive design principles will be essential to ensuring that the resulting systems expand, rather than limit, equitable access to transportation. Furthermore, in addition to addressing the specific transportation barriers faced by people with epilepsy, this work reinforces the importance of approaching autonomous vehicle development through the lens of accessibility and inclusive design, highlighting how such a framework can guide engineers, policymakers, and researchers toward solutions that are not only technologically feasible but also inherently more inclusive. Such an approach can and should be used to consider a wide variety of other accessibility needs that people may have.

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Statement on the Use of AI in the Writing Process. In this paper, AI tools were used for final editing and refinement; specifically, they were used to identify issues with inconsistent wording and unclear statements, and to detect differences between UK and US spellings of various words. In the case of unclear statements, the AI tool suggested new language, which was then edited heavily before being incorporated into the manuscript.

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Proposal for a definition of Universal Digital Accessibility - UDA

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Abstract: The main objective is to establish a conceptual definition of Universal Digital Accessibility (UDA), based on legislation, standards, and specialised literature. The concept of accessibility, originally associated with geography and urban transport, later developed its own theoretical framework within linguistics, and has recently become widely associated with urban mobility. This study takes a qualitative approach, based on a theoretical and normative review, The methodological process was structured in four stages: 1) literature review and analysis; 2) analysis of legislation and standards; 3) structuring and transposition of concepts; 4) Relationship of digital accessibility and artificial intelligence. This study was built on established references in physical accessibility – including standards, legislation, indicators, and foundational concepts, as well as the principles of universal design – integrating them with content related to digital accessibility. Although the term "digital accessibility" already has definitions in certain fields, the innovative contribution of this research lies in the development of a new definition grounded in the convergence of these references. The proposed definition seeks to expand the understanding of digital accessibility beyond websites and online platforms, incorporating multiple perspectives and contexts of application.

Keywords: digital accessibility, universal digital accessibility, definition development, theoretical definition, conceptual definition.

1. Introduction

Accessibility has been widely discussed in several areas of knowledge, such as linguistics, transportation, and urban mobility, and is also one of the main components of Universal Design (Ariel, 1988 and 1990; Hansen, 1959; Koenig, 1974 and 1980; Morris, Dumble & Wigan, 1979; Handy, 2020). In matters of physical accessibility, adapting spaces for people with disabilities has traditionally been advocated (ABNT, 2020). However, the concept of Universal Design, created by Ronald Mace in 1987, proposes a more comprehensive view; from projects to environments, products and services, all must be designed inclusively, catering to everyone, regardless of age, weight, height, motor skills or disabilities (Mace, Hardie & Place, 1991).

In the digital field, debates on the matter of accessibility gained strength with the emergence of concepts and technologies from different decades. Terms such as Artificial Intelligence (AI), first mentioned in the 1950s, and Information and Communication Technologies (ICT), which became popular in the 1980s, became part of the technical vocabulary related to digital inclusion (Brazil, 2024). In the 1990s, the creation of the World Wide Web Consortium (W3C) by Tim Berners-Lee

brought important regulatory milestones, including the Web Content Accessibility Guidelines (WCAG), now in version 2.2, which continue to guide digital accessibility today, particularly regarding websites (W3C, 2025).

Within this context and considering the WCAG, web/digital accessibility often remains restricted to the web environment, focusing on the barriers faced by people with visual, hearing and motor impairments. This delimitation, although fundamental, does not fully cover the various dimensions that impact different audiences' access to digital resources.

This research is justified by the growing relevance of accessibility in multidisciplinary contexts and by the absence, to date, of a consolidated and broad definition of Universal Digital Accessibility, capable of integrating physical accessibility, universal design, and digital technology. The concepts of digital accessibility and universal design share significant similarities; however, certain key aspects are not incorporated into these concepts, such as consideration of physical, digital, linguistic, and communicational dimensions, as well as human diversity and attitudinal, cultural, and informational barriers, ensuring the full and equal promotion, participation and interaction of all people, regardless of their physical, mental, or cognitive characteristics. For this purpose, the world's most significant legislation and standards were taken into account, selected for their historical and political relevance: the United States, for its pioneering role in discussions about accessibility and its global influence; the United Kingdom, for the creation of the W3C and WCAG; and Brazil, for its specific legislative context and because it is the researchers' country of origin, where the research can be applied and initially tested.

The main question guiding this research is: What is the proposed definition of Universal Digital Accessibility (UDA), considering the concepts of renowned authors and the main legislation and standards existing worldwide in this area?

In this way, the core objective was to structure a new definition of UDA, bringing together digital and physical accessibility concepts. The specific objectives were: a) to review the work of well-known authors on the subject; b) to analyse pertinent national and international legislation; c) to examine related technical standards; d) to integrate these elements, formulating a definition for Universal Digital Accessibility (UDA); e) to understand the pros and cons of the relationship between digital accessibility and artificial intelligence.

Considering that there is a gap in the existing literature, and although there are definitions of digital accessibility (Kravchenko et al., 2022; Brazil, 2023), as well as web accessibility (W3C, 2025a), these concepts are largely related only to the digital environment of websites and portals designed specifically for people with disabilities or aimed at the use of government content and services by Brazilians. However, in order to ensure universal digital accessibility, adaptations and measures are first needed in the physical environment.

This article is organised into the following sections: Section 2.0 - Literature review, including accessibility and universal design foundations; Section 3.0 - Methodology; Section 4.0 - Results; Section 5.0 – Discussion; Section 6.0 - Conclusions; Section 7.0 - R eferences and Section 8.0 - Appendices.

2. Theoretical Reference

This theoretical reference covers the areas of universal design, accessibility, technology, and digital accessibility. The Universal Declaration of Human Rights (2025) states in Article 1 'All human beings are born free and equal in dignity and rights'. Article 2 states that it applies to

everyone regardless of genetic or social characteristics, and Article 7 states that 'All are equal before the law and are entitled without any discrimination to equal protection of the law'.

Throughout history, there have been several attempts to define a 'standard man' or 'standard measurements' such as: a) Leonardo d a Vinci's Vitruvian Man, 1490; b) Ernst Neufert's 'Architects' Data', published in 1936, an encyclopaedia of standard measurements related to the body of this so-called 'standard man'; c) Le Corbusier's Modulor, 1948 (Cambiaghi, 2007). Nowadays, we are dealing with exactly the opposite issue: there is no such thing as a 'standard man', and projects, whether environmental or product-related, must account for diverse user groups, making them more inclusive and accessible.

In 1961, in Sweden, nations such as Japan, the United States, and European countries gathered at an international conference with the aim of reducing architectural barriers for people with disabilities (Cambiaghi, 2007). Two years later, barrier-free design was created in Washington, with a commission focused on enabling architectural, urban and equipment designs suitable for people with disabilities or reduced mobility (Cambiaghi, 2007). The concept of barrier-free design evolved into universal design in the US, with the aim of accommodating everyone.

The Centre for Universal Design at the University of North Carolina's School of Design, in the United States, established by Ronald Mace in 1989, defined universal design as: 'The design of products, environments, buildings, and external areas, to be used by all people, to the greatest extent possible, without the need for adaptation or specialised design, in other words, it must have greatest possible extent of usability ' (Mace, Hardie & Place, 1991; Centre for Universal Design; Cambiaghi, 2007).

The same Centre also established the seven principles of universal design: equitable use, flexibility in use, simple and intuitive use, perceptible information, tolerance for error, low physical effort, and size and space for approach and usable design for all (Mace, Hardie & Place, 1991; Centre for Universal Design, 2025; Cambiaghi, 2007; ABNT, 2020): 1) Equitable use - same means for all users, without segregating or stigmatising, promoting privacy, safety, comfort, and protection, and providing an attractive environment for all users. 2) Flexibility in use - choice of methods of use, ease of access and use with both hands, facilitating accuracy, precision, and adaptability to the user's pace, considering their reaction times to stimuli. 3) Simple and intuitive use - eliminate complexities, be consistent with users expectations and intuition, make the design easy to understand, adapt to the user's reading ability and skills, and provide information in order of importance. 4) Perceptible information - the design/project effectively communicates the necessary information to the user, regardless of environmental conditions or the user's sensory abilities. Effective communication through different modes (pictorial, tactile, and verbal); clarity of information and instructions, with adequate contrast in the use of space, equipment and elements; increasing the readability of information, so that it can be understood by people with visual or hearing impairments, people who are illiterate, and others; compatibility with a variety of techniques or devices used by people with sensorial limitations. 5) Tolerance for error - the design/project mitigates risks and the undesirable consequences of accidental or unintentional actions. In the first instance, by grouping, isolating and eliminating these elements, with the most frequently used and accessible elements being retained, dangerous elements being eliminated, isolated or protected, and warnings of potential dangers and errors being provided; in the second instance, by minimising errors and focusing more on tasks that require vigilance. 6) Low physical effort - the design/project can be used efficiently and comfortably, with users in a neutral body posture, minimising physical effort and repetitive actions. 7) Size and space for approach and usable design for all - adequate size and space are provided for approach, reach, manipulation,

and use, regardless of the user's body size, posture, or mobility. A clear line of sight to essential elements is provided, together with adequate reach to all components, for any user sitting or standing; variations in hand and wrist size are accommodated; and adequate space is provided for the use of personal assistance or assistive devices.

Universal design focuses on human diversity in the fields of architecture and design, aiming to serve everyone with better ergonomics and considering physical characteristics, abilities, and age groups. It is used in buildings, indoor and outdoor environments, products, software, and services in such a way that they do not require adaptation or specialised design, as they are already designed to be accessible and may include assistive technology features (ABNT, 2020). Terms such as design for all, design for diversity, inclusive architecture, and barrier-free architecture are commonly used to refer to approaches related to universal design, which creates environments that are understandable and usable by most people, rather than only by specific groups within the population, applying this concept across all areas of life: housing, education, work, recreation, transport, etc. (Cambiaghi, 2007). These include elements and solutions that contribute to accessibility in the design of spaces, artefacts, and products, serving people with different anthropometric and sensory characteristics (Brazil, 2004).

Accessibility is integrated to universal design, in other words, it is one of the aspects of universal design (Cambiaghi, 2007; Centre for Universal Design, 2025; ABNT, 2020). The term ‘accessibility’ derives from the Latin word ‘accessibilitas’, meaning: ‘quality of what is accessible, of what one has access to’, or even referring to the properties of a material that enable the social inclusion of people with disabilities, as well as that of any human being, allowing them to see it, use it and comprehend it (Dicio, 2025). The word accessibility also derives from the term accessible, from the Latin ‘accessibile’: that which can be attained, achieved, obtained, or possessed; intelligible, comprehensible, modest, moderate, reasonable (Brazil, 2007).

Accessibility was commonly described as the distance between human activities, considering the spatial separation between them; it also meant reaching a specific activity from a given location via a public transport system (Morris, Dumble & Wigan, 1979).

The term has already been used in linguistic theory, specifically Accessibility Theory, developed by the linguist Mira Ariel, which investigates how speakers choose different expressions to refer to entities in discourse, linking cognitive psychology with linguistic pragmatics to explain sentence structure and the fluency of human communication (Ariel, 1988 and 1990).

Different levels of accessibility are found on the scale of referential expressions in linguistics; for example, low accessibility is characterised by definite descriptions and proper nouns; medium accessibility by demonstrative pronouns; and high accessibility by pronouns and zero anaphora (where the subject is omitted but can be understood from the context) (Ariel, 1988 and 1990).

Ariel (1988; 1990) also identifies three universal principles of decoding: informativeness, rigidity, and attenuation. The referent is considered to be a mental representation stored in the recipient’s memory during an interaction. Informativeness refers to the richer information retrieved from less accessible referents; rigidity refers to the more rigid forms used for referents with low accessibility; attenuation would be the duality between longer forms associated with less accessible referents and shorter forms associated with high accessibility.

Accessibility has been defined by established authors in the field of urban transport and urban mobility and, currently, there are regulations that define its guidelines for the physical environment in most of the world, including: Brazilian standard NBR 9050 (ABNT, 2020), the American with Disabilities Act - ADA (2025), the principles of universal design (Mace, Hardie &

Place, 1991) from the USA, and the Web Content Accessibility Guidelines - WCAG developed by the World Wide Web Consortium - W3C, from the United Kingdom. The term accessibility also has its origins in transport literature, and researchers believed a few years ago, it was both a land-use function and function of transport system performance function (Batabyal, 2016).

Considering a timeline of developments in accessibility: 1959, Hansen defined accessibility as the potential for interaction opportunities, introducing the idea of measuring accessibility (Hansen, 1959). In the 1960s and 1970s, European countries, including Germany, the United Kingdom, and Sweden, as well as the United States, Canada, and Japan began to discuss accessibility and architectural barriers for people with disabilities, and, in 1974, the United Nations established a group of experts in barrier-free design (Cambiaghi, 2007).

Koenig created the 'Economic Theory of Urban Accessibility' (Koenig, 1974 and 1980). The 1980s were marked by Ronald Mace's pioneering work in developing the concept of universal design, as well as the establishment of his Centre for Universal Design at North Carolina State University. However, Mace, Hardie and Place published their work on the concept of Universal Design in 1991 (Mace, Hardie & Place, 1991). The first version of the NBR 9050 was also published in the 1980s (ABNT, 2020).

The Americans with Disabilities Act (ADA) was enacted in 1990 by the United States Department of Justice (DOJ), which is responsible for enforcing and administering this legislation (DGS, 2025). Also in the 1990s, the International Organization for Standardization (ISO) created standards established technical committees to provide technical assistance on the subject, in 2021, the International Organisation for Standardisation (ISO) published ISO 21542:2021(E) on accessibility and usability of the built environment (ISO, 2021). The Pan American Standards Commission (COPANT) approved the first accessibility standards (Cambiaghi, 2007; COPANT, 2025). The first version (1.0) of the WCAG (Web Content Accessibility Guidelines), developed by the W3C, was published in 1999 and focused on making websites more accessible to people with disabilities (W3C, 2025c).

In Brazil, the main technical standard concerning accessibility, in addition to other legislation on a national, state, and municipal level - is the NBR 9050/2020, published by the Brazilian Association of Technical Standards (ABNT). This norm 'establishes technical criteria and parameters to be observed in the design, construction, installation and adaptation of urban and rural environments and buildings, in terms of accessibility conditions' (ABNT, 2020, p. 1).

The concept of accessibility according to standard is the possibility and condition of reaching, perceiving and understanding, for the safe and autonomous use of spaces, furniture, urban equipment, buildings, transport, information and communication, including their systems and technologies, as well as other services and facilities open to the public, for public or private use, for collective use, both in urban and rural areas, by people with disabilities or reduced mobility (ABNT, 2020, p.2).

NBR 9050 (ABNT, 2020) is comparable to the set of United States legislation comprising the Architectural Barriers Act (ABA), the Americans with Disabilities Act (ADA), and the Uniform Federal Accessibility Standards (UFAS).

The first is the oldest and addresses architectural barriers in federal buildings; the second is the principal accessibility-related civil rights law in the United States, which expanded the scope of accessibility beyond the federal government to areas such as employment, public services, state and local government, commerce, private spaces open to the public, and telecommunications, as well as, more recently, digital accessibility requirements incorporating the WCAG; the third is not

a law, but rather a technical standard concerning architectural measurements and specifications related to circulation spaces, sanitary facilities, and signage.

In Europe, some legislation and regulations are important in these areas, such as EN 301 549, Directive (EU) 2016/2102, and Directive (EU) 2019/882. EN 301 549 is the main technical reference for digital accessibility; Directive (EU) 2016/2102 is a legal obligation regarding digital accessibility in the public sector; and Directive (EU) 2019/882 extends digital accessibility to products and services available on the European market.

According to Sassaki (2009), accessibility is divided into six dimensions: architectural, communicational, methodological, instrumental, programmatic, and attitudinal.

The terminology 'spatial accessibility' refers to the user's ability to understand the function, organisation, and spatial relationships of an environment, participating in the activities carried out there safely, comfortably and independently (Dischinger, Bins Ely & Piardi, 2012). Spatial accessibility is divided into four categories: spatial orientation, communication, displacement, and usage.

Considering accessibility in the field of technology, we must first define the term 'technology', which relates to procedures and methods derived from technical and scientific knowledge and involves processes, techniques, procedures, methods and rules applied to various areas of human knowledge, such as industry, commerce, art, education, among others (Priberam, Michaelis & Dicio, 2025).

Technology has not always been linked to the digital world or to electronics. Since the dawn of mankind, humans have developed methods, techniques and procedures involving objects, in the past, they were not bound to electronics, computing or digital technology. Some examples include: the wheel, hand tools such as hammers, saws, pliers, ploughs, as well as windmills, watermills, sundials, wood-burning stoves, telegraphs, hand looms and Gutenberg's printing press (Basalla, 1988). Thus, the definition of the word 'digital' is complex even for dictionaries, as it includes concepts that may be unfamiliar, and so we will use the more accessible definition of 'digitise', which considers the conversion of analogue data into digital systems, where processing takes place using devices that are usually computers, whereas non-digital aspects are not related to electronic circuits, computers or digital systems (Brazilian Ministry of Education, 2005).

Section 508 was considered relevant to this research due to its relationship with information technology and digital accessibility. This United States legislation is comparable to Brazilian digital government legislation, as both establish accessibility requirements for websites at the federal-level. However, the United States government ([n.d.]) explains that Section 508 is not limited exclusively to federal websites, although it does not apply to private-sector websites.

The WCAG, previously mentioned, aims to provide a single standard for the digital accessibility of web content (websites and web-based tools) that meets the needs of individuals, organisations, and governments internationally, making the web environment more accessible (W3C, 2025c). It consists of 13 guidelines, organised into four principles: perceivable, operable, understandable, and robust, and accessibility is evaluated at three levels: A (low), AA (medium), and AAA (high) (W3C, 2025c).

Among the definitions of digital and web accessibility, the following can be identified: web accessibility allows all people with or without disabilities, older people with 'temporary disabilities', with 'situational limitations', as well as those who have slow internet connections or limited and/or expensive bandwidth, and those who live in rural areas or emerging countries, can perceive, understand, navigate, interact, and contribute to the web, i.e., websites, tools, and

technologies that are developed with inclusion in mind (W3C, 2025a). 'The Web is fundamentally designed to work for all people, whatever their hardware, software, language, location, or ability' (W3C, 2025a).

For Kravchenko et al. (2022), digital accessibility enables access to digital infrastructure, as well the computerisation of public institutions and services in accordance with current regulations and legislation. For Brazil (2023), digital accessibility means eliminating barriers on the web, in other words, websites and portals must be designed in such a way that everyone can access, understand, navigate, and interact effectively with web pages. This definition is part of Brazil's digital government initiative, whose goal is to ensure access, comprehension, and control when navigating government content and services.

3. Methodology

This study takes a qualitative approach, based on a theoretical and normative review, aiming to build a robust conceptual definition of universal digital accessibility. The methodological process was structured in three stages: 1) literature review and analysis; 2) analysis of legislation and standards; 3) analytical and comparative conceptual synthesis; and 4) analysis of the relationship between digital accessibility and artificial intelligence.

The selected sources are justified as follows: dictionaries clarify the general meaning of the term; legislation establishes its legal and institutional meaning; standards demonstrate technical and operational requirements; and academic literature emphasises its scientific conceptualisation.

3.1. Review and analysis of academic literature

Concepts from relevant authors with significant historical contributions in the areas of universal design, accessibility theory, accessibility, urban accessibility, universal design, and digital and web accessibility were used. This stage consisted of an analysis of definitions and concepts of accessibility in a variety of fields, such as linguistics, transport and mobility, Table 1, Appendix A.

3.2. Analysis of legislation and technical standards

Brazilian and international legislation was consulted, including technical standards published by renowned bodies, such as the Americans with Disabilities Act (ADA), and Section 508, in addition to Brazilian documents such as the Brazilian Inclusion Law (LBI) and standards from the Brazilian Association of Technical Standards (ABNT). International guidelines were also included, such as the WCAG, developed by the W3C. At this stage, Brazilian legislation on 'accessibility' and 'digital' was obtained from the Brazilian federal legislation websites (Brazil, 2025) and state legislation websites (São Paulo, 2025), as well as Brazilian standards (ABNT, 2025). This search was conducted between March 23 and April 5, 2025. The number of results found to each theme and selected are presented in Appendix B. The criteria for inclusion and exclusion of sources prioritised documents with technical or scientific backing, official publications in the field. Additionally, normative documents that are effectively applied or commonly used as references by public bodies and international institutions were selected.

The following inclusion criteria were defined: a) Only legislation containing the keywords 'accessibility' and 'digital' in the preamble was included; and b) legislation containing definitions of concepts such as 'accessibility' and 'digital' or related aspects such as 'barriers', 'universal design', 'communication' or any other issues related to the digital environment. The following exclusion criteria were defined: a) Legislation repealed in its entirety; b) Legislation on specific

subjects that are not related to the research topic, and c) Legislation that does not define the concept.

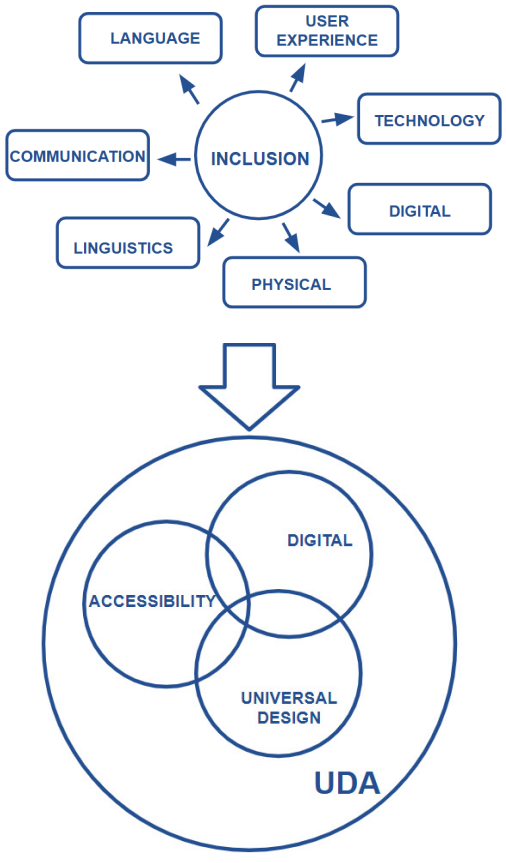
Thus, the research was conducted on the official websites of government bodies responsible for legislation and the standards of the Brazilian Association of Technical Standards legislation and standards of the Brazilian Association of Technical Standards.

3.3. Analytical and comparative conceptual synthesis

After analysing and systematising the theoretical and normative material, the concepts extracted were compared, grouped, and reinterpreted in the light of the principles of universal design, aiming to go beyond the limits of traditional digital accessibility. This stage culminated in the formulation of the proposed definition of Universal Digital Accessibility (UDA).

Figure 1 shows that UDA evolved from the term inclusion and its association with other terms, such as language, user experience, communication, digital, physical, and linguistics, towards a concept based on three relevant terms: accessibility, digital, and universal design.

Figure 1. Diagram – from Inclusion to UDA.



Despite digital accessibility, universal design, and accessibility having different meanings, and considering that the first is applied to technical aspects, interfaces, and digital interaction, while the second is applied to physical environments and products, particularly in relation to people with disabilities, they have a guiding thread that enables them to form an integrated model of accessibility that addresses conceptual gaps that current models cannot address in isolation. More than a combination of terms (universal design and digital accessibility), UDA is a structure that connects, through a systemic approach, physical and digital environments, communication,

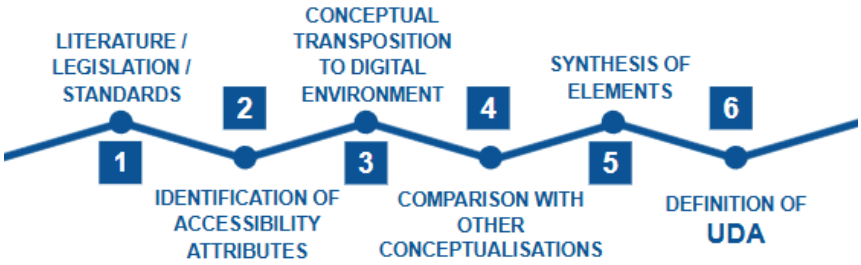
language, technology, user experience, and linguistics in hybrid ecosystems, considering human diversity and informational, cultural, and attitudinal barriers.

An analytical and comparative procedure was undertaken to develop the definition of UDA. The analysis began with established definitions and conceptualisations of accessibility, including those originally formulated for physical environments. Their underlying attributes were identified and conceptually transposed to the digital environment, preserving the core meaning of each attribute while adapting its contextual expression.

For example, concepts such as safe and autonomous use, barrier-free communication, and barrier-free access were examined in terms of their applicability to digital environments. These transposed elements were then compared with definitions of digital accessibility, as well as with relevant legislation, technical standards, dictionaries, and academic literature.

The methodological steps were as follows: 1. literature/legislation/standards → 2. identification of accessibility attributes → 3. conceptual transposition to the digital environment → 4. comparison with other conceptualisations → 5. synthesis of the elements → 6. definition of UDA, as shown in Figure 2.

Figure 2. Methodological step-by-step.



This comparison enabled the identification of convergent, divergent, and complementary elements, which were synthesised into the underlying conceptual components of the proposed definition of UDA. Tables 1 to 3, presented in the Appendix, document the extraction, conceptual transposition, comparison, and synthesis of these elements.

3.4. Relationship of digital accessibility and artificial intelligence

To understand the influence of artificial intelligence on digital accessibility was conducted a search in August 2026 using the Web of Science platform with the search strings “digital accessibility” (All Fields) and “artificial intelligence” (All Fields). The search yielded 75 articles, of which 12 were selected. Three additional articles were selected from previous issues of JACCES, considering the theme and the keyword on title, and one was identified through the snowballing technique.

A total of 16 articles were selected and used to discuss and understand the influence of artificial intelligence on digital accessibility nowadays.

4. Results

Like the methods, this section has been divided into four stages, demonstrating the results for each stage: a) review and analysis of academic literature; b) analysis of legislation and technical

standards c) analytical and comparative conceptual synthesis, and d) analysis of the relationship of digital accessibility and artificial intelligence.

4.1. Review and analysis of academic literature

Renowned authors were selected in the fields of universal design, accessibility theory, accessibility, urban accessibility, universal design, and digital and web accessibility, considering the theoretical relevance and historical contribution of these authors to the development of the analysed concepts.

The articles and papers selected in the accessibility theory section were written by the following authors: Koenig, 1974 and 1980; Morris, Dumble and Wigan, 1979; Mace, 1987 and 1991; Sassaki, 2003; Ariel, 1988 and 1990; Bock and Warren, 1985; Sassaki, 2009; and Dischinger, Bins Ely and Piardi, 2012. These include Hansen (1959), who established the operational concept of accessibility related to urban accessibility; Koenig (1974), who developed the economic theory of urban accessibility; pioneers in the development of measurable accessibility indicators related to transport planning (Koenig, 1980; Morris, Dumble & Wigan, 1979); authors of the theory of accessibility in the field of linguistics and reference (Ariel, 1988 and 1990; Bock & Warren, 1985); Mace (1987 and 1991), a pioneer of universal design; and, in Brazil, authors who are important for defining dimensions within accessibility, as well as the concept of spatial accessibility (Sassaki, 2003; Sassaki, 2009; Dischinger, Bins Ely & Piardi, 2012).

Appendix A contains a conceptual table, Table 1, showing the transposition of concepts from the area of physical accessibility to digital accessibility, which were subsequently used in the definition of Universal Digital Accessibility (UDA), the objective of this research, as discussed further below.

4.2. Analysis of legislation and technical standards

Subsequently, Appendix B contains a summary and analysis of the survey of legislation and technical standards that was conducted through official websites, including the legislative website of the Presidency of Brazil (Brazil, 2025), Table 2, the website of Legislative Assembly of São Paulo - Alesp (São Paulo, 2025), and the ABNT collection for Brazilian technical standards (ABNT, 2025).

The number of results found was analysed according to the inclusion and exclusion criteria outlined in the 'method' section; in other words, legislation in force, related to the researched topic, with the keywords 'accessibility' and 'digital' in the preamble and definitions related to the topic.

The initial result of the research carried out on these three main websites, before applying the criteria, was: 3,270 pieces of legislation. After applying the criterion of the presence of keywords in the preamble: the number was reduced to 1,751; of these, 68 adhered to the theme, and 19 contained definitions of concepts. A further four pieces of legislation and standards were then added which, despite not meeting the keyword criteria, adhered to the theme and contained definitions of concepts, resulting in a total of 23 pieces of legislation and standards selected.

Once the legislation and regulations had been selected, concepts were found for terms such as: accessibility, universal design, barriers, digital or electronic media, communication, and information technology. These definitions were grouped together when they specified the same concept and separated when they covered different concepts (Table 3, Appendix B) while the

most relevant items were used in the proposed definition of Universal Digital Accessibility at the end of the study.

4.3. Analytical and comparative conceptual synthesis

In Appendix C, Table 03 presents the source terms for the composition of the definition of Universal Digital Accessibility (UDA).

Considering that accessibility is only one part of universal design, and that the latter is intended to cater to all people and needs, while also taking into account the needs of people with disabilities, this definition also encompasses aspects of universal design, in addition to physical and digital accessibility, which is why it is called 'Universal Digital Accessibility'.

The term 'universal' refers to universal design, considering that digital platforms and tools can already be designed to be accessible to all people, not just those with some type of disability, a role traditionally associated with accessibility. Thus, accessibility (access for people with disabilities) + digital (digital media, websites, platforms, and tools) + universal (derived from universal design; in other words, for all people, regardless of age, height, weight, cognitive characteristics, disability, individual condition, or reduced mobility).

The concatenation of concepts results in the definition of Universal Digital Accessibility - UDA: it refers to the possibility and conditions of access, approximation, reach, perception, comprehension, use, interaction as well as entry into and exit from environments, and access to products, digital programmes, equipment, information, and communication technologies, systems and other digital services, whether for public or private use, individual or collective purposes, in urban or rural areas. This accessibility should occur in a safe, comfortable, and autonomous manner, with clear and effective instructions and communication, for everyone, regardless of anthropometric characteristics (such as height and weight), sensory characteristics (auditory, visual, intellectual, cognitive, among others), age, ability, reduced mobility, or any other individual condition. This includes, where necessary, the use of technical aids and assistive technology resources. The objective of this definition is to promote social inclusion, equal opportunities, the exercise of citizenship, and respect for the fundamental rights of all individuals (Mace, 1991; Brazil, 2000b, 2004, 2009, 2012, 2015, 2024, 2025; ABNT, 2005, 2008, 2012, 2016a, 2016b, 2020, 2022, 2025; Cambiaghi, 2007; São Paulo, 2008; ISO, 2021; Centre for Universal Design, 2025; Brazil, n.d; UFAS, 2025; W3C, 2025).

For this definition to be met, it is necessary to incorporate the following guidelines:

- Guarantee access to devices (computer, notebook, tablet, among others) for users;
- Guarantee access to quality internet (broadband) for users;
- Guarantee training and technical support from information and communication technology professionals in a digital environment (synchronous or asynchronous) to improve users' digital competence or skills;
- Ensure easy access, interpersonal information exchange, and digital interactions (Hansen, 1959; Koenig, 1974; Dischinger, Bins Ely, & Piardi, 2012) for users;
- Reduce the distance between human activities, in other words, reduce the spatial separation between them (Morris, Dumble, & Wigan, 1979) through the internet, in a digital environment;

- Understand the function, organisation, the movement (between websites and digital platforms without barriers), the use, the spatial relations, and the materials of a digital environment (ABNT, 2020; Dischinger, Bins Ely, & Piardi, 2012; Ariel, 1988);
- Ensure the dimensions of accessibility and digital quality are being attended to: a. Without barriers of physical architecture, and digital (architectural); b. without barriers to communication between people, in a digital and physical environment (communicational); c. without barriers on methods and techniques in a digital and physical environment (methodological); d. without barriers of instruments and tools in a digital and physical environment (instrumental); e. without barriers embedded in public policies, legislation, standards, related to a digital and physical environment (programmatic); f. without prejudices, stereotypes, stigmas, and discrimination in society's behaviour towards people in the physical and digital environment (attitudinal) (Sassaki, 2009).

Based on this process, we sought to ensure that the proposed definition was comprehensive, applicable to different digital contexts, and capable of guiding policies, projects, and practices aimed at promoting genuinely inclusive digital environments.

4.4. Relationship of digital accessibility and artificial intelligence

Nowadays, with the advent of artificial intelligence, a number of studies are linking it to digital accessibility or digital literacy, or digital competence.

Inal and Papachristos (2026) conducted a study on the use of Artificial Intelligence in digital accessibility among university students through a questionnaire composed of open-ended questions and divided into three sections: (i) participant information, including gender, level of knowledge, frequency of AI use throughout the day, preferred AI tools, and purposes for using AI; (ii) considerations regarding the use of AI in digital accessibility, including advantages, disadvantages, examples, potential risks, challenges related to AI integration, and ethical and social issues; and (iii) a single question through which students could provide comments, opinions, reflections, and/or criticisms concerning the use of AI solutions to improve the lives of persons with disabilities. The responses were analysed qualitatively through a top-down thematic analysis, resulting in four main themes: (i) Opportunities and Benefits of AI in Accessibility — positive impacts and potential benefits; (ii) Risks and Challenges in AI Integration — risks, concerns, and challenges related to the greater integration of AI into accessibility technologies; (iii) Ethical and Social Implications — how AI may affect privacy, inclusion, and security, particularly regarding bias, transparency, and accountability; and (iv) Promoting AI for Accessibility — strategies and approaches for effectively integrating and promoting AI in accessibility (Inal and Papachristos, 2026). The results demonstrated positive perceptions among participants regarding the integration of AI to improve the lives of persons with disabilities, establishing a bridge between persons with disabilities and digital society through solutions such as image recognition, speech recognition, text processing, natural language processing, and affective computing (Inal and Papachristos, 2026).

Cortês Vieira et al. (2022) conducted a study with elderly tourists in the Algarve region of Portugal in order to assess their digital literacy regarding the use of the internet, Quick Response (QR) codes, and Near Field Communication (NFC) technology. Data collection was carried out through questionnaires administered to 851 older adults aged 60 years or above at Faro International Airport, as part of the ACCES4ALL - Accessibility for All in Tourism (2017 - 2019) project. The methodology employed descriptive and inferential statistical analyses, leading to the following results: (i) the older the participants were, the less they used the internet; (ii) higher levels of

education were associated with greater internet use; (iii) elderly tourists without disabilities used the internet more frequently than those with disabilities; (iv) only a small number of elderly tourists were familiar with the use of QR codes and NFC technology; and (v) a digital exclusion profile emerged, composed of tourists over 80, women, people with disabilities, lower education levels, and rural residents. The study concludes that fostering digital inclusion in smart tourism requires developing interfaces based on Universal Design principles and actively involving older adults in co-design and co-creation processes (Cortês Vieira et al., 2022).

Real-Fernández et al. (2025) link information technology and artificial intelligence to the design of smart learning platforms, ensuring that these platforms can be used by individuals with diverse abilities. The CALM (Customised Adaptive Learning Model) was developed by the lead author of the paper as part of their doctoral thesis in 2022. The model aims to structure a learning environment that is both adaptive to learners' pace and personalised to their individual needs. To achieve this, the model is based on three fundamental pillars: i) the division of competencies and activities; ii) a competency map; and iii) an AI-based decision-making engine. As a practical application and case study of CALM, the authors' research group developed the Khipulearn platform. The methodology adopted in the paper involved conceptual mapping and a theoretical discussion of the model. The authors describe the smart learning platform and explain which aspects of digital accessibility can be applied to it. Three key dimensions were identified: platform accessibility, content accessibility, and compatibility with assistive technologies. The results demonstrate that, to ensure inclusion in smart and visual competency maps, AI needs to operate natively and automatically, taking into account the principles established by international accessibility guidelines, such as Accessible Rich Internet Applications (ARIA), the Authoring Tool Accessibility Guidelines (ATAG), and the World Wide Web Consortium (W3C) (Real-Fernández et al., 2025).

Akeroyd and Merlo (2023) discuss digital accessibility standards and practices in relation to global sustainability goals in university libraries. Their methodology encompasses a general review and qualitative interviews with librarians as a means of diagnosing the challenges involved in transforming printed and digital materials into formats that are readable by screen readers and accessible through Braille. The study indicates that, despite the availability of new technologies and institutional guidelines, libraries continue to face the dual challenge of managing large historical collections while ensuring their accessibility within the academic environment (Akeroyd & Merlo, 2023).

Chakraborty et al. (2023) present a theoretical and conceptual discussion of the role of artificial intelligence as a future tool for the social inclusion of people with disabilities. The authors analyse several AI-based assistive solutions, including voice-activated personal assistants (VAPAs); sensory and language recognition systems, such as image and facial recognition, auto-captioning, and language technologies; mobility and smart hardware, including route-planning and navigation software, assistive prostheses and robotics, robotic arms, prosthetic limbs, and autonomous vehicles; and reading devices and interface adaptations, such as physical reading machines and the transition from physical to digital commands. The paper argues that these innovations can significantly mitigate the digital divide and concludes that AI can enhance the daily autonomy of people with disabilities, transforming the ways in which they communicate and navigate their everyday lives (Chakraborty et al., 2023).

Chemnad and Othman (2024) conducted a comprehensive mapping of the global research landscape at the intersection of AI and digital accessibility for people with visual, hearing, motor, or cognitive disabilities. The methodology consisted of a bibliometric analysis and a systematic

literature review, initially identifying 3,706 scientific publications published between 2018 and 2023. Following a refinement process, 42 high-quality studies were selected. The research revealed that the primary focus of these publications is on the needs of people with visual disabilities, highlighting a significant gap in intelligent solutions addressing other physical or cognitive impairments (Chemnad & Othman, 2024).

Esposito et al. (2026) evaluated the usability of an intelligent conversational assistant called ConWeb, developed by two of the paper's authors in collaboration with Marcos Báez, to facilitate Web navigation for people who are blind or have low vision (BLV). A comparative experimental study was conducted with 30 real users, in which the authors compared voice-based navigation with conventional screen readers, such as NVDA and JAWS. Qualitative and quantitative data were collected using user satisfaction questionnaires, including the Subjective Assessment of Speech System Interfaces (SASSI) and the User Experience Questionnaire – Short Version (UEQ-S). The study demonstrated that, with ConWeb, conversational interaction significantly reduced participants' cognitive effort and physical fatigue by enabling them to ask direct questions and obtain summaries of complex webpage content, thereby outperforming conventional screen readers in terms of facilitating Web navigation (Esposito et al., 2026).

Jaya et al. (2026) evaluated the "Magnetcode" application, which is used to teach concepts of logic and programming (coding), with the aim of facilitating teaching and computational thinking in agricultural projects. The authors employed a qualitative case study with data triangulation, collecting coding logs (digital records), analyses of physical portfolios, and semi-structured interviews with teachers and agricultural educators in Zambia. The research revealed that the use of the tool had positive outcomes and enabled educators to address complex logical challenges, thereby strengthening the integration of technological skills into the local curriculum (Jaya et al., 2026).

Jones and Echeles (2026) investigated the practical accuracy of AI-generated automatic image descriptions in alternative text (alt text) for online courses designed for nursing educators. The methodology consisted of a qualitative evaluation study using reflexive thematic analysis, in which feedback from teaching staff was collected and categorised after they evaluated the descriptions generated by the language model. The results revealed that, although the use of AI was useful for optimising teaching staff's time, the automated drafts contained serious conceptual errors and omitted essential pedagogical nuances. This indicates that its use is beneficial only as an initial assistant and requires critical human validation by a subject-matter expert (Jones & Echeles, 2026).

Moreno et al. (2019) aimed to integrate accessibility and pedagogical quality criteria into the development of Digital Educational Materials (DEMs). The methodology combined empirical case studies, including teacher training workshops, with quantitative analyses of statistical reliability using Cronbach's alpha and the Intraclass Correlation Coefficient (ICC), based on 30 assessments and 15 surveys completed by teachers and educational material evaluators. The authors successfully validated the integrated accessibility model, which provided the basis for the Spanish standard UNE 71362. The authors of the paper are members of Working Group 12 (WG12), which developed this standard. The results demonstrated that the model was statistically reliable, and the authors recommend that accessibility features should not be treated in isolation, but rather incorporated into the pedagogical and technical characteristics of educational content (Moreno et al., 2019).

Nacheva and Jansone (2023) conducted an in-depth technical evaluation of commercial web accessibility assistants (AI-based overlays), including accessiBe, AllAccessible, and UserWay. Using

a multicriteria heuristic modelling approach, the authors employed the Analytic Hierarchy Process (AHP) to rank these technologies, focusing on web developers and users with sensory or motor impairments. The research assigned important heuristic priorities, such as support for assistive hardware, which accounted for 19.3% of the overall relevance, and revealed limitations in these tools, showing that overlays often operate superficially within the user's browser without addressing the underlying problematic code on the servers (Nacheva & Jansone, 2023).

Pereira and Duarte (2025) investigate the ethical, operational, and practical aspects involved in the large-scale monitoring and evaluation of digital accessibility. The methodology employed a mixed-methods approach, combining online questionnaires and semi-structured interviews with 27 experts from 16 countries. The authors interpreted the responses using reflexive thematic analysis. The main findings highlight a gap between technical compliance and the actual user experience, as well as the need to integrate AI technologies and Large Language Models (LLMs) to optimise professional auditing workflows in complex digital environments (Pereira & Duarte, 2025).

Rehman et al. (2024) analysed the impact of ChatGPT use on individuals' life satisfaction in academic settings. The methodology consisted of a structured quantitative study involving 305 higher education students. Using covariance-based structural equation modelling (CB-SEM), the researchers examined the moderating role of subjective well-being in this relationship. The main findings show that daily interaction with artificial intelligence positively influences academic engagement, academic self-esteem, and student resilience, factors that substantially increase students' sense of control and personal satisfaction with their educational experience. The main factors limiting improvements in quality of life in the context of AI use are related to biased responses, limited knowledge, and the lack of emotional intelligence in AI systems, which reduce their perceived reliability and consequently diminish engagement (Rehman et al., 2024).

Santos (2025) evaluated the accessibility conditions of the interface and scientific publications deposited in the RIMA digital repository of the Federal Rural University of Rio de Janeiro (UFRRJ) against W3C criteria and the Brazilian Inclusion Law (LBI). The research was exploratory and applied, incorporating automated auditing using the Brazilian ASES software, conventional semantic and structural scanning, and manual inspection of a sample of 10 recent academic papers in PDF format. The repository achieved a score of 84.53%, classified as regular, due to barriers related to colour contrast, the lack of keyboard shortcuts, and HTML markup failures. Furthermore, the documentary analysis revealed that only one of the 10 dissertation and thesis PDFs was fully accessible to people with disabilities. The study concluded that the use of artificial intelligence resources for audio description and the automatic formatting of PDFs will be urgent and indispensable in the near future (Santos, 2025).

Todorov (2024) discusses the practical limitations and capabilities of generative artificial intelligence tools, such as ChatGPT, Gemini, and Copilot, in assisting content creators in the development of accessible websites. The methodology involved a state-of-the-art review accompanied by programming code tests and alternative image description tasks. The author demonstrated contrasting results regarding the effectiveness of these tools, focusing on designers and users with special accessibility needs. While ChatGPT successfully optimised problematic HTML code for screen readers, Gemini failed to restructure the code and merely suggested additional labels for the original, inadequate code (Todorov, 2024).

Volkmann et al. (2025) mapped how formal levels of technical accessibility in web interfaces directly affect the well-being of individuals with cognitive processing difficulties and disabilities. The authors employed a qualitative methodology based on empirical website usability testing,

structured through individual interviews, with the data categorised using structured content analysis in the MAXQDA software. The results showed that the lack of Easy-to-Read language, excessive dynamic background animations, and complex navigation layouts cause severe disorientation, fatigue, and extreme frustration among these users, demonstrating that cognitive accessibility requires guidelines as rigorous as those addressing sensory disabilities (Volkmann et al., 2025).

The results of a search about the relationship between digital accessibility and artificial intelligence showed that despite the AI helping a lot of people with disabilities, this tool is not so reliable and still needs to be revised by humans.

5. Discussion

The results of this search were a definition of "Universal Digital Accessibility - UDA", as well as the guidelines for ensuring that it is addressed comprehensively. The definition enables the ideal relationship between users and environments, products, equipment, and digital programmes, as well as defining how this relationship should occur and identifying the actors involved in the process. The definition dismisses the "standard human" imposed by Le Corbusier, Neufert and Da Vinci, because it considers people in all their individual characteristics, including age, anthropometrics, sensory characteristics abilities, movements, or any other individual condition (Cambiaghi, 2007; Brazil, 2004).

The definition aims to strengthen the definitions of digital accessibility (Brazil, 2023) and web accessibility definition (W3C, 2025a) making them more robust, not only in relation to barriers on the web or the application of the WCAG on the web (W3C,2025a), but also considering certain physical aspects that precede the digital aspect, as well as not focusing solely on persons with disabilities (ABNT, 2020 and Brazil, 2004), but rather on all persons with diverse characteristics (Mace, 1991).

The guidelines established address physical issues (offline) before digital issues (online) to be met to ensure digital accessibility, such as access to mobile devices; quality of internet; training and technical support; reduction of physical distance through digital proximity; as well as the reduction of architectural, communicational, methodological, instrumental, programmatic, and attitudinal barriers within physical and digital environments.

The term 'universal', derived from universal design, was added to the definition to emphasise that digital environments, products, programmes, and services should not require adaptation, but rather be designed in an accessible manner (ABNT, 2020); allowing people with or without disabilities, older people, people with situational limitations, those using slow or limited internet connections, and those living in rural areas or developing countries to perceive, understand, navigate, interact with and contribute to the web, in others words, websites, tools, and technologies that are developed with inclusion in mind (W3C, 2025a). "The web is fundamentally designed to work for all people, regardless of their hardware, software, language, location or ability" (W3C, 2025a).

The term digital was used in the definition because most of what is covered in this research is related to the digital environment, although the physical environment is not disregarded.

The term 'accessibility' is at the heart of the name given to the definition and is related to the main concepts, whether in the work of recognised authors in the field (Hansen, 1959; Koenig, 1974; Morris, Dumble and Wigan, 1979; Sassaki, 2009; Dischinger, Bins Ely and Piardi, 2012);

standards (ABNT, 2005, 2008, 2012, 2016, 2020, 2022, 2025), Brazilian legislation (Brazil, 2004, 2008, 2012, 2015) foreign standards and legislation (ISO, 2021; ADA, 2025, UFAS, 2025) or international guidelines (W3C, 2025a, W3C, 2025b, W3C, 2025c, W3C, 2025d).

The structure of UDA, as shown in Figure 3, was established through five steps: the search for concepts, national and international legislation, standards, and the main authors on the subject, as well as, at this stage, the influence of artificial intelligence in this field.

Figure 3. UDA Structure.



The aim was to understand how the subject has been discussed and defined in the literature and how it has been addressed by legislation and technical standards.

At this stage, the influence of artificial intelligence in the field was also considered, particularly its potential to improve accessibility and inclusion, as well as the new challenges it may create. This helped to establish the theoretical and normative basis for the following stages of the research.

The Social Model of Disability understands disability as a societal issue rather than an individual problem (Barnes, 1996). The traditional concept that associated disability with the individual, as if the problem lay within the person, is no longer adopted. The recent concept of the Social Model of Disability explains that disability is produced by and is a problem of the environment, communication, technology, and society. The UDA also incorporates this perspective, recognising that all these barriers can occur in both physical and digital environments, and seeks to eliminate barriers in these environments and ensure full participation for all people with diverse characteristics.

Studies on digital accessibility and artificial intelligence have focused on university students, older tourists, and libraries (Inal & Papachristos, 2026; Cortês Vieira et al., 2022; Akeroyd & Merlo, 2023), or have evaluated tools, whether AI-based or not, including applications (Nacheva & Jansone, 2023; Jaya et al., 2026; Todorov, 2024; Volkmann et al., 2025). Other studies have proposed models, platforms, standards, and assistants (Real-Fernández et al., 2025; Moreno et al., 2019; Esposito et al., 2026). More theoretical research has encompassed theoretical and conceptual discussions, bibliometric analyses, systematic reviews, and state-of-the-art surveys (Chakraborty et al., 2023; Chemnad & Othman, 2024; Todorov, 2024). More specific studies have analysed automatic image descriptions (alt text), the life satisfaction of ChatGPT users in academic settings, and the accessibility conditions of scientific publications (Jones & Echeles, 2026; Rehman et al., 2024; Santos, 2025).

This research falls primarily within the category of theoretical studies, with the aim of contributing to the development of a new definition, termed Universal Digital Accessibility (UDA).

6. Conclusions

The research aimed to propose a definition of UDA for three main reasons: (a) Accessibility, especially in Brazilian legislation, only considers people with disabilities or reduced mobility, while ISO 21542:2021(E) and Universal Design consider all people, regardless of physical characteristics, cognitive abilities, age, and skills; (b) in accessibility, the dimensional specifications details established in legislation and regulations define the requirements that should be met to adapt existing environments or artefacts, while in universal design, the artefact is conceived from the outset by considering the principles of physical and digital accessibility for all people; and (c) UDA provides a structure that systemically connects through a systemic approach physical and digital environments, communication, language, technology, user experience, and linguistics within hybrid ecosystems, while considering human diversity and informational, cultural, and attitudinal barriers.

The definition encompassing both concepts—accessibility and universal design—was necessary because, during the research, no definition was found that encompassed both physical and digital accessibility, universal design, and technology.

The review and analysis of the literature led the research to widely recognised authors, while the analysis of legislation and technical standards enabled an understanding of the concepts known and defined by these documents, so that they could be incorporated into the definition of Universal Digital Accessibility (UDA) in a structured manner and through the transposition of concepts, and the research about AI complemented the main research with important perspectives on current technology

In light of this analysis, this study consolidates the following definition of Universal Digital Accessibility - UDA: it refers to the possibility and conditions of access, approximation, reach, perception, comprehension, use, interaction as well as entry into and exit from environments, and access to products, digital programmes, equipment, information, and communication technologies, systems and other digital services, whether for public or private use, individual or collective purposes, in urban or rural areas. This accessibility should occur in a safe, comfortable, and autonomous manner, with clear and effective instructions and communication, for everyone, regardless of anthropometric characteristics (such as height and weight), sensory characteristics (auditory, visual, intellectual, cognitive, among others), age, ability, reduced mobility, or any other individual condition. This includes, where necessary, the use of technical aids and assistive technology resources. The objective of this definition is to promote social inclusion, equal opportunities, the exercise of citizenship, and respect for the fundamental rights of all individuals (Mace, 1991; Brazil, 2000b, 2004, 2009, 2012, 2015, 2024, 2025; ABNT, 2005, 2008, 2012, 2016a, 2016b, 2020, 2022, 2025; Cambiaghi, 2007; São Paulo, 2008; ISO, 2021; Centre for Universal Design, 2025; Brazil, n.d; UFAS, 2025; W3C, 2025)..

This research contributed to the fields of accessibility, the digital environment, and universal design by grouping interrelated concepts into a single concept and providing a more solid and complete definition that meets the principles of digital inclusion.

The research on AI has raised some interesting perspectives, such as greater autonomy for people with disabilities in a digital environment and assistance with creating drafts of alternative text in the educational area. The negative aspects include the potential for AI use to create human dependence, as the technology is not yet fully reliable, as well as the lack of context. AI frequently "hallucinates" information, while ethical barriers, privacy concerns, and algorithmic bias are also issues that need to be considered. The authors argue that AI and intelligent systems still fail to

adequately address the needs of vulnerable populations and those with lower levels of digital literacy.

The limitations of the main study are related to its failure to consider legislation from all countries; the analysis predominantly considered Brazilian, North American and European legislation was considered, but the inclusion of legislation from other continents would make future research more applicable to other realities.

With the consolidated definition of Universal Digital Accessibility (UDA), it is suggested that future research should expand its application to various areas, making it a precursor to the development of definitions such as Universal Digital Accessibility for X, following the Design for X approach.

As future research, it is proposed to apply the proposed definition in the educational, business, commercial, and other areas, as well as at various levels within these sectors and in other related thematic areas, so that the tool can adapt and evolve according to the realities of other countries and researchers.

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Appendices

Appendix A

Table 1. Conceptual

Author (year)	Physical Accessibility	Digital Accessibility
Hansen (1959)	potential for interaction opportunities.	potential for digital interaction opportunities.
Koenig (1974)	allows for exchanges and easy interaction.	allows for exchanges and easy digital interaction.
Morris, Dumble and Wigan (1979)	The distance between human activities, considering the spatial separation between them.	The distance between human activities in the digital environment, considering the spatial separation between them through the internet.

Author (year)	Physical Accessibility	Digital Accessibility
BRASIL (2004) e ABNT NBR 9050:2O20 (Brazilian Association of Technical Standards)	Condition to use with security, autonomy, total or assisted, of the environment.	Condition to use with security, autonomy, total or assisted, of in a digital environment.
Sassaki (2009)	Architectonic accessibility - without physical barriers.	Architectonic accessibility - without digital barriers.
Sassaki (2009)	Communicational accessibility - without barriers to communication between people.	Communicational accessibility - without barriers to communication between people, in the digital environment.
	Methodological accessibility - without barriers to methods and technicians of leisure, work, education, etc.	Methodological accessibility - without barriers to methods and technicians of leisure, work, education, etc, in the digital environment.
Sassaki (2009)	Instrumental accessibility - without instrumental, tool or utensil barriers.	Instrumental accessibility - without instrumental, tool or utensil barriers, in the digital environment.
Sassaki (2009)	Programmatic accessibility - without barriers integrated in public policies, laws, standards, etc.	Programmatic accessibility - without barriers integrated in public policies, laws, standards, etc, in the digital environment.
Sassaki (2009)	Attitudinal accessibility - without prejudices, stereotypes, stigmas and discrimination in society's behaviours towards people with disabilities.	Attitudinal Accessibility: without prejudices, stereotypes, stigmas and discrimination in society's behaviours towards, in physical and digital environment.
Dischinger, Bins Ely and Piardi (2012)	Spatial Accessibility: encompasses the users understanding of the function, organisation and spatial relationships of an environment, participating in the activities developed there with safety, comfort and independence.	Spatial Accessibility: encompasses the users understanding of the function, organisation and spatial relationships of a digital environment, participating in the activities developed there with safety, comfort and independence.
Dischinger, Bins Ely and Piardi (2012)	Spatial orientation: identifies the functions of a space, defines how to implement the movement and use.	Spatial orientation: identifies the functions of a digital space, defines how to implement the movement and use.
Dischinger, Bins Ely and Piardi (2012)	Communication: exchange interpersonal information, with or without the use of assistive technology.	Communication: exchange interpersonal information, with or without the use of assistive technology, in a digital environment too.

Author (year)	Physical Accessibility	Digital Accessibility
Dischinger, Bins Ely and Piardi (2012)	Movement: vertical movement (stairs, ramps and lifts) and horizontal movement with independence, security and comfort, without barriers.	Movement: digital movement between websites, teaching platforms and systems with independence, security and comfort, without barriers.
Dischinger, Bins Ely and Piardi (2012)	Use: effective participation and carrying out activities by all people.	Use: effective participation and carrying out activities by all people, in a digital environment.
Ariel (1991)	Relative accessibility will be constant on every language, and not the absolute degrees of accessibility.	Digital accessibility will be constant in every language, and not the absolute degrees of accessibility.
Ariel (1991)	Accessibility is not only a cognitive concept, but also a linguistic characteristic.	Digital accessibility ought to be cognitive to encompass people with learning difficulties, with intellectual disabilities, autism or ADHD .
Ariel (1988)	Factors affecting antecedent accessibility: a. Distance between the antecedent and the anaphora. b. Number of competitors for the antecedent function. c. Importance of currency in antecedent attributions. d. Role of tables in antecedent identification.	Factors affecting digital accessibility: a. lack of electronic devices b. lack of internet access c. lack of access to learning websites and platforms d. lack of digital skills e. lack of digital skills training f. lack of accessibility of websites, learning platforms and apps.
Ariel (1988)	Three types of contexts (general knowledge, physical environment, and linguistic material).	Knowledge of the use of the digital environment and digital materials (digital skills, websites, learning platform, email, text, documents, audio, images, software, apps, data, downloading and uploading).
Ariel (1990)	Function is fulfilled by the accessible information.	Function of accessible digital information.
Ariel (1990)	Hypothetical connection between what is named accessibility marking and the memory nature can help to understand what happens during the discuss progression in terms of the choose of referential expressions.	Marking of digital accessibility.

Author (year)	Physical Accessibility	Digital Accessibility
Bock and Warren (1985)	Conceptual accessibility is connected to a hierarchy of grammatical relationships that influences the formulation of phrases.	Digital Accessibility is connected to digital access by means of device.
ABNT NBR 9050:2O20 (Brazilian Association of Technical Standards)	Accessible route: a continuous route, without obstruction and signalised, that connects indoor environments to outdoor environments on buildings. Spaces that can be used in an autonomy and safety way for all people, including those with some disabilities or reduced mobility. This route covers car parks, pedestrian crossings, floors, corridors, stairs, and ramps, amongst others.	Accessible digital route: a continuous route, without obstruction that connects digital environments in a way that can be used with autonomy and security for all the people, including those with some disabilities or reduced mobility. This digital route covers websites, learning platforms, email, and digital media, amongst others. The accessible route in a digital environment is to get all the access to every information on websites, learning platforms in an educational and efficient manner to all people.
ABNT NBR 9050:2O20 (Brazilian Association of Technical Standards)	In buildings, essential signage elements include information on toilets, bathrooms, changing rooms, vertical and horizontal accesses, floor numbers, and escape routes.	In digital environment, essential signage elements and digital accessibility are defined by the Web Content Accessibility Guidelines (WCAG).
ABNT NBR 9050:2O20 (Brazilian Association of Technical Standards)	The signage must be arranged in accessible locations.	The signage in a digital environment must be arranged in accessible locations.
ABNT NBR 9050:2O20 (Brazilian Association of Technical Standards)	The Pedestrian traffic lights must be equipped with a mechanism and synchronised devices that have visual and audible signs.	Digital environments must be equipped with mechanisms: audible, screen reader, amongst others.

Appendix B

Table 2. Legislation and standards

Term	Source	Results	Keywords	Alignment to the theme	Conceptual definition
Accessibility	Brazil	310	13	3	2
Accessibility	State of São Paulo, Brazil	157	13	1	1

Term	Source	Results	Keywords	Alignment to the theme	Conceptual definition
Accessibility	Brazilian Association of Technical Standards (ABNT)	61	45	9	8
Digital	Brazil	1249	66	45	5
Digital	State of São Paulo, Brazil	1079	64	4	1
Digital	Brazilian Association of Technical Standards (ABNT)	414	263	6	2
SUBTOTAL		3270	1751	68	19
ADDED					4
DECREE Nº 6.949/2009	Brazil	-	-	1	1
ABNT NBR 15290:2OO5 (Brazilian technical standard)	Brazilian Association of Technical Standards (ABNT)	-	-	1	1
ISO 21542:2021(E)	International	-	-	1	1
DECREE Nº 67.641/2023	Brazil	-	-	1	1
TOTAL					**23**

Appendix C

Table 3. Terms that helped on a definition composition of "Universal Digital Accessibility"

Source	Concepts
Michaelis online dictionary (2025)	Accessibility: Facility to access, quality of what is accessible. Facility of approach, procedure, or obtaining.
ABNT NBR 15290:2OO5, ABNT NBR 9050:2O20), ABNT NBR 15290:2O16, ABNT NBR 15599:2OO8 (Brazilian technical standard). Law Nº 10098:2000 amended by Law Nº 13146:2015, São Paulo State Law Nº 12907:2008	Accessibility: Possibility and condition of reach, perception and understand to use, with safety and autonomy, spaces, furniture, urban equipaments, buildings, transport, communication and information, including systems and technologies, as well as another services and installations open for public, from private or public uses, individual or collective, in both urban and rural areas, from people with disabilities or reduced mobility.

Source	Concepts
ABNT NBR 17060:2O22 (Brazilian technical standard)	Accessibility: The scope in which products, systems, services, environments, and infrastructure can be used by people of a population with a larger variety of characteristics and capacities, to achieve a specific aim in a context of specific use (both the use facility - task efficiency and user satisfaction - and use success, that is, the system effectiveness).
Decree Nº 5296:2004 and ABNT NBR 14022:2O25 (Brazilian technical standard)	Accessibility: Condition for use, with safety and autonomy, total or assisted, spaces, furniture and urban equipment, buildings, transport services and device services, systems and communication environment, and information, by people with disabilities or with reduced mobility.
ISO 21542:2021(E)	Accessibility: Provision of buildings or parts of buildings for people, regardless of their age, size, ability, or disability, to be able to gain access to them, into them, to use them and exit from them. Note 1 to entry: Accessibility includes ease of independent approach, entry, evacuation and/or use of a building and its services and facilities, by all building's potential users with an assurance of individual health, safety, and welfare while those activities.
Law Nº 12587:2012	Accessibility: A facility that enables autonomy for everyone in desired movements, respecting legislation currently in force.
ABNT NBR 15610-2 and -3:2O12 (Brazilian technical standard) - part 2 and 3	Accessibility: Possibility scope for use, with safety and autonomy, in a physical environment, systems and communication environment, products and services, by people with hearing, visual, or intellectual impairment.
Uniform Federal Accessibility Standards (UFAS)	Accessible: a place, building, installation, or part of them that agrees with standards and that can be reached, entered, and used by people with physical disabilities.
W3C	Web accessibility means that websites, tools, and technologies are designed and developed so that people with disabilities can use them. More specifically, people can: a. perceive, understand, navigate, and interact with the Web; b. contribute to the Web. Web accessibility encompasses all disabilities that affect access to the Web, including auditory, cognitive, neurological, physical, speech, visual. Web accessibility also benefits people without disabilities, for example: A. people using mobile phones, smart watches, smart TVs, and other devices with small screens, different input modes, etc. B. older people with changing abilities due to ageing. C. people with “temporary disabilities” such as a broken arm or lost glasses. D. people with “situational limitations”, such as in bright sunlight or in an environment where they cannot listen to audio. E. people using a slow Internet connection, or who have limited or expensive bandwidth.
Mace (1991)	Universal Design: Designing all products, buildings, and exterior spaces to be usable by all people to the greatest extent possible.

Source	Concepts
ABNT NBR 9050:2O20 (Brazilian technical standard) and Law Nº 10098:2000 amended by Law Nº 13146:2015	Universal Design: Conception of products, environments, programs, and services to be used by all people, without adaptation or specific design, including the assistive technology resources.
ABNT NBR 15599:2O08; ABNT NBR 17060:2O22 (Brazilian technical standard); Cambiaghi (2007); Center for Universal Design (2025); Decree Nº 6949:2009	Universal Design: Way to concept products, communication environments, services, and environments to be used by all people, most of the time, without adaptation, benefiting people of all ages and capacities. The concept of universal design has seven principles: 1. Equalisation of use possibilities; 2. Use flexibility; 3. Use simple and intuitive;4. Perceptive information; 5. Error tolerance; 6. Minimum physical effort; 7. Dimensioning of access spaces and use by all users.
Decree Nº 5296:2004	Universal Design: Conception of places, artefacts, and products to simultaneously satisfy all people, with different anthropometric and sensorial characteristics, in an autonomy, safe, and comfortable way, constituting the elements or solutions that constitute accessibility.
Decree Nº 5296:2004; State Law of São Paulo Nº 12907:2008; Law Nº 10098:2000 amended by Law Nº 13146:2015	Barriers: Any obstacle that prevents access, movement, the circulation with safety and the possibility of communication by people and access to information: a. Urban barriers: on streets and public use spaces; b. Building barriers: contemplates barriers that exist around the buildings and indoors, can be buildings of different uses (public or private); c. transport barriers: on transport services; d. Communication and information barriers: any obstacle that prevents the expression or reception of messages by a device, environment or communication system and information.
Michaelis online dictionary (2025)	Digital: From Latin “digitalis”: a device that operates with binary values exclusively, in contrast with an analogue system that operates with a continuous range of values; a greatness assuming integer values; a computer that operates with numeric quantities or expresses information by algorithm; a computer with data processed by a graphic representation. Digitise: change movements or analogue signals to a digital form that can be processed by computers. Digitised: converted to a digital system. Digitisation: a process through which analogue data is digitised.
Digital Government of Brazil (2025)	Digital accessibility: elimination of barriers on the web. The concept assumes that websites and portals are designed for all people, to make them understand, navigate, and interact with effective ways with the websites.
Inal and Papachristos (2026)	Digital accessibility is a field that aims to ensure equal access to online information and services for everyone, regardless of skills and abilities.

Source	Concepts
Decree Nº 12069:2024	Digital Government of Brazil: management approach focused on the transformation of public organisations, supported using digital technologies, with a view to delivering public value to society by improving its processes, the provision of public services and the implementation of public policies.
ABNT NBR 17225:2025 (Brazilian technical standard	Information Technology and Communication - ICT: technology to collect, store, retrieve, process, analyse and transmit information.
United States Government Publishing Office (2011)	Information Technology: any equipment or interconnected system or subsystem of equipment, used in the automatic acquisition, storage, analysis, evaluation, manipulation, management, movement, control, display, switching, interchange, transmission, or reception of data or information by the executive agency .
Decree Nº 6949:2009	Communication: encompasses languages, text visualisations, Braille, tactile communication, enlarged characters, accessible devices, as well as simple language, writing and speaking, auditive systems, and digital voice means and augmentative and alternative modes, means and formats of communication, including accessible information and communication technology.
Law Nº 10098:2000 as amended by Law Nº 13146:2015	Communication: an interaction form of citizens that encompasses languages, including the Brazilian Sign Language (Libras), text visualisations, Braille, tactile communication, enlarged characters, accessible devices, as well as simple language, writing and speaking, auditive systems and digital voice means and augmentative and alternative modes, means and formats of communication, including accessible information and communication technology.
Directive (EU) 2016/2102	accessibility (in a digital context): the principles and techniques to be followed in the design, development, maintenance, and updating of websites and mobile applications in order to make their content more accessible to users, especially persons with disabilities.

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A rule-based multimodal computer-access system for upper-limb accessibility

Design and preliminary usability evaluation of the Turkish voice-command module

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Abstract: Computer access can be difficult for people who cannot use conventional mouse-and-keyboard input effectively. This study documents the design of a rule-based multimodal computer-access prototype comprising a Turkish voice-command module and a face/head-motion cursor-control module, and reports a preliminary usability evaluation limited to the voice-command component. Before development, formative consultations were conducted with two individuals with upper-limb impairments, one individual with a visual impairment, and six non-disabled stakeholders. After development, 25 non-disabled proxy participants completed a predefined scenario of 19 common computer tasks using the Turkish voice-command module. Task completion, completion time, facilitator assistance, and descriptive post-scenario feedback were recorded. All participants reached the predefined outcome for every task within an assisted protocol. Facilitator assistance was required in 28 task-participant instances across six tasks, most frequently when copying selected text, selecting a search-result link, and creating a new file. Mean task-completion times ranged from 9 to 240 seconds. The observations point to command operations and workflow transitions that may warrant further refinement, including clearer feedback, more visible error recovery, simplified multi-step interactions, and greater personalisation. However, the evaluation did not include participants with upper-limb impairments, did not test the face/head-motion module, and did not use standardised usability, workload, or cognitive-load measures. The results therefore offer preliminary proxy-user observations about the Turkish voice-command module rather than validation of the complete multimodal system or its accessibility for the intended user population.

Keywords: Assistive technology, computer accessibility, Turkish voice-command interface, multimodal interaction, upper-limb impairment, usability evaluation, Design for All

1. Introduction

Digital participation has become integral to education, employment, health services, communication, and civic life. However, access to digital systems is shaped by design decisions, and people with disabilities may be excluded when interfaces presume a narrow range of physical, sensory, or cognitive abilities. The World Health Organization estimates that approximately 1.3 billion people, corresponding to about 16% of the global population, experience significant disability, with prevalence increasing partly because of population ageing

and a rise in chronic health conditions (World Health Organization [WHO], 2023). Article 9 of the Convention on the Rights of Persons with Disabilities further recognises access to information and communication technologies as a condition for independent living and participation on an equal basis with others (United Nations, 2006). Digital accessibility should therefore be treated not as a specialist addition introduced after development, but as a fundamental requirement of inclusive design.

For people with upper-limb impairments, conventional desktop interaction may be difficult when keyboard and mouse use requires sustained fine motor control, reach, grip, or repetitive movement. Alternative computer-access methods include switch-based input, eye tracking, head-based pointing, and speech input. These methods impose different motor, sensory, cognitive, environmental, calibration, and equipment requirements; therefore, no single access method can be assumed to meet every user's abilities and preferences.

Research on head-mounted pointing devices indicates that technical feasibility alone does not determine whether an assistive interface will be adopted; perceived usefulness and ease of use are also important (Kabir et al., 2023). Research on multimodal alternative access has likewise demonstrated the potential value of offering more than one input pathway, while also identifying challenges involving modality coordination, personalisation, and task-specific interaction demands (Mandak et al., 2022). In the present study, this literature provides the design context for developing voice-command and face/head-motion modules. It should not be interpreted as evidence that both modules were evaluated with participants.

Speech recognition has long been considered an alternative input method within electronic assistive technology, particularly for users who experience difficulty operating conventional physical controls (Hawley, 2002). However, speech-based computer access depends on more than the conversion of speech into text. Users also require clear feedback about what the system has recognised, predictable relationships between spoken expressions and resulting actions, and recoverable responses when a command is misunderstood or unsupported.

These requirements also have a language-specific dimension because command wording, alternative expressions, and recognition errors may differ across languages. The prototype examined in this study addressed this design context through a Turkish command vocabulary and explicit rule-based mappings between recognised utterances and predefined computer actions (Keleş, 2024). The present evaluation therefore focuses on the usability of these Turkish voice-command interactions rather than on the performance of speech-recognition technology in general.

Accessibility standards provide useful design guidance, but their scope should be distinguished from formal conformance. WCAG 2.2 organises web-content accessibility around four principles: perceivable, operable, understandable, and robust. Because the present prototype is desktop software rather than web content, WCAG 2.2 is not treated as a direct conformance framework. The W3C's WCAG2ICT guidance explains how WCAG principles and success criteria can inform non-web documents and software, while noting that non-web accessibility may require considerations beyond WCAG alone (World Wide Web Consortium [W3C], 2023, 2025).

ISO 9241-171:2025 is more directly relevant because it specifies requirements and provides guidance for the accessibility of interactive software across a wide range of physical, sensory, and cognitive abilities (International Organization for Standardization [ISO], 2025). Applied to the present prototype, this perspective directs attention to predictable command–action relationships, perceivable system status, error prevention and recovery, user control, and

adaptability. These standards are used in this article to frame design requirements and future evaluation; the prototype was not subjected to a formal WCAG or ISO conformance assessment.

Against this background, the present article documents an early-stage rule-based computer-access prototype developed as part of a master's thesis in Türkiye. The prototype comprised a Turkish voice-command module for discrete computer operations and a face/head-motion module intended to support cursor movement. The development process was preceded by formative stakeholder consultations, whereas the subsequent participant-based evaluation was limited to the Turkish voice-command module (Keleş, 2024).

The empirical component had three objectives: first, to report task completion and facilitator-assistance patterns within a predefined 19-task voice-command scenario; second, to describe task-completion-time profiles and identify operations requiring further investigation; and third, to use the preliminary observations to outline considerations for subsequent inclusive design and target-user evaluation. The study did not compare the two input modules, evaluate multimodal conflict resolution, or assess the face/head-motion module with participants.

Within these limits, the article documents the prototype architecture, reports preliminary task-level observations from non-disabled proxy participants, and outlines design and methodological considerations for future work. It does not validate the complete multimodal system or establish that the prototype is accessible, effective, or independently usable by individuals with upper-limb impairments.

2. Methodology

2.1. Study design

The study followed a sequential development-and-evaluation design comprising three stages. First, formative consultations were conducted to explore perceived barriers to computer access and expectations regarding alternative interaction methods.

Second, a rule-based multimodal computer-access system was developed. The system comprised a Turkish voice-command module for discrete computer operations and a face/head-motion module intended to support cursor movement.

Third, a preliminary scenario-based usability evaluation was conducted with 25 non-disabled proxy participants. This evaluation focused on the Turkish voice-command module and included 19 everyday computer tasks. Task completion, completion time, facilitator assistance, and post-scenario feedback were recorded.

The face/head-motion cursor-control module was technically examined by the developer during implementation but was not included in the participant-based usability evaluation. Accordingly, the empirical findings reported in this article represent preliminary proxy-user evidence concerning the Turkish voice-command module and should not be interpreted as target-user validation of the complete multimodal system (Keleş, 2024).

2.2. Formative needs elicitation

Before system development, a formative needs-elicitation stage was conducted to explore perceived barriers to computer access and expectations regarding alternative interaction methods. The consultation group comprised two individuals with upper-limb impairments, one individual with a visual impairment, and six non-disabled stakeholders.

An initial feedback form was prepared using Google Forms to introduce the proposed system and collect preliminary views. Participants who indicated an interest in seeing the preliminary prototype were subsequently contacted. Consultations were conducted either face-to-face or online, depending on participant availability (Keleş, 2024).

The participants with upper-limb impairments described the proposed system as potentially relevant to computer-access needs. Their suggestions included allowing users to choose between alternative face-based cursor-control options, such as eye- or head-based movement, where technically feasible. Audible system feedback was also identified as a potentially useful feature. The participant with a visual impairment similarly emphasised the potential value of audible feedback. The non-disabled stakeholders provided additional observations concerning the possible usefulness and broader application of the proposed approach (Keleş, 2024).

These consultations informed the initial system requirements and design direction. However, they were conducted before completion of the system and did not constitute a usability or effectiveness evaluation. The views reported in this subsection should therefore be interpreted as formative stakeholder input rather than evidence of performance among the intended user population.

2.3. System architecture and evaluated scope

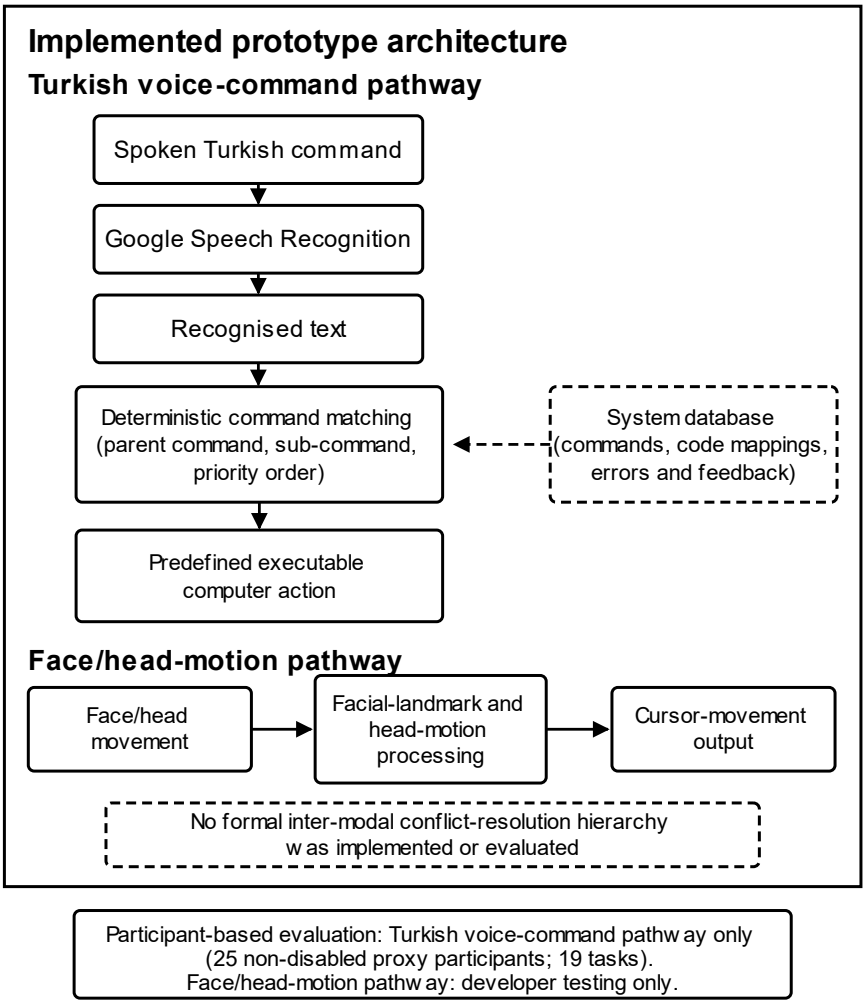
The developed system comprised two complementary interaction modules. The Turkish voice-command module was designed to execute discrete computer operations, including application and browser actions, text entry and editing, file operations, keyboard functions, and system-volume controls. Spoken Turkish utterances were converted into text using Google Speech Recognition and were subsequently processed through deterministic command-matching rules (Keleş, 2024).

The voice-command architecture was supported by a database containing user, command, parent-command, sub-command, code, error-category, feedback, and feedback-category records. Commands were organised hierarchically through parent-command and sub-command relationships. Priority fields determined the order in which command conditions were checked, while error and feedback records supported the identification of recurring interaction problems and subsequent system refinement (Keleş, 2024).

The second module used facial landmarks and head movement to support cursor navigation. Although this module formed part of the complete system architecture, it was not included in the 25-participant usability evaluation. The participant-based findings reported in this article therefore concern the Turkish voice-command module only. The face/head-motion module is described as a developed system component, and no participant-level performance or usability claims are made for it.

Figure 1 summarises the implemented processing pathways and distinguishes the component included in the participant-based evaluation from the module examined only during development.

Figure 1. Implemented system architecture and scope of the participant-based evaluation.



2.4. Rule-based voice-command processing

Following speech-to-text conversion, the recognised utterance was processed through a deterministic, hierarchical command structure. The system first identified the relevant parent command and then examined the associated sub-command conditions to determine the intended computer action. The resulting action was executed through predefined code mappings for operations such as cursor movement, clicking, application control, text entry, file management, and system-volume adjustment (Keleş, 2024).

Parent commands, sub-commands, executable code mappings, and command priorities were stored in the system database. Priority values determined the order in which command conditions were examined. This database-driven structure also enabled new commands or command variants to be incorporated by updating the corresponding command and code records rather than redesigning the entire processing architecture (Keleş, 2024).

The rule-based approach was selected in the original development because the system was intended to perform a bounded set of explicitly defined computer tasks for a specific accessibility context. The approach provided direct control over the relationship between recognised expressions and resulting actions. However, it did not learn from new utterances automatically, and extensions to the command vocabulary required manual intervention. These limitations are

considered in relation to contemporary adaptive and machine-learning-based interfaces in the Discussion section.

2.5. Preliminary usability participants

The post-development usability evaluation involved 25 non-disabled participants who acted as proxy users for a preliminary technical and interaction-level assessment. Participants were recruited through convenience sampling. They did not simulate upper-limb impairment during the sessions. The sample comprised 14 men and 11 women, with a mean age of 28 years. Participants had varied educational and professional backgrounds, including individuals with and without experience in information technology (Keleş, 2024).

None of the 25 participants was reported as having an upper-limb impairment. The purpose of this sample was to identify preliminary problems involving command use, task sequences, feedback, and facilitator-assistance requirements before conducting validation with the intended user population.

The findings from this sample should therefore not be interpreted as evidence of usability, accessibility, or effectiveness for individuals with upper-limb impairments. Participant information was reported only in aggregated or anonymised form.

Table 1. Characteristics of the preliminary usability participants.

Characteristic	Description
Number of participants	25
Participant role	Non-disabled proxy participants
Simulation of impairment	No impairment was simulated
Gender	14 men and 11 women
Mean age	28 years
Educational and professional background	Varied; included participants with and without information-technology experience
Reported upper-limb impairment	None
Evaluated module	Turkish voice-command module
Face/head-motion module used in sessions	No

The proxy-participant sample was used to identify preliminary technical and interaction-level problems before target-user validation. It was not intended to represent the functional diversity or lived experience of individuals with upper-limb impairments.

2.6. Task scenario

A predefined scenario comprising 19 sequential tasks was used to examine the preliminary usability of the Turkish voice-command module. The tasks represented common computer operations involving browser use, tab navigation, web-content interaction, text manipulation, file operations, and system-audio control. Participants completed the tasks in the same order, and each task had a predefined observable outcome (Keleş, 2024).

The scenario was designed as a procedural usability assessment rather than as a controlled pointing-device experiment. Target distance, target width, and movement amplitude were not

systematically manipulated or recorded. Consequently, the scenario does not provide the variables required for a retrospective Fitts's Law analysis.

Table 2. Tasks included in the preliminary usability scenario.

Task	Predefined task
1	Open a web browser.
2	Perform a search using the web browser.
3	Open a new browser tab.
4	Switch to the previous tab.
5	Switch to the next tab.
6	Close the newly opened tab.
7	Select the fifth link in the search results.
8	Select a paragraph on the opened web page.
9	Copy the selected paragraph.
10	Return to the desktop.
11	Create a new file.
12	Name the file using the participant's own name.
13	Open the file.
14	Paste the copied text into the file.
15	Move to a new line and enter the participant's own name.
16	Save the file.
17	Increase the system volume.
18	Decrease the system volume.
19	Mute the system audio.

The scenario progressed from browser initiation and tab management (Tasks 1–6) to web-content selection and copying (Tasks 7–9), desktop and file operations (Tasks 10–16), and system-audio control (Tasks 17–19). Several later tasks depended on outputs produced in earlier tasks; for example, the paragraph copied in Task 9 was pasted into the newly created file in Task 14.

2.7. Measures

Three task-level measures were recorded during the preliminary usability evaluation.

Task completion indicated whether the participant reached the predefined outcome for each task. Because verbal assistance could be provided when a participant reached an impasse, task completion should be interpreted within the assisted study protocol rather than as a measure of fully independent completion.

Completion time was recorded in seconds for each task. Timing began when the participant started the relevant task and ended when the predefined outcome was reached. Task-level times were used descriptively to compare durations across the scenario and to highlight operations that may warrant further investigation.

Facilitator assistance indicated whether the participant required a verbal hint to continue after reaching an impasse. Assistance consisted of verbal guidance and did not involve the facilitator completing the task on the participant's behalf. The number of participants requiring assistance was summarised separately for each task (Keleş, 2024).

After completing the scenario, participants provided comments and suggestions concerning the voice-command interaction. These comments addressed issues such as command phrasing, command coverage, feedback visibility, and difficulties encountered during multi-step operations. The feedback was used descriptively to support the interpretation of the task-level results; it was not collected using a standardised usability or cognitive-load scale.

2.8. Procedure

The usability sessions were conducted after completion of the initial software-development stage. Participants were informed about the Turkish voice-command interaction and the sequence of activities included in the scenario. They were then asked to complete the 19 tasks in the predefined order using the voice-command module.

For each task, the evaluator recorded the completion time and whether the participant required assistance to proceed. When a participant reached an impasse, brief verbal guidance was provided to enable continuation of the scenario. The evaluator did not complete the task on the participant's behalf. Assistance events were recorded because completion achieved after guidance could not be interpreted as fully independent task completion.

After completing the scenario, participants were asked to comment on the strengths and limitations of the interaction and to suggest possible improvements. These comments were collected as descriptive feedback; no standardised usability, workload, fatigue, or cognitive-load questionnaire was administered (Keleş, 2024).

The face/head-motion cursor-control module was not used during the participant sessions. It was examined only through developer testing during the implementation stage and is therefore excluded from the participant-based usability and performance findings reported in this article.

2.9. Analysis plan

The analysis was descriptive and was conducted at both task and scenario levels. At the scenario level, the number of completed tasks and the overall distribution of facilitator-assistance events were summarised. At the task level, completion time and the number of participants requiring assistance were examined to identify tasks associated with comparatively greater interaction difficulty (Keleş, 2024).

Task results were interpreted according to the operations required in the scenario, including browser initiation, tab navigation, web-content selection, text manipulation, file operations, and system-audio control. Because the participant sessions evaluated the Turkish voice-command module, the analysis focused on command use, task sequencing, interaction feedback, and multi-step workflow demands. No participant-level analysis of face/head-motion cursor performance was conducted.

Post-scenario comments were reviewed descriptively and grouped according to recurring issues explicitly raised by participants, such as command phrasing, command coverage, feedback visibility, and suggestions for simplifying multi-step operations. These comments were used to

explain or contextualise the task-level findings. No formal qualitative coding framework, inferential statistical analysis, or standardised cognitive-load analysis was applied.

2.10. Ethical considerations

All participants provided informed consent before taking part in the usability evaluation, and participation was voluntary. Participants could withdraw at any time without penalty. No personally identifying information is reported in this article, and the findings are presented in anonymised or aggregated form.

3. Results

3.1. Evaluation sample and scope

A total of 25 non-disabled proxy participants completed the preliminary scenario-based usability evaluation of the Turkish voice-command module. The participant group included 14 men and 11 women, with a mean age of 28 years. The face/head-motion module was not used during the participant sessions and is not represented in the results reported in this section. The reported outcomes comprise task completion, task completion time, facilitator assistance, and descriptive post-scenario feedback (Keleş, 2024).

3.2. Task completion and facilitator assistance

All 25 participants reached the predefined outcome for each of the 19 tasks. However, task completion occurred within an assisted evaluation protocol and therefore does not represent fully independent completion. When participants reached an impasse, brief verbal guidance was provided so that they could continue the scenario (Keleş, 2024).

Facilitator assistance was recorded in six of the 19 tasks, corresponding to 28 task-participant instances. The highest assistance frequency occurred in Task 9, copying the selected paragraph, for which 8 participants required guidance. This was followed by Task 7, selecting the fifth search-result link, and Task 11, creating a new file, with 6 participants each. Assistance was also required in Task 1 by 5 participants, Task 10 by 2 participants, and Task 8 by 1 participant. No assistance was recorded for the remaining 13 tasks (Keleş, 2024).

Table 3. Task-level facilitator-assistance frequency.

Task	Task operation	Participants requiring assistance, n	Percentage of sample
1	Open a web browser	5	20%
7	Select the fifth search-result link	6	24%
8	Select a paragraph on the web page	1	4%
9	Copy the selected paragraph	8	32%
10	Return to the desktop	2	8%
11	Create a new file	6	24%

The distribution suggests that some operations were more likely than others to produce an impasse during the preliminary voice-command evaluation. Because the sample comprised non-disabled proxy participants, these observations point to interaction points that may warrant further examination but do not establish the accessibility barriers or assistance requirements experienced by individuals with upper-limb impairments.

Percentages were calculated using the full sample of 25 participants. Assistance was recorded as a task-level occurrence indicating that verbal guidance was required for the participant to continue. The table does not indicate the severity or cause of the impasse.

3.3. Task completion time profile

Mean completion times varied across the 19 tasks, ranging from 9 seconds for Task 6 to 240 seconds for Task 7. The longest mean completion times were recorded for Task 7 (240 s), Task 1 (222 s), Task 11 (214 s), Task 9 (161 s), Task 8 (141 s), and Task 10 (139 s). By contrast, Tasks 6, 18, and 19 had mean completion times of 9, 10, and 10 seconds, respectively (Keleş, 2024).

Table 4. Mean task-completion times in the preliminary usability scenario.

Task	Task operation	Mean completion time, s
1	Open a web browser	222
2	Perform a web search	19
3	Open a new browser tab	41
4	Switch to the previous tab	13
5	Switch to the next tab	11
6	Close the newly opened tab	9
7	Select the fifth search-result link	240
8	Select a paragraph on the web page	141
9	Copy the selected paragraph	161
10	Return to the desktop	139
11	Create a new file	214
12	Name the file	24
13	Open the file	17
14	Paste the copied text into the file	96
15	Enter the participant’s name on a new line	38
16	Save the file	14
17	Increase the system volume	11
18	Decrease the system volume	10
19	Mute the system audio	10

These values describe the time required to reach each predefined outcome within the assisted proxy-user evaluation. Because the tasks differed in their content, number of steps, and dependence on previous scenario actions, the mean times should not be interpreted as

controlled comparisons of command efficiency. They also do not provide direct evidence of fatigue, cognitive load, accessibility for individuals with upper-limb impairments, or performance relative to conventional mouse-and-keyboard input.

Mean times represent complete task durations within the sequential scenario and may include time spent interpreting the task, formulating or repeating a command, waiting for system response, and receiving verbal assistance where required. They are not isolated speech-recognition latency or movement-time measurements.

4. Discussion

4.1. Interpreting task-level impasses in the preliminary voice-command evaluation

Although all 25 participants reached the predefined outcome for every task, facilitator assistance was required in 28 task-participant instances across six tasks: Tasks 1, 7, 8, 9, 10, and 11. The concentration of assistance in a limited subset of the scenario distinguishes assisted completion from independent operability. In particular, Task 9 produced the highest assistance frequency, followed by Tasks 7 and 11.

The affected tasks involved different forms of interaction, including initiating an application, selecting web content, copying text, returning to the desktop, and creating a file. The available records do not support a definitive explanation for every impasse because assistance was not classified using a formal error taxonomy. Nevertheless, the pattern points to voice-command operations and task transitions that may warrant closer examination in subsequent design iterations. Because the evaluation involved non-disabled proxy participants, these impasses should not be interpreted as direct evidence of the barriers experienced by individuals with upper-limb impairments. They instead suggest areas in which the current voice-command implementation might benefit from clearer command phrasing, improved feedback, or simplified workflow support.

4.2. Interpreting task-completion time in the preliminary evaluation

Task-completion times varied considerably across the scenario, ranging from 9 to 240 seconds. The longer mean durations recorded for Tasks 1, 7, 8, 9, 10, and 11 indicate that these operations required more time within the assisted evaluation protocol. However, the tasks differed in their number of steps, command requirements, dependence on previous actions, and likelihood of facilitator assistance. The observed time differences therefore cannot be attributed to a single interaction problem.

The task durations are useful as descriptive indicators of operations requiring further investigation, but they should not be interpreted as direct measures of efficiency, accessibility, fatigue, frustration, cognitive load, or willingness to adopt the system. No standardised workload, fatigue, satisfaction, or cognitive-load instrument was administered, and the study did not include a comparison condition using conventional mouse-and-keyboard interaction.

Cognitive-load theory distinguishes demands inherent in a complex task from avoidable demands introduced by the way information and interaction are structured (Paas & van Merriënboer, 2020). In the present scenario, command formulation, state tracking, error recovery, and

transitions across multi-step operations could plausibly contribute to cognitive demand. This interpretation remains theoretical because cognitive load was not measured directly.

Future evaluations should separate speech-recognition latency, command-formulation and repetition time, system-response time, facilitator assistance, and independent task-execution time. Studies involving the intended user population should also combine performance measures with validated self-report instruments and qualitative accounts of effort, comfort, and interaction experience.

4.3. Positioning the rule-based approach in relation to adaptive AI

The deterministic architecture used in the original development should not be interpreted as a claim that rule-based systems are technically superior to machine-learning or generative-AI approaches. The prototype was designed to execute a bounded set of computer operations through explicit parent-command, sub-command, priority, and executable-code mappings. For this early-stage implementation, the architecture allowed the command logic and action mappings to be inspected directly, did not require a task-specific training dataset, and permitted the command vocabulary to be extended through database updates (Keleş, 2024).

These properties were accompanied by important limitations. The system depended on predefined expressions, required manual intervention when new commands or alternative formulations were added, and could not learn automatically from user interaction. Recent voice-interface research includes more adaptive alternatives. AutoVCI, for example, generates voice-command mappings from smartphone operation sequences and uses accumulated interaction information to improve semantic understanding. More recently, Savant has used large language models to enable blind screen-reader users to issue flexible natural-language commands across different computer applications (Kodandaram et al., 2024; Pan et al., 2022).

One possible future direction would be a hybrid architecture in which an adaptive language model interprets paraphrases or higher-level intentions, while a deterministic execution layer restricts the resulting action to a predefined set of validated computer operations. Such an architecture could request confirmation when the interpreted intention is ambiguous and could use logged corrections to support subsequent personalisation. This hybrid proposal was not implemented or evaluated in the present study. Because no direct comparison with machine-learning or large-language-model approaches was conducted, the current findings do not establish the superiority of the rule-based architecture.

4.4. Implications for Design for All and inclusive interaction design

Design for All requires more than the provision of an alternative input channel. It requires interaction methods that accommodate diverse abilities and preferences, provide meaningful choices, and avoid placing the full burden of adaptation on the user. The Universal Design principles most relevant to the present system include equitable use, flexibility in use, simple and intuitive use, tolerance for error, and low physical effort. Ability-Based Design similarly emphasises what individual users can do and how an interactive system can adapt to those abilities rather than designing solely around diagnostic categories (Center for Universal Design, 1997; Wobbrock et al., 2011).

Within the limited scope of the preliminary voice-command evaluation, the observations suggest the following considerations for future design:

- Provide choice without requiring every user to employ every modality. A future multimodal version should allow users to select voice commands, face/head-based control, or other compatible access methods according to their abilities, preferences, context, and task. The modalities should offer alternative or complementary routes rather than requiring a fixed combination. Command vocabulary, confirmation requirements, and interaction pace should also be adjustable where technically feasible.
- Simplify and clarify multi-step workflows. The concentration of facilitator assistance in selected browser, text-manipulation, and file-operation tasks indicates that users may benefit from explicit step prompts, clear information about the current system state, and confirmation before consequential actions. These features would support simple and intuitive use without assuming that all users have the same technical experience.
- Make recognition, errors, and recovery visible. The interface should communicate what expression was recognised, what action will be performed, and why an action could not be completed. Functions such as repeating the last command, displaying available commands, cancelling an action, and undoing the previous operation could help reduce reliance on external assistance. Audible and visual feedback should be considered as complementary options rather than as interchangeable requirements for every user.
- Support personalisation where feasible. Differences in motor control, speech, preferred interaction pace, fatigue, prior computer experience, and environmental conditions may affect which interaction configuration is appropriate. Future versions could therefore include user-adjustable settings rather than assuming that one default configuration will serve all intended users.
- Involve intended users throughout design and validation. Proxy-user evaluation may identify preliminary technical and workflow problems, but it cannot establish equitable use or accessibility for individuals with upper-limb impairments. Subsequent development should involve people with diverse upper-limb access requirements in requirements elicitation, iterative co-design, usability testing, and longer-term evaluation.

These considerations translate the preliminary observations into prospective inclusive-design considerations rather than validated accessibility outcomes. The present study points to interaction points that may warrant refinement within the Turkish voice-command module; it does not demonstrate that the current prototype already achieves equitable use, low physical effort, or effective personalisation for the intended user population.

4.5. Accessibility as a socio-technical and rights-based concern

Disability is not treated in this study solely as an individual deficit to be compensated for through technology. The social model of disability directs attention towards barriers created by environments, institutions, and design decisions. Disability Studies has similarly encouraged assistive-technology researchers to examine how problems are defined, whose expertise is prioritised, and whether disabled people participate meaningfully in research and design (Mankoff et al., 2010; Oliver, 1990). In the context of computer access, exclusion may emerge from the interaction among individual motor or speech characteristics, hardware, operating-system conventions, command vocabulary, application design, recognition performance, environmental conditions, and available support.

The World Wide Web Consortium (2024) also presents accessibility as the outcome of interdependent components rather than of content alone. These components include content,

user agents, assistive technologies, users' knowledge and strategies, developers, authoring tools, and evaluation tools. WCAG primarily addresses web content, whereas the wider W3C framework also includes guidance for user agents and authoring tools. Although the present prototype was not evaluated for conformance with WCAG, UAAG, or ATAG, this wider perspective is relevant because successful computer access depends on how the speech-recognition service, operating system, applications, feedback mechanisms, access technologies, and user strategies function together.

Article 9 of the Convention on the Rights of Persons with Disabilities frames access to information and communication technologies as a condition for independent living and participation on an equal basis with others (United Nations, 2006). Accordingly, future evaluation should consider not only whether a predefined task can eventually be completed, but also whether users can interact with autonomy, choice, privacy, acceptable effort, and reduced dependence on third-party assistance. These questions require direct participation by people with diverse upper-limb access requirements and evaluation within realistic contexts of use.

Within this socio-technical and rights-based framing, the current proxy-user study should be understood as a preliminary engineering and workflow evaluation. Non-disabled proxy participants may help identify initial technical problems and unclear task transitions, but they cannot substitute for the lived expertise of intended users or establish equitable access, independent participation, or social inclusion. The scope of the present evaluation is therefore limited to documenting the prototype, reporting preliminary interaction points that may warrant refinement, and outlining considerations for subsequent co-design and target-user validation.

4.6. Limitations

The most important limitation is that the post-development evaluation involved 25 non-disabled proxy participants rather than individuals with upper-limb impairments. Although the earlier formative consultations included two individuals with upper-limb impairments and one individual with a visual impairment, those consultations occurred before completion of the system and did not constitute usability or performance testing. The findings therefore cannot establish accessibility, usability, effectiveness, autonomy, or reduced physical effort for the intended user population.

The participant-based evaluation concerned only the Turkish voice-command module. The face/head-motion cursor-control module was examined through developer testing during implementation but was not used by the 25 participants. Consequently, the study does not provide participant-level evidence concerning cursor accuracy, pointing performance, multimodal interaction, modality switching, or conflict resolution between voice and head-motion input.

Task completion occurred within an assisted protocol. All participants eventually reached the predefined outcome for every task, but verbal guidance was provided when they reached an impasse. Completion should therefore not be interpreted as fully independent performance. Assistance was recorded as a task-level occurrence but was not classified using a formal error or assistance taxonomy, which limits conclusions concerning the precise causes and severity of the observed difficulties.

The study used a small and heterogeneous convenience sample. Prior experience with voice interfaces, familiarity with the applications used in the scenario, digital proficiency, age-related

factors, and individual command strategies were not systematically measured or controlled. These limitations restrict the interpretation and generalisability of the descriptive results.

The reported completion times represented whole-task durations within a sequential scenario. They may include task interpretation, command formulation or repetition, speech-recognition and system-response time, dependence on earlier tasks, facilitator assistance, and task execution. Fitts's Law requires movement amplitude and target width, whereas Steering Law requires path geometry such as path width and length (Accot & Zhai, 1997; Soukoreff & MacKenzie, 2004). Because target width, movement amplitude, target coordinates, isolated movement time, and path geometry were not recorded, the available data do not support a valid Fitts's Law or Steering Law analysis.

No conventional mouse-and-keyboard condition, alternative voice interface, machine-learning system, or large-language-model-based interface was included for comparison. The findings consequently do not demonstrate that the developed rule-based architecture is more efficient, usable, accurate, or accessible than contemporary alternatives.

No standardised instrument was used to measure usability, satisfaction, workload, cognitive load, fatigue, comfort, perceived autonomy, or intention to use the system. Post-scenario comments were collected and interpreted descriptively rather than through a predefined qualitative coding framework. The study was also limited to short, researcher-observed sessions and did not examine longitudinal use, learning effects, personalisation, environmental variation, privacy concerns, or integration into participants' everyday computer activities.

Speech-to-text conversion relied on Google Speech Recognition. Recognition performance may therefore be influenced by the external service, microphone characteristics, network conditions, background noise, pronunciation, and changes to the service beyond the control of the developed system. The present study did not isolate or systematically compare these factors.

4.7. Future work

Future research should directly involve individuals with diverse upper-limb access requirements. Intended users should participate not only as final evaluators but also in requirements elicitation, iterative co-design, prototype refinement, and the selection of meaningful outcome measures. Participant reporting should describe relevant functional abilities, preferred access methods, prior experience, and contextual factors without reducing participants to diagnostic labels.

The Turkish voice-command and face/head-motion modules should initially be evaluated separately. For the voice-command module, future studies should record recognition accuracy, command-success rate, response latency, repetitions, reformulations, errors, recovery actions, independent task completion, and facilitator assistance. Testing should also examine variation in pronunciation, speech characteristics, background noise, microphone quality, network conditions, and familiarity with the command vocabulary.

The face/head-motion module requires a controlled participant-based pointing evaluation. Target width, movement amplitude, target location, movement time, selection errors, and calibration requirements should be recorded systematically. These data would permit appropriate Fitts's Law analyses (Soukoreff & MacKenzie, 2004) and, where path-constrained movement is examined, Steering Law analyses (Accot & Zhai, 1997). The evaluation should also consider comfort, physical effort, unintended movement, fatigue, and the need for adjustable sensitivity, dwell time, and confirmation mechanisms.

After each input method has been evaluated independently, the complete multimodal system should be assessed to explore whether the modalities function as useful alternatives or complementary forms of interaction. Future work should define how users select or switch modalities, how ambiguous input is handled, whether confirmation is required before consequential actions, and how the system responds when the modalities produce conflicting signals. These mechanisms should be evaluated rather than assumed from the existence of multiple input channels.

Multimodal interfaces may use complementary input signals to reduce recognition ambiguity, but this benefit depends on explicitly designed temporal integration, confirmation, and conflict-resolution rules (Oviatt, 2000). The present prototype did not implement or evaluate such mutual-disambiguation mechanisms.

Comparative studies should examine the rule-based system alongside conventional mouse-and-keyboard interaction, existing accessibility tools, and adaptive voice-interface approaches. A hybrid architecture could use an adaptive language model to interpret paraphrases or higher-level intentions while retaining a deterministic execution layer that restricts actions to a validated command set. Such a design would require explicit confirmation, transparent feedback, error recovery, privacy protection, and safeguards against unintended computer actions. Its effectiveness should be established through direct comparison rather than theoretical claims.

Future evaluations should combine objective performance data with validated measures of usability, workload, cognitive load, comfort, satisfaction, perceived autonomy, and intention to use. Qualitative interviews or think-aloud sessions could provide further insight into command formulation, trust, privacy concerns, preferred feedback, and dependence on external assistance. Any qualitative analysis should use a clearly described coding and reliability procedure.

Finally, longitudinal studies in realistic contexts are needed to examine learning, personalisation, sustained use, environmental variation, and integration into everyday computer activities. Evaluation should consider not only task completion and speed but also autonomy, user choice, acceptable effort, privacy, reliance on third-party assistance, and participation in education, employment, communication, and other areas of digital life.

5. Conclusion

This study documented an early-stage computer-access prototype comprising a Turkish voice-command module and a face/head-motion cursor-control module, and reported a preliminary scenario-based evaluation limited to the voice-command module. Twenty-five non-disabled proxy participants completed 19 tasks within an assisted protocol. All participants reached the predefined outcome for each task, but facilitator assistance was recorded in 28 task-participant instances across six tasks, and mean task-completion times ranged from 9 to 240 seconds. These observations point to operations that may warrant further examination, particularly web-content interaction, text manipulation, file creation, and application navigation.

Within its limited scope, the study documents an early-stage Turkish computer-access prototype and reports preliminary interaction problems observed in the voice-command evaluation. The observations suggest possible areas for future development, including clearer command and system-state feedback, accessible error recovery, personalisation, user choice, and direct involvement of intended users in co-design and evaluation. Future studies could evaluate the two modules independently before examining their combined use, recruit participants with diverse upper-limb access requirements, collect the variables required for appropriate pointing-

performance analyses, and compare the deterministic architecture with adaptive alternatives. The present results should be treated as preliminary and should not be interpreted as evidence that the system has achieved effective or equitable computer access.

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Mobile streaming applications for ADHD

Barriers, features, and design principles for neurodivergent accessibility

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Abstract: When discussing accessibility, neurodivergent individuals, such as people with attention deficit hyperactivity disorder (ADHD), are often not considered. Existing research suggests that the needs of users with ADHD differ from those of neurotypical users. However, research in this field is sparse, and often results in design implications that are not thoroughly validated with users.
This research aims to find accessibility barriers faced by adults with ADHD when using mobile applications, and which design elements can help mitigate these barriers. To answer these questions, an exploratory approach was chosen, including structured interviews, the development of a prototype, and testing the prototype.
The results of this research show that adults with ADHD are hindered by various barriers such as nested layouts, too much irrelevant content, features that require too much effort from the user, navigation issues, and lack of user control. These barriers can be minimized by reducing the number of animations and videos, utilizing more colours, and incorporating minimalist design principles when designing a mobile application.

Keywords: ADHD, neurodivergence, software accessibility, accessible mobile design, mobile streaming applications

1. Introduction

Following the EU directive on the accessibility requirements for products and services (Publications Office of the European Union, 2019), mobile applications must be accessible for everyone from 28 June 2025 on. This is to remove barriers for people with various kinds of disabilities, and therefore to enhance inclusion in the European society (Publications Office of the European Union, 2019). But how does accessibility look like for people with different disabilities, and what qualities do applications need to have to be considered as accessible, or even inclusive? Currently, applications lack accessibility for neurodivergent groups. An example of this is Google Maps, which conveys information in a way that does not allow users with ADHD to extract important pieces of information about their route, while users without ADHD can understand the displayed information without becoming overwhelmed (Smits, 2022). This is because user interface (UI) design principles are developed for neurotypical people and it is not clear to which extent they can be applied to neurodivergent individuals such as people with ADHD. In the past, it was believed that ADHD only existed in children, and not in adults (Barkley, 2019), which would lead to the conclusion that additional research on adults with ADHD is unnecessary. However, the belief of ADHD being a condition only present in children has been proven to be a myth (Barkley, 2019). Furthermore, ADHD differs in children and adults (CDC, 2024), so additional research is needed on adults with ADHD. Thus, this research aims to understand the needs of adults with

ADHD, and to identify guidelines for design principles in respect to mobile applications that are suitable to make those apps more accessible to people with ADHD. This could help developers avoid exclusion and discrimination in the future.

In previous interviews regarding the user experience of adults with ADHD (Smits, 2022), users repeatedly reported facing problems such as navigational issues when trying to understand where they came from and where to go next, when using the music streaming application Spotify[1]. Furthermore, existing research on accessibility for users with ADHD by Santos (2022) and Turner (2023) also focused on the use case of video streaming applications. Therefore, streaming applications could be suspected as posing more challenges than other types of applications to people with ADHD and are considered as suitable for exploring these challenges more. Thus, the use case of a mobile music streaming application is used as an example domain to define and discover design principles for users with ADHD. The scope of this research is defined as accessibility in mobile music streaming applications, and the target group is scoped to adults with ADHD.

This leads to two main research questions (RQ) and their sub-questions (SRQ):

- RQ1: What are the accessibility barriers adults with ADHD face when *accessing mobile streaming applications?*
  - SRQ1.1: What is the most prominent barrier?
  - SRQ1.2: What features do users with ADHD want in their mobile streaming apps?
- RQ2: Which design principles minimize or remove the accessibility *barriers?*
  - SRQ2.1: How do these principles relate to existing general UI design principles?

2. Related Work

In UI design, a popular set of principles that is commonly used and referred to, e.g., by Smits (2022), are the Nielsen Heuristics. These heuristics are ten principles for improving the usability of applications which were developed by Nielsen in 1994. They include giving the user appropriate feedback to actions, incorporating error prevention measures and showing clear error messages to the user to help figuring out the next steps, and reducing cognitive load by making important options visible, while avoiding showing irrelevant pieces of information (Nielsen, 1994).

To find complementary work regarding UI design for adults with ADHD, a scholarly keyword search with the search terms *UI design for ADHD* and *ui design guidelines for ADHD* was carried out in January 2025 and March 2026, using Google Scholar[2]. The results were filtered for articles that were published in 2020 or later to get more recent results.

2.1. Traditional UI Design for adults with ADHD

Building on the Nielsen Heuristics, Smits (2022) investigated usability adaptations of mobile applications for adults with ADHD. To investigate barriers faced by users with ADHD, Smits conducted interviews and surveys. Afterwards, two minimal user interfaces for a navigation application were designed, tested and compared to an existing navigation application (Smits, 2022).

[1] https://open.spotify.com
[2] https://scholar.google.nl

Smits found that it was necessary for participants with ADHD to have important pieces of information highlighted by colour, removing elements from the interface and limiting the overall amount of information presented to the user eased the application usage. Furthermore, people with ADHD were enabled to achieve their goals inside the application by applying these design principles, while neurotypical people preferred the accessible design, but did not need it to carry out their tasks (Smits, 2022). These results are relevant for this work, as they present barriers such as not being able to identify relevant information due to a high density of (textual) elements on the screen, or being distracted by moving content such as videos (Smits, 2022). However, these barriers and the respective approaches to remove them have never been validated in another way than by designing exemplary mock-ups (Smits, 2022).

The importance of colour for users with ADHD, and the barriers posed by interfaces which are densely filled with information are also recurring in Turner's research (Turner, 2023). Turner identified issues when designing for an audience with ADHD by doing interviews, tests and workshops with participants with ADHD, as well as trained professionals in the domain of UI design. Based on these barriers, Turner developed guidelines for designing interfaces for users with ADHD. These guidelines were validated by testing simple principles like whether icons are easier to understand than text. The problems identified through the interviews were finding the balance between not overloading interfaces, and therefore overstimulating users with ADHD, versus designing too minimalist interfaces, which are not suitable for grabbing the focus of users with ADHD, the choice of colours which can also influence how users with ADHD perceive information, and a lack of feedback in case of errors, leaving users with ADHD with a greater feeling of self-doubt. Furthermore, participants with ADHD reported on facing navigational issues connected to nested menus, and understimulation or overstimulation caused by either a lack of personalization, too many elements on a single page, or auto-playing contents (Turner, 2023).

Guidelines to mitigate these barriers include principles such as conveying information in multiple forms, providing possibilities for personalization, highlighting important information with colour or contrast, preferring short texts, and not sending too many notifications to the user (Turner, 2023).

Additional design principles were collected by Kletenik et al. (2024) in a literature review of resources that teach about software accessibility for users with ADHD, autism or dyslexia. In these principles, guidelines that have also been presented in Smits' (2022) and Turner's (2023) work reoccur, such as applications being easier to use for people with ADHD when a neat layout without too many elements on the same page is given, the page's content is organized clearly, and important information is highlighted by colour or a bolder font weight. However, there is no additional explanation provided about what it means to have page content clearly organized or how much information is too much information. Furthermore, they advise using a 12-14pt sized font without serifs, give clear instructions about what the user must do, allow for user customization of an application's appearance and show information long enough for users to process the information (Kletenik, Minkowitz, Peric, Sahin, & Adler, 2024).

2.2. Features for adults with ADHD

In the article by Santos (2022), it was explored how people with ADHD and dyslexia experience video streaming platforms, and how they think about the issues they are facing when navigating these platforms by conducting interviews and co-design sessions (Santos, 2022).

Santos (2022) found that the participants disliked the automatic recommendations of shows to watch, as they felt like the algorithm for creating recommendations would leave them out and

did not represent their interests well. Another finding was that even if categories can be helpful, they pose challenges to participants with ADHD when sub-categories are introduced. Features liked by the participants were the functionality of going back to where the user was when using the application, the previous time, and the direct search, as it allows them to avoid diving into categories. They also underlined the importance of sufficient search algorithms (Santos, 2022). Santos' findings inform this research, because she identified challenges for users with ADHD, such as nested categories adding cognitive load, and dynamic content like auto-played media, which can also be transferred to the domain of music streaming applications.

3. Methodology

This research is positioned in the research field of user experience design and followed an exploratory mixed-methods approach including structured interviews, developing a prototype, and conducting experiments with users to validate the findings. The qualitative part of the research can be found in different phases of the methodology: The structured interviews, and the prototype evaluation, as users were asked for their opinion in an interview setting. The quantitative part of the research lies within the prototype evaluation, as participants had to fulfil tasks while their actions and task completion times were recorded and was added for indicative, preliminary results that can be used as an introduction for further research.

3.1. Ethical Considerations

Various ethical challenges can be encountered when working on inclusive software projects (Dirks, 2022). According to Susanne Dirks (2022), these problems could concern the group of researchers themselves, and the participants of the study. As this research was not conducted in a team, but by a single person, the challenges regarding researchers will not be discussed further.

One possible obstacle regarding study participants is that they must give informed consent. The participants must be informed about their tasks and the research goal in a way that is easy to understand before they begin to participate (Dirks, 2022). This is an issue that could be encountered when conducting interviews with people with ADHD, as well as when testing the prototype with users. Therefore, an information and consent sheet was handed out to potential participants which they had to read and sign before the interviews and experiments were done. Furthermore, the researcher was available in person and via email for giving additional information before the interviews and user tests.

3.2. Structured Interviews

For the qualitative part of this research, structured interviews were chosen to find common barriers faced by adults with ADHD when using mobile music streaming applications, and to derive requirements for a prototype.

Other interview settings would have been possible, too, but structured interviews were preferred. During structured interviews, a fixed script is followed, which was favoured over semi-structured interviews, to get a higher consistency across participants to make comparison easier. This script is grounded in data gathered from semi-structured interviews previously done by Smits (2022), and it aims to test against the findings from these previous interviews. The interviews consisted of 14 questions, starting by gathering demographic information, covering the participant's smartphone and music streaming usage, and ending with detailed questions about the participants likes, dislikes, wishes and expectations regarding their music streaming applications.

The full list of questions can be found in Appendix A. The aim of these questions was to gather a list of barriers that adults with ADHD face while using those applications, discover how these barriers might connect to ADHD, and get insights into what could make their experience more pleasant. These findings formed the basis of the prototype requirements.

The participants for the interviews were recruited through convenience sampling on social media platforms like LinkedIn, Instagram, Whatsapp and Signal. This method of sampling is a biased method, but it has been chosen due to difficulties in getting access to adults with ADHD in a non-clinical setting, and convenience sampling is a way to connect to this population. With this approach, 15 participants were recruited.

From these 15 participants, 14 used Spotify as their main music streaming application, and one person used YouTube. Other streaming apps mentioned but not mainly used were SoundCloud, Apple Music, and Audible. Despite the biased sampling method, the group showed diverse features such as different genders and an age range from 20 to 47. Still, a bias towards younger women could be detected, as the average age was 28.6, and 73.33% of the participants identified as female.

This study focuses on adults with ADHD in a Western culture, since all participants were residing in Germany and the Netherlands. This sample is valuable, as it enabled finding common barriers faced by people with ADHD and was suitable for finding common wishes the participants expressed regarding mobile music streaming applications. It could be verified by comparing the results from the interviews to related research by Smits (2022) and Santos (2022).

3.3. Prototype

Based on the interview transcripts, the responses were analysed for common themes and issues with music streaming applications mentioned by multiple participants. The themes and issues were then used to collect requirements for a prototype that is more accessible to people with ADHD. Moreover, the requirements for the prototype were matched to existing UI design principles to explore the suitability of general UI design principles for people with ADHD and, therefore, to answer SRQ2.1. This prototype was developed with NextJS[3] and used the Spotify API[4] as the backend to be able to play music when interacting with the prototype. This has been done to make the prototype resemble a real music streaming application, which makes the tests simulate a real everyday scenario for the participants, and therefore, enable a better comparison between the prototype and real music streaming applications.

3.4. Validation

To improve the internal validity of the prototype, it was tested utilizing qualitative and quantitative methodology. The tests were done with 14 participants which were split into two groups: A test group, consisting of 7 adults with ADHD, and a control group with 7 adults without ADHD. The average age of the test group was 27.7 years, ranging from 22 to 43 years, while the control group featured an average age of 33 years, ranging from 23 to 54 years. In addition, the test group consisted of 4 female participants, 2 male participants, and one participant who did not identify within binary gender categories. In the control group, there were 5 female and 2 male participants. In the test group, 2 of the participants were taking ADHD medication. The participants were acquired using convenience sampling. During the tests, the participants had to

[3] https://nextjs.org
[4] https://developer.spotify.com/documentation/web-api

perform tasks using an iPhone 13 Pro provided by the researcher. The tasks were defined based on the findings from the interviews, so they are listed in the results section. The time to complete the tasks was measured with a stopwatch and timestamps in the application logs, and the areas on which the participants focused were recorded using the built-in eye tracking using the front-facing camera and screen recording functionality in iOS 18, so no third-party tooling was utilised. The participants had to give their own opinion on the prototype as well, to be able to connect the subjective experiences of participants with the measurements. The goal of this procedure was to ensure the internal validity of this research, as well as to investigate the elements of the prototype that posed barriers or removed barriers for users with ADHD. Additionally, the overall results of this research were being validated by triangulating these results with related work by Smits (2022) and Santos (2022). The goal of comparing the findings of this research with other findings is to improve the external validity, as this research's results could either fit in with previous results, which confirms and strengthens previous research, or they could challenge existing research. In the second case, the differences between the studies would be investigated to explain the varying results.

4. Results

The results of the interviews and the prototype validation are presented in the following.

4.1. Structured Interviews

Common themes that were coming back throughout the interviews were presentation issues, issues regarding the ratio between cost and benefit of the streaming applications' functions, consistency issues, and the reinforcement of problems regarding the users' self-esteem. Additionally, participants mentioned features they liked or would like to have.

4.1.1. Barriers

The barriers that users with ADHD faced when using their music streaming apps can be divided into categories of problems.

First, there are presentation issues: confusing nested layouts leading to mis-clicks, an overload of (irrelevant or auto-generated) content, and videos which are seen as a distraction. Other concerns in this category are cluttered home screens, especially when filled with irrelevant material. Also, participants described their app interface as chaotic due to a lack of categorization. One participant also found the dark colour scheme not engaging enough.

Another category of barriers are issues regarding the effort of using the application. There are user actions which require too much cost and lead to too few benefits for the users, e.g., creating and managing playlists, as users mentioned the process being too complicated, and not having enough patience to keep up with maintaining playlists over time. Furthermore, long texts and instructions are usually not being read.

The third category of barriers is navigation issues. Participants reported not knowing how to go back when they reached certain places in the application, getting lost in their music streaming app, not knowing what buttons do, and accidentally clicking on elements like buttons or links, causing unintended actions. Two of the participants also talked about a lack of user control. Their music streaming app was showing them pop-ups that came back often, even if they did not want to see it. Functions inside their application (like downloading songs automatically) were started regularly without giving users the option to abort these processes.

Then, there are concerns, which were raised by various participants but did not fit into the previous categories. Users often faced the situation of being stuck in a certain set of songs because they thought it was too much effort or even overwhelming to discover new music. This problem was recently approached by Spotify, as the respondents also reported that new features were introduced which led to new, matching music being automatically added to the user's current playlist. This was liked by the participants and mitigates the matter of never discovering new music. The next point is the inflexible search functionality. Users often misspell song titles, which leads to the music streaming applications not finding the songs the users wanted to find, which is an even bigger problem for users who heavily rely on listening directly from the search results instead of discovering generated or recommended content. Throughout all interviews, the topics of having too many (distracting and irrelevant) elements on the home screen and actions requiring too much effort were mentioned most often, so they are considered the most important barriers.

4.1.2. Popular Features

One of the most popular features is the *liked songs* playlist in Spotify. This feature consists of a playlist that is created by default, which can be updated by clicking on a heart-shaped button when playing a song. This button serves as a shortcut to add songs to this playlist. Furthermore, participants reported to rather have one single playlist for their own music than managing music in different playlists. This also becomes relevant on the technical side, as one of the participants complained about their music streaming application not being designed for this use case, since their own playlist got large enough to cause the app to crash when scrolling through this playlist. Other features that were commonly used by the participants are searching for single songs using the search bar and playing them from there directly, looping songs, and listening to playlists curated by other people or organizations. Moreover, features like auto-play or getting a personal mix of songs were mentioned as helpful for finding new music without getting overwhelmed.

4.1.3. Most Wanted

The wishes that were expressed most often by the participants are having an easier workflow to add songs to the own music collection, getting exposed to less auto-generated or irrelevant content, and having a clearly structured interface with easily visible buttons. Regarding the question about what they would like to see when opening the music streaming app, half of the participants wanted to see their own music library, and half of them would like to see what they listened to most recently.

4.1.4. Change Management in Complex Systems

Another takeaway from the interviews was that users often find their own simplified routines through complex systems. These routines might differ heavily from what the designers and developers had in mind when creating the system. An example for that is the participant experiencing trouble with their music streaming application, because they stored all music in a single playlist, which is not intended by the developers, as the app starts to crash when scrolling to the playlist. This must be taken into consideration when introducing changes to the application, for example when removing or replacing features, because these changes might lead to the users' pathways to suddenly get blocked. In that case, users must spend effort again to try to find new routines. This can be seen in the interview answers, as one participant collected all their music by using a heart-shaped button in Spotify, until the button got (re-)moved. This change made it impossible for the user to navigate the application in the same manner as before, making the experience unpleasant.

4.1.5. Reinforcement of Self-Esteem Issues

The next finding from the interviews is a more general problem about the effects of inaccessible design on people with ADHD. As already stated by Dirks (2022), people with cognitive conditions might have lower levels of self-esteem and assertiveness. This phenomenon was also observed during the interviews, in which participants with ADHD referred to themselves as “not normal“. Furthermore, participants seemed to attribute ways in which their music streaming applications did not work well to their own disability instead of seeing them as failures in the application. One example for this is a participant who told about a process in which their app would download songs without giving them an option to abort the download process, but then added that this probably was their own fault, because maybe there was an option to stop this download, but they “just might have missed it“ as they “often miss things“. This shows how an insufficient design can reinforce existing issues with the user’s self-esteem: when applications are not working well, the user contributes this failure to their own disability, which might influence their self-esteem in a negative way again, consolidating existing assumptions the user already has about themselves.

4.2. Prototype

Based on the themes found in the interviews, requirements for a prototype were developed. These requirements were used to create a prototype for testing previous findings and validating design principles for users with ADHD.

4.2.1. Requirements

The requirements for the prototype were derived from the previously presented interview findings. They are based on the features the participants liked to use most, the expectations they had like seeing their own music collection and the music they listened to most recently on startup, and the barriers they faced. To overcome the matter of applications including too much functionality that the users do neither need nor like, the requirements were limited to the most important features that the application should have and did not include additional features. As most of the requirements either exist to help the users reach their main goal (listening to music) or are directly related to the interview outcomes, all requirements are considered user requirements. There are two exceptions in the category of non-functional requirements which are explained and justified below in more detail.

Functional Requirements (FR)

1. The application’s content must be minimized to the features listed in the following requirements.
2. The application must be able to play music.
3. The application must include the functionality of searching for music.
4. The application must provide a personal music collection for each user.
5. The application should enable the user to accomplish the following tasks in a minimal number of steps[5]: searching music, playing music, saving music
6. The application should include a short cut to save music to the user’s music collection.
7. The application’s startup page should not include more than the last listened music, the user’s music collection and a personalized recommendation.
8. The application could group music to categories.

[5] not more steps than required in Spotify, if applicable

The functional requirements specify that the application should be serving the purposes most of the participants used their music streaming applications for. Furthermore, the prototype should make the participants' workflows such as saving music to an own collection as efficient as possible, measured by the number of steps required to fulfil a certain task. To prevent overloading the prototype with unnecessary features that lead to the participants getting distracted again, FR1 specifies that the application's content should be limited to the features that are listed below, aiming for a minimalist design.

Non-Functional Requirements (NFR)

1. The application must be possible to access through a browser on iOS and Android-smartphones.
2. The application should not take longer than 1 second to load on user actions.
3. The application should contain only clear buttons highlighted by using contrasting colours. NFR 1 and NFR 2 are grounded in the methodology of this work: To properly test the prototype with users later, it is important to be able to access the prototype through a browser on common smartphones, as well as it is necessary for the prototype to offer sufficient response times to the users. Otherwise, the validation results might get influenced by users being irritated by a prototype that does not run smoothly. NFR 3, in turn, is based on users who reported accidentally clicking on the wrong elements in their app, getting confused on where to go back or abort actions, and facing trouble with dark colour schemes that often do not offer a lot of contrast.

4.2.2. Minimalist Design Principles

In a blog entry by Fessenden (2021) published by the Nielsen Norman Group, the concepts of signal and noise are introduced as important in minimalist design: Signals are elements holding a lot of information for the user, and noise are elements in an interface without much information, such as technical terms or irrelevant information. According to Fessenden, signal elements must be maximized while noise has to be reduced. This means, that all elements of an interface that are necessary to fulfil the user's tasks should be at hand, but any elements besides that distract from these necessary functions (Fessenden, 2021). These principles can be connected to the results of the interviews, as the participants disliked the cluttered homepage and the video-based features inside Spotify. Therefore, these principles were utilized when developing a prototypical music streaming application.

4.2.3. Development

A prototype of a mobile music streaming application was developed as a progressive web app (PWA). This is an application running in a browser which can be accessed via a smartphone in the same way as any native app. It was developed using NextJS and the Spotify API and then deployed on Vercel[6]. The aim of the prototype was to implement the previously listed requirements and create a tool to assess the usefulness of different design principles in terms of improving usability for people with ADHD. Screenshots of the prototype can be found in figures 1 to 6 in Appendix C. As can be seen there, a minimalist design was created by using large simple buttons, a flat interface without many animations or auto-playing videos. The pages of the application were limited to a homepage to fulfil FR7, a search page for searching and saving music (FR3, FR5, FR6), and a page for the user's own music collection (FR2, FR4). The only requirement that was

[6] https://vercel.com

dismissed is grouping music into categories (FR8), as this was the least important requirement and bloated the prototype, interfering with other requirements regarding minimization (FR1).

4.3. Validation

For validating whether the prototype adheres to the previously identified needs of people with ADHD, it was tested with a group of participants with ADHD and a group of participants without ADHD, which all had to fulfil a set of four tasks.

4.3.1. Tasks

The tasks used to validate the prototype were defined based on the features that were identified as most important and most used by the participants in the interviews. Common usage patterns identified throughout the interviews were that users liked to have a single place in which they can quickly and easily save the music they like, and that users wished to see what music they last recently listened to as well as their own music collection when opening the application.

Therefore, the following four tasks were defined:

1. Tell what songs were played last.
2. Go to a recommended playlist and then go back to the previous screen.
3. Search for a song of your choice and save it to your music collection.
4. Go to your music collection and play a song from there.

4.3.2. Evaluation

In Table 1, the task completion times of the ADHD group (test group) and the non-ADHD group (control group) are displayed. A more detailed comparison of the task completion times in the form of box-plot charts can be found in the appendix in figures 7 to 10. Table 2 shows how many steps the participants needed on average to fulfil the given tasks, together with the minimal number of steps that is required for completing each task.

Table 1. Average Task Completion Times per Group (Ranges of Task Completion Times in Brackets)

Task Number	ADHD Group (n=7)	Non-ADHD Group (n=7)
1	9.34s (1.7s – 28s)	14.62s (3.55s – 36.6s)
2	4.92s (1.79s – 9.1s)	5.12s (2.6s – 11s)
3	13.17s (6.8s – 27.4s)	19.36s (8s-52s)
4	4.67s (1.6s – 9.5s)	4.27s (1s – 13s)

Table 2. Average Number of Steps for Task Completion per Group, compared to minimal number of steps required

Task Number	ADHD Group (n=7)	Non-ADHD Group (n=7)	Min. Required
1	1.71	2.43	1
2	2.29	2.29	2
3	3.57	3.29	3
4	2.29	2.29	2

The results suggest that the group of participants with ADHD completed the first and the third tasks faster on average than the group of participants without ADHD. For tasks 2 and 4, marginal differences regarding the average task completion times could be observed between both groups. Due to the sample size, Mann-Whitney U tests were applied to each task. And even if the

plain averages show faster task completion times for the ADHD group, none of the comparisons between the two groups reached statistical significance (all $p > 0.05$). So, these findings are not describing a definitive performance, but an indicative trend, and should be interpreted with caution.

When analysing the eye tracking data, certain patterns of eye movement could be identified in the ADHD group (n=7): Randomly looking at different points on the screen, looking at interesting (e.g. moving or colourful) elements first, and scanning the page from top to bottom and left to right (like reading a book). Two participants were looking around the page in seemingly random patterns, but one of them, who was also taking medication, was slowing down when they came across interesting elements. Two other participants fitted into the category of interesting elements first, and two more participants were scanning the screen from top to bottom and left to right.

Lastly, there was one participant who fitted in both categories, as they also scanned the page from left to right, but stopped more often at moving and colourful elements.

In the non-ADHD group (n=6, due to missing eye-tracking data for one participant), the following patterns of eye movement were observed: Looking at areas where elements were expected first and scanning from top to bottom. Three participants looked at the location on the screen where they expected the elements they were searching for first, while three people looked at the entire page from top to bottom. One person could not be classified due to missing eye-tracking data. Furthermore, it was noticeable that the participants without ADHD moved their eyes much slower when scanning the interface than the ADHD group did.

After performing the tasks, all participants were asked four questions regarding challenges they faced when interacting with the prototype, aspects they liked and disliked, and improvements they would like to see in the prototype. Challenges faced by the ADHD and non-ADHD group are presented in Table 3. These challenges are ordered by their relevance (amount of being mentioned by single participants). The non-ADHD group did not face common challenges besides technical questions due to the application being in the state of a prototype, as all the listed challenges were reported just once. One participant in the non-ADHD group also stated to not have faced any challenges.

The aspects liked most by the participants are displayed in Table 4, also sorted by relevance. One of the participants with ADHD took her own phone out to present to the researcher how the workflow in her regular music streaming application would be and expressed preferring the interface of the prototype to the one she is used to.

Table 3. Challenges faced by the participants when fulfilling prototype validation tasks (number of mentions in brackets)

ADHD Group (n=7)	Non-ADHD Group (n=7)
• Being distracted by the eye-tracking (3) • Understanding the tasks given by the researcher (2) • Navigating a different interface than they were used to (2) • Not finding the interface intuitive (2) • Looking at wrong parts of the screen (1) • Using a type of device they are not used to (1)	• Feeling stressed (“Like in an exam”) (1) • Expecting the recently listened songs at another page (1) • Thinking of a song to add to the music collection (1) • Understanding the difference between the two most recently played songs on the homepage (1) • “None” (1)

Table 4. Aspects the participants liked about the prototype (number of mentions in brackets)

ADHD Group (n=7)	Non-ADHD Group (n=7)
• The clear and simple structure of the application (5) • The functionality for adding a song to the user's own collection (2) • The button for going back from nested pages (1)	• The clear and simple structure of the application (5) • The navigation (2) • The large buttons (1) • The similarity to known apps (1)

Aspects that were disliked by the participants were shown in Table 5, ordered by relevance. As the wrong page that was opening on startup was mentioned by a participant who faced a technical bug in the beginning, leading to seeing another page on application startup than intended, this aspect can be disregarded.

Table 5. Aspects the participants disliked about the prototype (number of mentions in brackets)

ADHD Group (n=7)	Non-ADHD Group (n=7)
• The prototypical state of the application in general (3) • No dark mode available (2) • The animation of recently listened to songs (1) • Having too many things on the home page (1) • Seeing too much text and too few icons (1) • Missing quick actions like swiping (1)	• Being used to another app (1) • Not finding the recently listened to songs (1) • Not understanding how the own music collection and the recommended playlist are distinguished (1) • Not being able to add and view more albums (1) • Too few colour (1) • Having only one playlist and not more nesting (1) • Not seeing enough images (such as album covers when searching for songs) (1) • The prototypical state of the application in general (1) • The wrong page opening on startup (1)

Suggested improvements can be found in Table 6 and are ordered by relevance (with one person from the ADHD group not suggesting any improvements).

One common theme that was brought up by different participants in both groups and appeared in all questions was the comparison to already known applications and devices, even if the participants were not asked to do that. However, there were more common themes in the answers by the participants with ADHD than in the group without ADHD, as participants in the non-ADHD group mostly gave responses that were not repeated by other participants. Furthermore, the group with ADHD expressed having challenges when using the application more clearly than the group without ADHD, even if they performed better in terms of task completion times. Lastly, there was a more direct expression of feelings and preferences (such as "I love it" or "Sorry, but it is just not beautiful") by participants in the ADHD group than in the group without ADHD.

Table 6. Improvements for the prototype, suggested by the participants (number of mentions in brackets)

ADHD Group (n=7)	Non-ADHD Group (n=7)
• Avoiding song titles that are running through (3) • Adding more colours (2) • The possibility to use dark mode (1) • Buttons that are easier to recognize (1) • A more responsive interface with more visual response to user action (1) • Having "a less horizontal layout" (1) • Adding quick actions (1) • More personalisation regarding the colours (1)	• Adding more icons and images (2) • Changing the placement of the recently listened song (2) • Further development of the prototype (1) • Adding more features (1) • Adding more colours (1) • Fixing a bug regarding the application's scroll behaviour (1) • More personalisation regarding creating and pinning playlists (1)

5. Discussion

In this study, barriers faced by users of music streaming applications with ADHD were identified through structured interviews and ways to remove these barriers were tested by developing a prototype and evaluating it with those users.

5.1. Findings

The analysis of the interviews yielded three categories of barriers: Presentation issues, actions in an application requiring too much effort, and navigation issues. The most important barriers identified were the display of too many elements on one screen and functions that require too much effort and are not used consequently. Another noticeable finding is related to the change management in applications, as sudden changes of an interface can lead to routines of the users being destroyed. Furthermore, ADHD users referred to themselves as "the problem" when their applications did not work properly, which shows how inaccessible systems can reinforce existing self-esteem issues. During the prototype validation, the group of users with ADHD managed to complete half of the tasks on average in less time, and the other tasks as quickly as the group without ADHD. There were cases of ADHD participants who were able to complete the tasks faster than the non-ADHD participants, even though they reported that they disliked the prototype or did not find it intuitive. What could also be observed (see Table 2 in comparison to Table 1) is that participants with ADHD often did not require fewer steps to complete the tasks, but they were able to follow these steps faster. 7 One observation that stuck after conducting the questionnaire with all participants was that people with ADHD gave more general feedback like "I love it!" or "It's just not beautiful", whereas participants without ADHD commented more on little details, but stated that they thought the application in general was satisfactory enough. There was also the same number of participants with ADHD as without ADHD saying that they did not face any specific issues when completing the tasks, even if the group without ADHD required a longer time to solve the tasks. Task 3 of the prototype validation required creativity, because the participants had to think of a song to add to their music collection. When working on this task, the group of people with ADHD required less time to spontaneously think of a song they liked. One person of the group without ADHD did not even think of a specific song and just searched the word song in the search bar. As described in the results section, three patterns of eye movement could be identified within the group of participants with ADHD. One of these patterns is scanning the page from top to bottom and left to right. One question that arises when examining this pattern is to

what extent the participants' eye movement patterns are influenced by the UI design of the prototype, as one participant also complained about a "too horizontal" layout. Additionally, the group of people with ADHD moved their eyes faster than the people without ADHD, resting on elements for shorter periods of time. Also, the group of people with ADHD did not look at the full screen before taking actions but instead turned their attention directly to elements that seemed interesting, such as moving song titles or album covers. The participants without ADHD got less distracted by moving content and stopped less at images with their eyes. However, when answering the open questions, they also expressed finding symbols and images more interesting. Moreover, participants with ADHD partly thought that there are too many elements in the prototype already, especially when looking at the homepage, while participants without ADHD would like to have more features, more content, and more images. Lastly, it occurred that explicit wishes of the users collide with existing design principles. For example, one participant with ADHD wished for having only one way to go to the music collection, because they thought having two possible ways of completing this task was confusing. This conflicts with the Nielsen heuristics (Nielsen, 1994), as they advise offering multiple ways for achieving one goal, so users can decide on what works best for them and create their own workflow. In conclusion, it can be said that design features like providing a minimalist design and marking functionality with colours and symbols seem to be a nice-to-have for neurotypical people and get appreciated by them, but present crucial support for people with ADHD.

5.2. Relation to existing work

This research's setting differs from the work of Smits (2022), Santos (2022), and Turner (2023), as design principles to mitigate barriers faced by people with ADHD were integrated into a prototype that was tested with users on a mobile device. In other studies, barriers were identified in interviews and surveys (Smits, 2022), and simple wireframes were designed (Turner, 2023), partly also in co-design sessions with users (Santos, 2022), but there was no further validation of the proposed designs. Despite the different methodologies, the outcomes of this work are in line with the findings present in another research. For instance, participants with ADHD felt distracted by a moving song title in the prototype developed for this research, which fits the aspect of users with ADHD disliking moving content, as described by Smits (2022). And users with ADHD being overwhelmed by interfaces with many elements in it confirms to the results by Smits (2022) and Turner (2023). Further, during the interviews, participants reported not liking the recommendations and thinking that the auto-generated content was too much, which has also been found by Santos (2022). The issue of nested categories of content inside an application adding mental load for users with ADHD was previously described by Santos (2022) and Turner (2023) and could also be observed in the answers to the interview questions in this work. Furthermore, Turner also found indications for inaccessible design increasing self-doubt of neurodivergent users (Turner, 2023), which is also reflected in this work's results. Other aspects like the importance of colour usage and rewarding the user to extend the user's attention span were repeatedly brought up during this research and have also been described by Smits (2022).

5.3. Strengths

The internal validity of the research is ensured, because different measures like using test and control groups for the same prototype validation tasks, and formatting the results against former research are employed. The construct validity is also given, as multiple indicators are combined. using interviews, numerical measurements and supplementary qualitative data. This approach allowed to measure the concept of accessibility in a more precise way, as qualitative

data that shows what users like was connected to numerical indicative data which approximates how fast users can do certain tasks in the prototype.

5.4. Limitations

However, there are limitations to this study. As a biased sampling method has been chosen for interviews as well as for user testing, the resulting samples are also biased. In addition, the sample size of the different user testing groups was 7 participants per group, which is not enough to reach statistical saturation (Hennink & Kaiser, 2022) and resulted in outcomes that do not reach statistical significance according to an inferential analysis using the Mann-Whitney U test. This limits the generalizability of the results. Furthermore, most of the participants came from central Europe, which means that it is not clear to what extent the results of this research can be applied to people who were not socialized in western society. Lastly, for the prototype validation, there are age differences between the control and test group with the group with ADHD participants being on average 5.3 years younger than the group of non-ADHD participants. This could mean that the ADHD group was more experienced with using mobile applications which would also partly explain why this group was faster in accomplishing the tasks. This could be clarified by conducting further similar studies with larger sample sizes and more similar demographics. Suggestions for experimental controls to mitigate this limitation can be found in the future work section.

5.5. Ethical Concerns

One question in the set of structured interview questions might have contributed to the phenomenon of self-esteem issues being reinforced. In question 10b in the Appendix B, participants are asked how ADHD could play a role in the challenges they are experiencing when using mobile music streaming applications. Thus, they are getting nudged to connect their ADHD to features that do not work properly in their preferred music streaming app. This might give them the impression that unintuitive interfaces would be their fault and could have led to the results of this work in which persons with ADHD talk more about their disability to achieve certain tasks on their own, instead of focusing on poorly designed user interactions. In further research, this question should be rephrased or completely left out. Approaches for more inclusive software design will be discussed in the future work section.

5.6. Future Work

This research has implications for both, the tech industry and scientific research. In industry settings, for example at music streaming companies, the question of how users with ADHD could get most value out of their applications could become relevant. How could users with ADHD get to experience the same feature richness as users without ADHD without getting overwhelmed by packed screens? Also, music streaming providers could introduce minimalist noise-reduction modes for their apps, so users could get the opportunity to access basic features without distractions. Moreover, there could be more options for personalization offered in music streaming apps, so users would be enabled to remove elements they consider irrelevant or pick colours on their own.

Regarding scientific fields, this research managed to find noteworthy aspects that present potential for further investigation. One intriguing question is how design and evaluation processes involving people with ADHD could be designed to avoid making the participants self-conscious and causing negative feelings. For further research on this requestion, the interviews

should be designed without questions about an individual's neurological condition to prevent establishing a connection between barriers in handling the application and their own condition. It would also be valuable to create and validate a framework for ethically interviewing neurodivergent persons. Additionally, there should be more focus on neuro-reflexive methods like (more fine-granular) eye-tracking or measuring other biometrics while users are testing a system. Another limitation of this research that could be addressed in future work is the age gap between the test and control group, leading to results that are potentially influenced by a different baseline familiarity with using mobile devices. For expanding research on this, the experiments could get repeated with larger sample sizes. Further, there could be either more restrictions in recruiting participants, for example by requiring participants to be in a certain age range, or the groups could get split up into more detailed categories to not only compare between ADHD and Non-ADHD, but also within groups with similar technological knowledge or age.

6. Conclusion

This research aimed to find accessibility barriers faced by adults with ADHD when using mobile applications and to find design elements that can help mitigate these barriers. To answer these questions, an exploratory mixed-method approach was chosen, including structured interviews, the development of a prototype, and testing the prototype by giving four tasks to users with and without ADHD, measuring task completion times, tracking the participants eyes, and asking four questions about their experience when using the prototype. The interviews showed that adults with ADHD are hindered by different barriers such as nested layouts, too much irrelevant content, features that require too much effort from the user, navigation issues, and lack of user control. The results of the prototype testing indicated that these barriers can be effectively minimized by reducing the number of animations and videos within an application, using more colours, and incorporating minimalist design principles.

Regarding SRQ1.1, the most prominent barriers are getting overwhelmed by having too much content displayed and actions that require too much effort (e.g., too many steps). Features that are liked by users with ADHD in mobile streaming applications are central collections and short-cuts, for example, for saving items to the collection in one click, clear and simple structures in the UI layout, and having a back-button which also indicates the previous location.

The different kinds of elements liked by participants with ADHD are also the elements that are in line with minimalist design and benefit general usability: Making information implicit, for example, by showing a button that indicates which page it leads to instead of a generic back button, using bright colours and connection colour to specific functionality, having a flat information organization, and avoiding showing moving content or content that is not relevant to the user. Thus, principles for removing accessibility barriers for people with ADHD can be linked to minimalist design principles, as they also recommend the reduction of noise and only presenting important information in a clear way.

Despite the results of this study being limited by the sample size and biased sampling method, these results agree with other related work, such as the research by Santos (2022) and Turner (2023).

One finding that arose from the interview responses was how self-esteem issues can be reinforced. Regarding future work, it is relevant to research on how design and evaluation processes can be designed to prevent making neurodivergent people feel self-conscious.

7. Acknowledgements and Conflict of Interest

The author thanks Prof. dr. J.A. Good for her input, her feedback, and her supervision.

The author declares no conflict of interests with regards to the research, authorship and/or publication of this article. The author received no funding or grants for the composition of this research.

AI Disclosure. For this research, generative AI was used in two ways:

First, the tool DeepL (https://www.deepl.com) was utilized to help with translating interviews that were not conducted in English initially.The structured interviews were partly done in English, but also partly in German. After administering the interviews, the transcripts were translated manually by the researcher, but for single phrases that stem from specific German dialects and do not have a literal English translation, DeepL was used to find the most appropriate English term.

Secondly, ChatGPT (https://chatgpt.com) was used to enhance the writing style, mainly to find synonyms for words that were repeatedly used to make the text more appealing. Usually, a regular thesaurus or dictionary was used first, but if these methods did not yield sufficient results, ChatGPT was asked for alternative terms. However, this AI tool never contributed whole sections of text, but only single expressions.

After using both tools, the author reviewed and edited the content as needed and assumes full responsibility for the publication's content.

Furthermore, data collected as part of this work has never been inserted into an AI model of any kind, since this research handles medical data, which should not be given away without consent of the participants.

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9. Appendices

9.1. Appendix A: Interview Questions

(1) How old are you?

(2) What is your gender?

(3) In case it was included in your diagnosis, what type of ADHD do you have?

(4) What is your current level of education?

(5) What job do you have?

(6) What else do you do in your daily life?

(7) What ADHD symptoms are affecting you most in your daily life?

(8) How much time do you spend on average using your smartphone per day?

(9) Which music streaming app do you mainly use?

(10) Do you face any specific challenges when using this app?

(a) If yes: Please describe these challenges further.

(b) If yes: How do you think ADHD plays a role in these challenges?

(11) What do you think could be improved or would make your experience easier when using this app?

(12) What is the first thing you would like to see or do when opening your music streaming app?

(13) What functions of your music streaming app do you use most often?

(a) Can you show me how you do that? While presenting this to me, could you comment on what you are doing and what you are trying to achieve?

(14) Do you use your music streaming app only for listening to music or also for other things, such as watching videos or listening to audio books?

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9.2. Appendix B: Screenshots of prototype

Figure 1. Home page

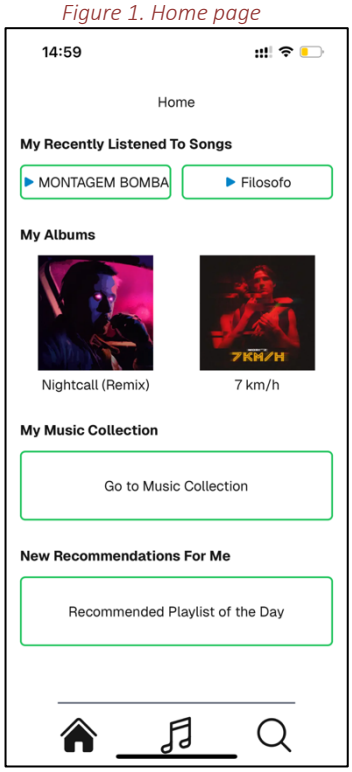


Figure 2. Album view

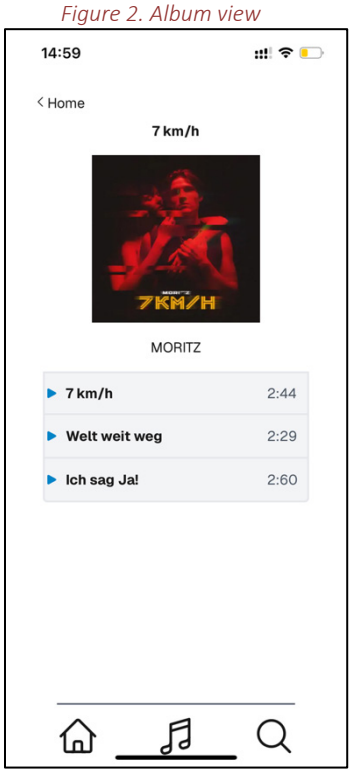


Figure 3. Playlist view

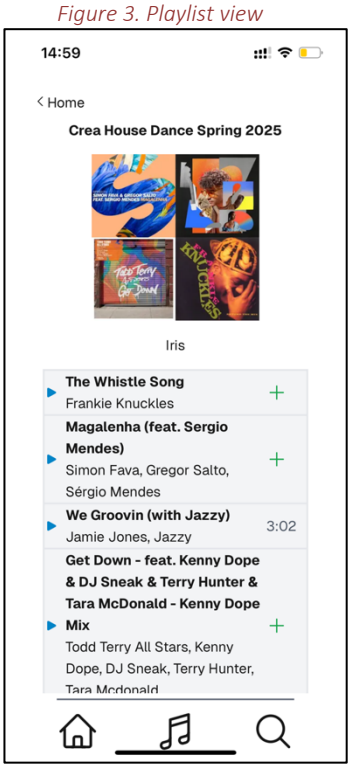


Figure 4. user's own music collection page

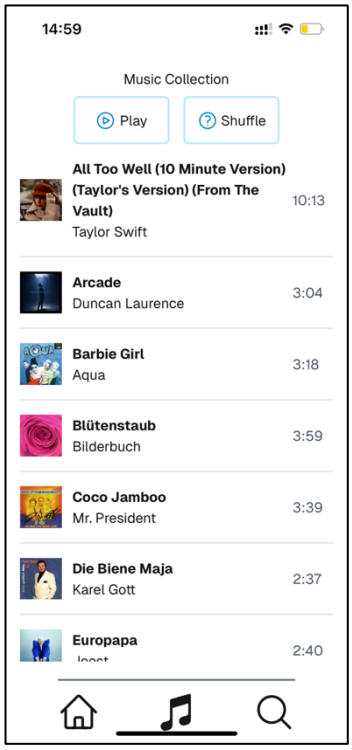


Figure 5.Ssearch page

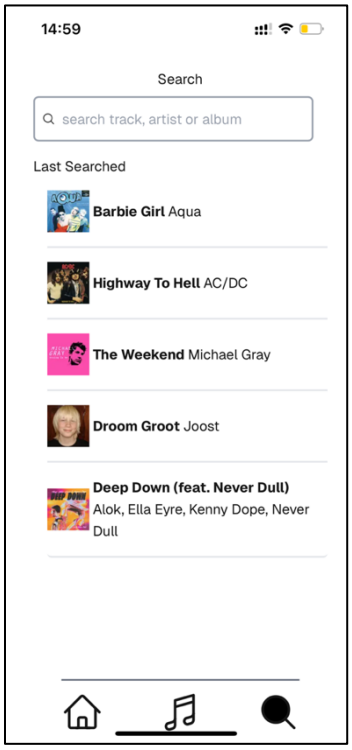
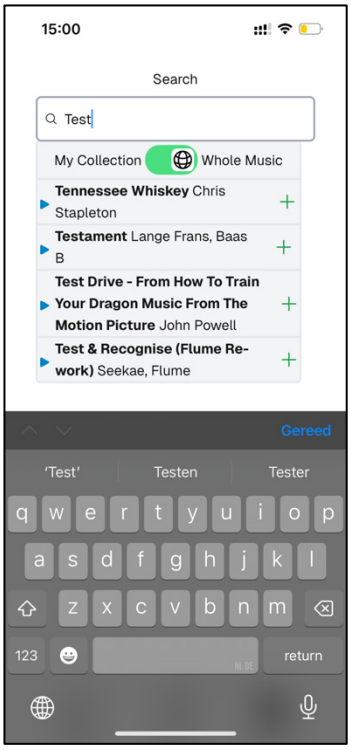


Figure 6. Search Page with activated search bar



9.3. Appendix C: Prototype Validation – Protocol

Demographics

1. Age
2. Gender
3. Experience with music streaming apps
4. ADHD or No ADHD
5. If ADHD: Is the participant currently taking any ADHD-related medication (such as Methylphenidate, also known as "Ritalin")

Tasks

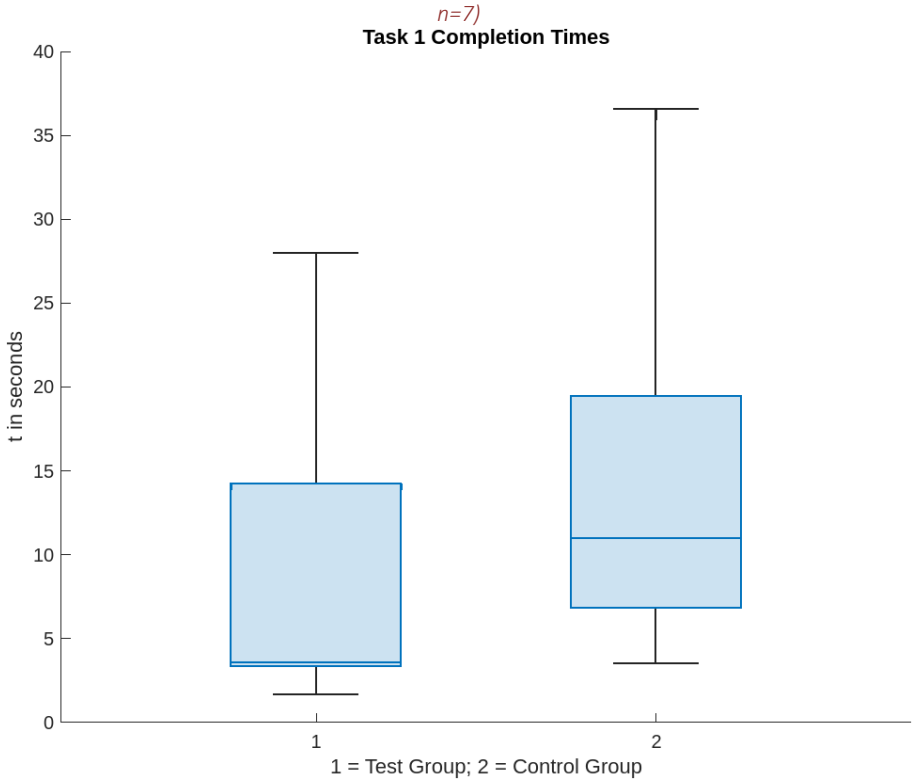
1. Tell me the songs that were played last.
2. Go to a playlist that is recommended for you and go back to the screen you looked at before.
3. Search for a song of your choice and save it to the music collection.
4. Go to your music collection and play a song from there.

Open Questions

1. Did you face any specific challenges when fulfilling the tasks given to you by the researcher?
2. Name at least one thing you liked about the prototype.
3. Name at least one thing you disliked about the prototype.
4. What do you think could be improved or would make your experience easier when interacting with this application?

9.4. Appendix D: Prototype Validation – Task Completion Times

Figure 7. Completion Times in Seconds for Task 1 (Finding Most Recently Played Songs) in Prototype Validation – ADHD Group (Test Group, n=7) and Non-ADHD Group (Control Group, n=7)



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Figure 8. Completion Times in Seconds for Task 2 (Opening Recommended Playlist and going back to Homepage) in Prototype Validation – ADHD Group (Test Group, n=7) and Non-ADHD Group (Control Group, n=7)

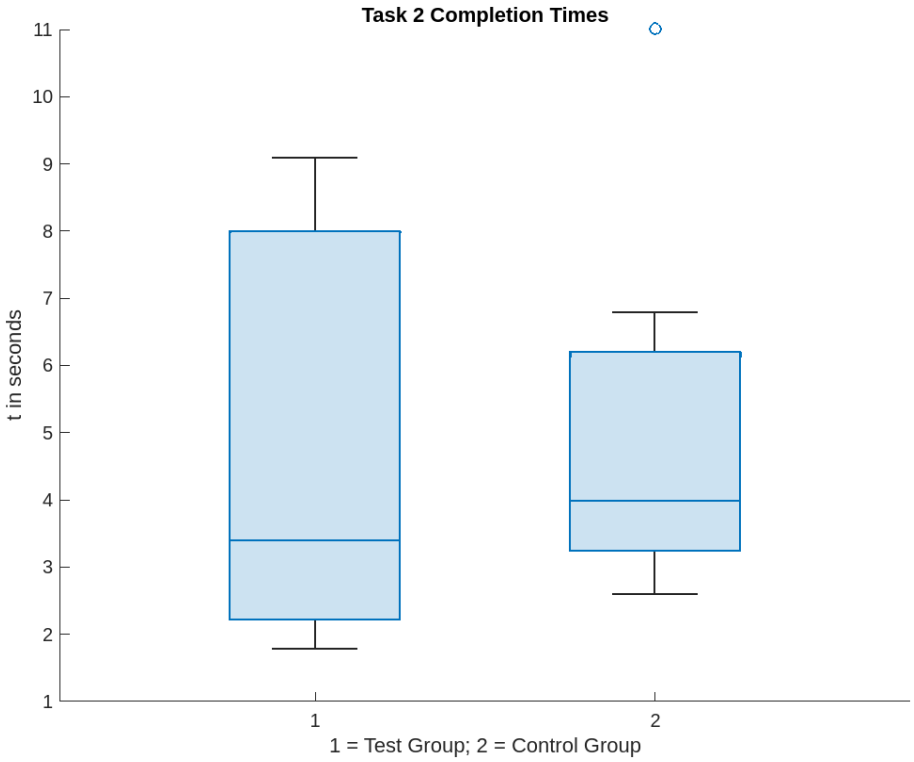
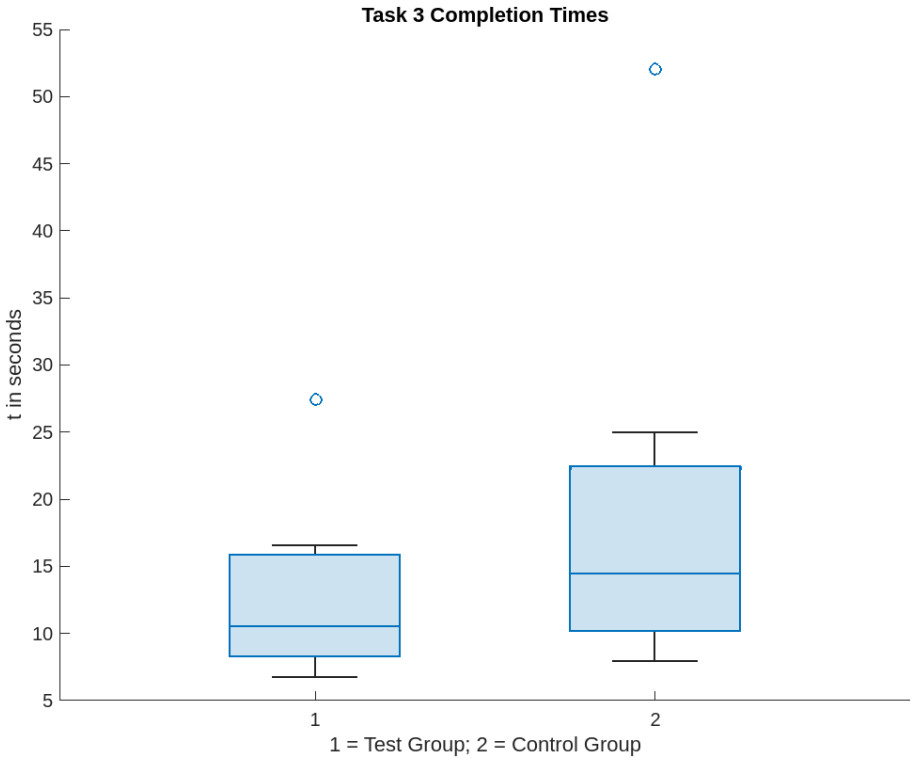
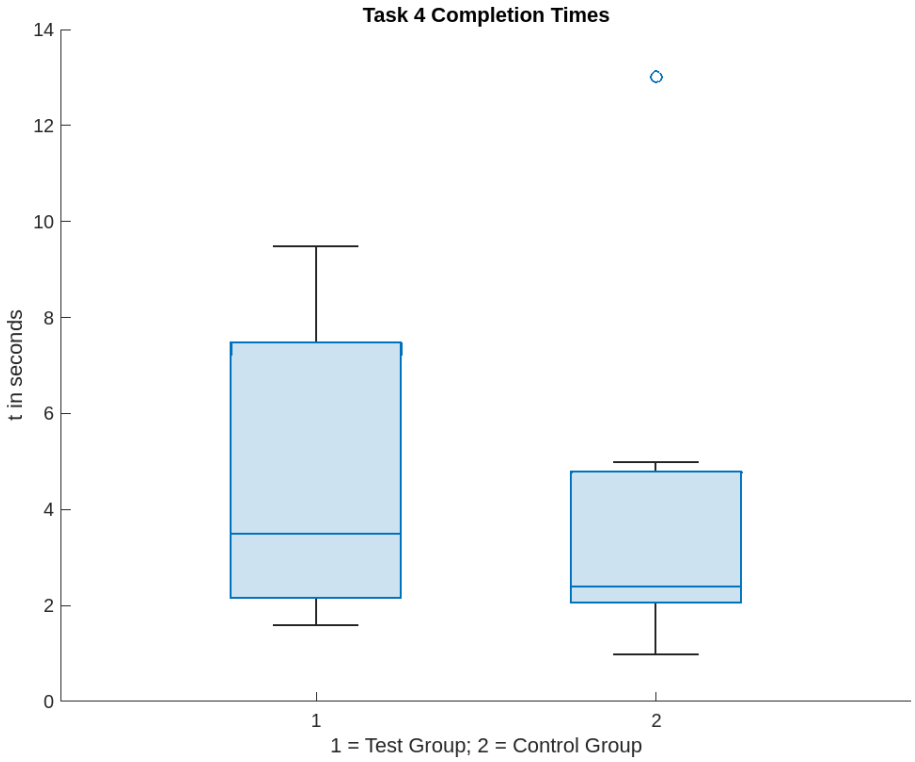


Figure 9. Completion Times in Seconds for Task 3 (Searching and Saving a Song of the Participant's Choice) in Prototype Validation – ADHD Group (Test Group, n=7) and Non-ADHD Group (Control Group, n=7)



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Figure 10. Completion Times in Seconds for Task 4 (Playing a Song from the Music Collection) in Prototype Validation – ADHD Group (Test Group, n=7) and Non-ADHD Group (Control Group, n=7)



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Swimming pool accessibility

An analysis of not-for-profit community recreation facilities and collegiate recreational facilities

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Abstract: Accessibility of fitness center swimming pools is of great importance as individuals with disabilities seek greater fitness levels and healthier lifestyles. This study assessed swimming pool facility accessibility according to Americans with Disabilities Act (ADA) guidelines utilizing Section L of the Accessibility Instruments Measuring Fitness and Recreation Environments (AIMFREE) survey. Direct site visits were conducted for 118 swimming pools located in community-based and university-based fitness facilities across eight U.S. states. ANOVA analysis revealed significant differences in mean pool accessibility for facility age. Pairwise comparisons with Bonferroni adjustments of the significant main effects indicated that pools built after the ADA implementation were significantly more accessible compared to those constructed before the ADA, as well as those originally built pre-ADA but renovated afterwards. These results demonstrate relative levels of ADA compliance for these collegiate and not-for-profit community recreation swimming pools and provide initial descriptive and analytical data that can impact pool accessibility.

Keywords: AIMFREE survey, Americans with Disabilities Act, aquatics, compliance

1. Introduction

Swimming pools serve as important components of fitness and recreation facilities, offering substantial health and wellness benefits for participants. To promote inclusivity and equitable access to exercise and recreation, these aquatic facilities must be designed and maintained to be accessible to all users. However, inadequate accessibility remains a persistent barrier across settings, including university campuses and not-for-profit community centers. Individuals with mobility challenges often encounter barriers such as poorly designed entrances, inaccessible changing areas, and the absence of necessary assistive equipment, including pool lifts or sloped entries. These barriers limit opportunities for regular aquatic exercise and undermine the inclusive purpose of facilities intended to support health and well-being.

2. Literature Review

Numerous studies have highlighted that individuals with disabilities often forego physical activities for various reasons, but one specially identified is the lack of access to facilities, sometimes expressed as oppressive messages from the built environment (Nikolajsen et al., 2021; Richardson et al., 2017, Rimmer et al., 2008). Additionally, the maturation or aging process often leads to increased rates of hearing, vision, ambulatory, self-care, and independent living disorders, as discussed by Kraus (2015). Of particular concern is the reduced ambulatory ability, which includes walking and balance tasks, as it is closely linked to cardiovascular fitness that illuminates the potential deficits in physical activity across an individual's lifespan (Michael et al., 2005). By improving the accessibility of swimming pools and fitness facilities for individuals with disabilities, their specific needs are addressed and inclusivity and support for overall health and wellbeing is promoted. While research and attention to the issue of facility accessibility for fitness centers in general has been fairly well established (Cardinal & Spaziani, 2003; Figoni et al., 1998; Johnson et al. 2012; Nikolajsen et al., 2021; Piletic et al., 2013 Rogers & LaRue, 2019), the body of research focusing specifically on pool settings within fitness facilities is severely underdeveloped, with the literature reflecting a significant gap in this area. To date, there has been a conspicuous scarcity of extensive investigation, evidenced by the mere presence of a singular published study by Pike et al. in 2008. This lack of comprehensive research not only highlights a critical oversight in understanding the unique challenges and opportunities presented by aquatic environments but also underscores an urgent need for more thorough scholarly exploration to inform best practices and improve accessibility in these essential fitness amenities.

Approximately 13.5% of the United States' (U.S.) population has a documented disability (Houtenville et al., 2023). Within that population, Rimmer et al. (2005) noted that the significantly low physical activity level among individuals with disabilities may be connected to environmental barriers such as facility architecture, design, or accessibility. Engagement in physical activity for people with disabilities declines during adolescence, with the most rapid decline noted during the college years (Yoh et al., 2008). For these reasons, swimming pool access for individuals with disabilities remains important in all settings, especially within the college or university setting.

Swimming pools have been shown to be the most popular activity in recreation facilities, and those with disabilities were more likely to swim compared to their non-disabled peers in England (Kung & Taylor, 2014). A survey of 458 public facilities using National Benchmarking Services for a seven-year period, comprising more than 150,000 participants from various demographic backgrounds found white females aged 60 and up with a disability were more likely to engage in swimming compared to their male counterparts who used other fitness equipment (Kung & Taylor, 2014). Additionally, this study found that people with disabilities were more likely to participate in a fitness class led by an instructor compared to their non-disabled peers.

The use of swimming pools for exercise or therapy for individuals with disabilities has proven to be beneficial for numerous conditions. Conatser (2007) has summarized prior research indicating the benefits of swimming pool use for adapted aquatics and other services for a multitude of disabilities and conditions including Angelman syndrome (Rider & Modell, 1996), arthritis (Archer, 2002), asthma (Rosimini, 2003; Weisgerber et al., 2003), autism (Martinez, 2006; Yilmaz et al., 2004), cerebral palsy (Hutzler et al., 1998), multiple sclerosis (Broach & Dattilo, 2001), quadriplegia (Lieberman, Lytle, & Irwin, 2003), Rett syndrome (Bumin et al., 2003), spinal muscular atrophy (Figuers, 1999), along with cardiac rehabilitation (Cider et al., 2005), and orthopaedic rehabilitation (Koury, 1996). The swimming pool can provide a beneficial exercise environment for many individuals with disabilities as the aquatic setting can create a reduction in

stress on muscles and joints due to reduced gravitational forces as well as thermal advantages like reducing body heat during exercise (Archer, 2002; Darby & Yaekle, 2000). Given these noted benefits and therapeutic treatments within the swimming pool setting, it is increasingly important to consider ways to maximize access for all individuals.

Barriers to swimming pool use include a lack of physical access to transportation services for getting to the facility (pool) and overall facility accessibility; the competence and schedule of staff members; and policy implementation (French & Hainsworth, 2001; Kung & Taylor, 2014). Pool usage in the disabled community may also be informed by considering the intersection of race, culture, socioeconomic status, gender identification, and other demographic factors as well as their perceptions of exercise and leisure.

The Americans with Disabilities Act (ADA) of 1990 is the primary federal law governing accessibility in public and private facilities, with enforcement and related litigation further shaping compliance expectations (Robledo, 2013). The ADA was built on earlier civil rights legislation, particularly the Civil Rights Act of 1964 and Section 504 of the Rehabilitation Act of 1973 (Anderson et al., 1995). Together, these statutes established a stronger legal framework for equitable access, increasing accountability for public institutions, including collegiate and community aquatic facilities. Title III of the ADA requires access to public accommodations and applies to key elements of the built environment, including parking, accessible routes, restrooms, signage, exercise equipment, and swimming pools (Anderson et al., 1995). For aquatic facilities, compliance is particularly significant because it often requires specialized infrastructure, accessibility features, and associated costs (Caden, 2014).

Although the Americans with Disabilities Act (ADA) establishes minimum accessibility requirements, scholars have argued that accessibility should be viewed through the broader framework of Universal Design (UD), which seeks to create environments, products, and services that are usable by the widest range of individuals without specialized adaptation (Connell et al., 1997; Steinfeld & Maisel, 2012). Recent accessibility scholarship has increasingly emphasized user-centered design, disability inclusion, and the evaluation of environments based on actual participation experiences rather than regulatory compliance alone (Watchorn et al., 2023). Within sport and recreation contexts, Universal Design has been advanced as a framework for moving organizations beyond minimum ADA compliance toward more meaningful inclusion of athletes, spectators, employees, and community members with disabilities (Hums et al., 2016). Consistent with this perspective, Universal Design scholars argue that sport and recreation facilities should be designed to maximize usability, access, and inclusion for diverse populations while minimizing the need for specialized accommodations (Sholanke & Eleagu, 2024). Recreation and disability researchers have likewise highlighted the continuing influence of environmental barriers on participation among individuals with disabilities despite decades of legislative protections and accessibility standards (Carbone et al., 2021). Together, these developments reflect a shift from viewing accessibility primarily as a compliance issue toward understanding accessibility as both a regulatory and experiential dimension of inclusion. It should be noted that consistent with contemporary disability scholarship, this study primarily uses person-first language (e.g., individuals with disabilities). However, the authors recognize that some members of the disability community prefer identity-first language (e.g., disabled individuals) as an expression of disability identity and culture.

The purpose of this study was to examine the effects of facility setting and construction period on swimming pool accessibility. Using Section L of the AIMFREE Fitness Center and Swimming Pool Accessibility Professional Version survey (Rimmer et al., 2004), the study assessed ADA-

related accessibility in collegiate and community recreation pools and identified priority areas for improvement in facility design and management.

3. Methods

3.1. Research Questions

The following research questions guided this investigation:

1. What is the level of ADA accessibility for not-for-profit community recreation centers and collegiate swimming pools, and do any differences in overall accessibility rating exist in these two categories of pool facilities?
2. What differences in overall accessibility ratings exist in ADA accessibility for not-for-profit community recreation centers and collegiate swimming pools used in the recreation setting based upon the date of facility construction or renovation?
3. Which accessibility elements regarding the swimming pool facilities on the AIMFREE assessment survey are identified to have the highest or lowest levels of ADA compliance?
4. Which elements of swimming pool accessibility from the AIMFREE assessment survey using an item analysis perspective are different based upon factors of organization type or construction/renovation era?

3.2. Study Design

The methodology employed in this research was an observational study design, structured to assess the accessibility of swimming pool facilities. This evaluation was anchored upon the utilization of the Accessibility Instrument for Measuring Fitness and Recreation Environments (AIMFREE) assessment tool. The AIMFREE is a comprehensive survey instrument devised with 37 items categorized into 12 distinct domains. These domains encompass critical elements of pool accessibility including but not limited to, modes of pool access, texture, and safety features of deck surfaces, as well as the readiness and accommodations provided by lifeguard services. Each item in the AIMFREE instrument was designed to capture discrete accessibility attributes of the facilities under scrutiny. Based on the accumulation of positive responses to these items, each facility was scored and assigned a scaled summary score. This score was indicative of the facility's overall accessibility, providing a quantifiable measure that reflects the extent to which it complies with inclusive design principles. Complementing the subjective assessments of the AIMFREE survey, the research protocol incorporated the precise acquisition of physical measurements of the facilities. To achieve a high degree of measurement accuracy that is crucial for the validity of the study, the latest technology in laser measurement was engaged, using Leica DISTO devices. During site evaluations, the research team employed these highly accurate instruments to measure distances and dimensions within pool facilities that are pivotal in determining adherence to accessibility standards. Prior to the commencement of data gathering, an ethical review process was undertaken. Approval was secured from the designated Institutional Review Boards (IRBs), ensuring that the study's conduct adhered to the highest ethical standards, safeguarding participant and facility confidentiality, and compliance with relevant regulatory and ethical guidelines for research. This step was vital not just for the integrity of the study but also to uphold the trust and cooperation of the participating facilities and their staffs.

3.3. Instrumentation

The researchers utilized the swimming pools portion (Section L) from the 16 sections included in the full AIMFREE survey professional version (Rimmer & Riley, 2004). The 37 items from Section L relate to the physical aspects of the pool facility. These items were grouped into 12 areas including the following: doors, pool ledge, deck surface, pool access, pool lift, pool ramp, pool perimeter to accessible entry, transfer wall, entry area clear space, slow swimming area, depth markers, and lifeguards. Each item within the survey included a “yes”, “no”, or “not applicable” response, with the positive response indicating “meeting accessibility standards” for the item. Consistent with AIMFREE scoring procedures, criteria designated as "not applicable" were excluded from summary score calculations. Facilities were therefore evaluated only against criteria relevant to their specific design configuration and were not penalized when alternative compliant accessibility features were present.

A scaled summary score of this section was determined for each facility based on the standardized scoring procedures summarizing all of the items contained within the AIMFREE instrument. The AIMFREE survey has demonstrated excellent content validity along with good internal consistency, good Item Response Theory (IRT), and fair structural validity (Calder & Mulligan, 2014). Additionally, Rimmer et al. (2004) reported excellent test-retest reliability with an intraclass correlation score of 0.97 for the swimming pools section of AIMFREE.

3.4. Data Collection

This study included an analysis of 118 college and not-for-profit community recreation centers in order to assess pool facility accessibility in these settings and to compare the impact of construction or renovation date on accessibility levels. A stratified sampling approach was used to ensure representation across facility type (collegiate and not-for-profit community recreation facilities), geographic region, and construction era. Facilities were first categorized according to these characteristics before selection to provide a more representative sample of aquatic facilities. To assess the first research question, the responses for each of the 37 AIMFREE items were tabulated for each facility and a scaled score from 0-100 was determined for each pool based upon a standardized system, with points determined by positive accessibility attributes. This scoring system allows for the creation of a raw score, a scaled score, and a percentile for the overall pool accessibility (Rimmer & Riley, 2004). An overall mean score was determined for the sample as a whole and a comparison of mean scores based on facility type was determined via a one-way ANOVA analysis.

To assess the second research question, the scaled scores for the pool facilities based upon the survey input of the 37 items were compared via a 3 X 2 ANOVA (facility construction/renovation date, facility type) analysis, and any significant main effects were further assessed with Bonferroni adjusted pairwise comparisons. The construction/renovation date category included three groups: 1) Pre-ADA construction (prior to 1990), 2) Pre-ADA construction with facility renovation post-ADA (after 1990), or 3) Post-ADA construction (after 1990). The facility type included either the collegiate fitness facility setting or the not-for-profit community recreation center setting. The collegiate setting included public and private colleges and universities, and the not-for-profit community recreation facilities included both YMCA/YWCA or Y Center venues along with other community recreation centers.

The third research question was assessed using a rank order of the top-to-bottom survey items based on ADA-compliant responses. Those items with the highest level of positive responses of

"yes" for the AIMFREE represented the facility trait or attribute that was most compliant with accessibility standards. Those survey items with the lowest levels of positive responses represent the facility trait or attribute that was least compliant with accessibility standards.

The fourth research question was assessed via an item analysis for the 37 questions from Section L of the AIMFREE survey instrument. This included an analysis of positive responses related to ADA compliance with comparisons made via Pearson chi-square analyses for facility type (collegiate and not-for-profit community recreation) and construction/renovation date (pre-ADA construction, pre-ADA construction with post-ADA renovation, and post-ADA construction).

Throughout the data collection, all physical measurements within the facilities were made via Leica DISTO laser measuring devices. The data collection protocols were reviewed and approved by the appropriate Institutional Review Boards to ensure the protection of all research subjects. All data was directly collected by members of the research team on-site at all the pool facilities.

3.5. Statistical Analysis

To analyse the data collected in this study, various statistical methods were utilized. Initially, descriptive statistics were computed to summarize and describe the key characteristics of the data. This involved calculating measures like the mean, standard deviation, range, and frequencies for each variable to gain an overview of the data distribution. To compare the mean scores of the pools based on facility type, the researchers conducted a one-way analysis of variance (ANOVA). To further examine the data, a 3 X 2 ANOVA analysis was performed to compare scaled scores based on facility construction/renovation date and facility type. To assess significant main effects, Bonferroni-adjusted pairwise comparisons were conducted. This type of comparison helps determine if there are significant differences among multiple groups after considering the probability of making Type I errors. For evaluating the 37 items on the AIMFREE, Pearson chi-square analyses were used. These analyses tested for significant differences in response distributions for categorical variables. The statistical analyses were performed using SPSS version 24.0 software, with the alpha level for significance set at the .05 level.

4. Results

A stratified sample of 118 university and not-for-profit community recreation facilities across eight states (IA, IL, IN, MI, MO, OH, TX, & WI) provided ample data for analysis. The demographic characteristics of this sample included a range of facility construction from 1916 to 2010, and 45.5% of these facilities had undergone renovation since initial construction. These renovations included 42 projects completed after 1990 when the ADA was enacted. The fitness center-based swimming pools included 51 located within college or university settings and 67 located in not-for-profit community recreation center settings.

The first research question was assessed via one-way ANOVA analysis with accompanying descriptive statistics. For the sample population, the mean percentile score for the 118 pools assessed was 44.17 (SD = 23.5) with a range of 7.0 to 96.0. ANOVA analysis determined no significant difference, $F(1,116) = 0.143$, $p = .706$, between the mean percentile score for university pools ($M = 45.12 \pm 25.64$) and the mean percentile score for not-for-profit community recreation pools ($M = 43.46 \pm 21.91$). In general, these mean percentile scores would be noted as low, with all mean values reported falling below the 50th percentile. Pool accessibility is grounded in many factors, but first and foremost would be the provision for direct access to the swimming pool via one of five primary modalities. The survey identified five methods for water entry access in the

following rank order of prevalence: stairs with handrails (84.7%), seated lift/hoist (63.6%), zero depth entry (16.9%), ramp with handrails (11.9%), and transfer wall (2.5%).

The second research question was assessed via a 3 X 2 ANOVA (facility age, facility type) analysis that revealed significant differences in mean pool accessibility for facility age [$F(2, 112) = 7.12$, $p = .001$]. The significant main effects of facility construction/renovation era were further analysed by Bonferroni adjusted pairwise comparisons. The mean accessibility percentile score for swimming pools constructed post-ADA ($M = 52.77$, $SE = 3.03$) was significantly greater than pools constructed pre-ADA ($M = 38.28$, $SE = 5.16$) $p = .017$, and for pools constructed pre-ADA but renovated post-ADA ($M = 36.41$, $SE = 3.50$) $p < .001$.

University pools constructed post-ADA ($M = 57.57$, $SE = 4.68$) were significantly more accessible than pools constructed pre-ADA ($M = 33.90$, $SE = 7.10$, $p = .003$), and university pools constructed post-ADA were also significantly more accessible than university-based pools that were built pre-ADA but renovated post-ADA ($M = 35.44$, $SE = 2.68$, $p = .012$). No main effects were determined for facility type (community-based to university-based). Table 1 displays a summary of mean total pool accessibility percentile scores comparing collegiate and not-for-profit community recreation pools constructed or renovated pre-ADA and post-ADA, and Figure 1 graphically illustrates these findings.

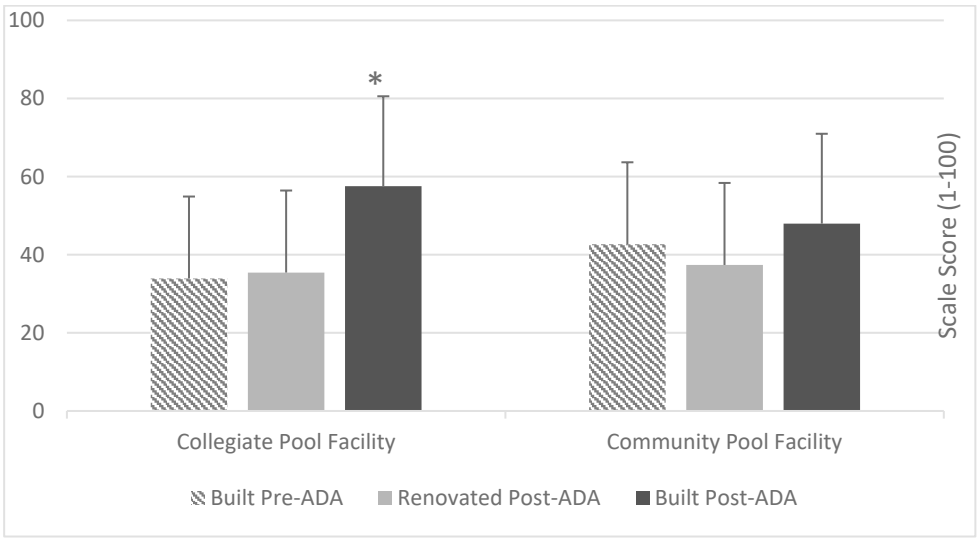
Table 1. Means Summary of 3 X 2 ANOVA (facility age, facility type)

Construction Timing	Stats.	University	Not-for-Profit Community
Built Pre-ADA (1990)	Mean	33.90	42.67
Built Pre-ADA (1990)	SD	22.73	21.81
Built Pre-ADA (1990)	N	10	9
Renovated Post-ADA (1990)	Mean	35.44	37.38
Renovated Post-ADA (1990)	SD	22.09	20.30
Renovated Post-ADA (1990)	N	18	24
Built Post-ADA (1990)	Mean	57.57*	47.97
Built Post-ADA (1990)	SD	24.71	22.57
Built Post-ADA (1990)	N	23	34

**Built Post-ADA for universities significantly more accessible ($p < .05$) than universities Built Pre-ADA or universities Renovated Post-ADA.*

The third research question was assessed via an item analysis of the 37 content items of the swimming pool section of the AIMFREE survey that aligned within the 12 item areas. The complete results of this item analysis for the full sample are displayed in Table 2 in the order of the survey instrument. It is of interest to consider both the items of the survey with the highest levels (an 80% or higher positive response) of compliance with accessibility standards including items with 1) Lifeguards present to assist at 95.8%, 2) Each accessible means of pool entry/exit connected to an accessible route at 93.2%, 3) Paths leading to and around the pool deck with a width of at least 3 feet at 89%, 4) Pool with a ledge to hold onto when entering the water at 88.1%, 5) Door entering the pool have a threshold of 0.5 inches or less at 86.4% 6) Clear space of at least 5’-0” x 5’-0” adjacent to each pool entry at 85.6%, and 7) Pool depth markers visible outside the pool and presence of pool stairs with railings both tied at 84.7%.

Figure 1. Mean percentile AIMFREE scores for fitness center pool facilities with SD



**Built Post-ADA for universities significantly more accessible ($p < .05$) than universities Built Pre-ADA or universities Renovated Post-ADA.*

The overall sample of pools also provided multiple items with very low levels of positive responses (below 10%) from an accessibility perspective including the following: 1) Access to the pool on a path without doors at 1.7%, 2) Presence of a transfer wall for pool entry at 2.5% along with the three transfer wall characteristics sub-items, 3) Presence of power assist features for door opening at 3.4%, and 4) Pool ramp landing length at least 5'-0" long at 9.3%. In total, there were 16 of 37 items in the survey with positive accessibility responses below 20%.

For research question four, item analyses were further reviewed based on two key study variables: (a) organization type (college/university or not-for-profit community recreation), and (b) construction/ renovation era (built pre-ADA, built pre-ADA but renovated post-ADA, built post-ADA. Table 3 summarizes the positive responses for each of the two organization types. The levels of positive responses were quite similar across the two organization types for the 37 items as would be expected given that this factor did not have a significant main effect as noted in research question 2. However, it should be noted that Pearson chi-square analyses did reveal three significant differences in the distribution of positive and negative responses amongst this sample. While 70.6% of the collegiate facilities had a detectable warning texture surrounding the pool, only 50.7% of the not-for-profit community recreation facility pools had warning textures, $\chi^2 = 4.72$, $p = .030$. A total of 80.6% of not-for-profit community recreation center pools for providing at least one accessible means of entry/exit for smaller pools (< 300' of linear pool wall) compared to 58.8% of collegiate pools, $\chi^2 = 6.76$, $p = .034$. Additionally, transfer walls as a means of pool access were significantly more prevalent in collegiate pools at 5.9% compared to the nonprofit community pools at 0%, $\chi^2 = 4.04$, $p = .044$.

The data for the variable of construction era was also compared, and Table 4 provides summary data for an item analysis of the AIMFREE swimming pool survey based upon the factor of construction/renovation era. Again, it should be noted that the chi-square survey item analyses indicated two areas of significant differences. Given the significant main effect of the construction/renovation era of the facilities noted in research question two, there appears to be more general variation in the percentage of positive responses amongst the three groups.

Table 2. AIMFREE Section L Item Analysis – Swimming Pools (N = 118)

Item Area	Item Content	Positive Response	Negative A or Missing Response	Response
Doors	Access without Doors	1.7%	98.3%	0%
Doors	Power Assist	3.4%	94.1%	2.5%
Doors	Threshold Height < 0.5”	86.4%	11.0%	0.8%
Pool Ledge	Present for Holding	88.1%	9.3%	2.5%
Deck Surface	Warning Texture at Edge	59.3%	40.7%	0%
Deck Surface	Clear Space 3’	89.0%	9.3%	1.7%
Pool Access	Pool lift/Hoist	63.6%	35.6%	0.8%
Pool Access	Wet/Dry Ramp	11.9%	88.1%	0%
Pool Access	Zero Depth Entry	16.9%	83.1%	0%
Pool Access	Transfer Wall	2.5%	97.5%	0%
Pool Access	Stairs with Rails	84.7%	14.4%	0.8%
Pool Access	Single Access Means	53.4%	23.7%	22.9%
Pool Access	Dual Access Means	66.1%	7.6%	26.3%
Pool Access	Access on Accessible Route	93.2%	2.5%	4.2%
Pool Lift	Lift Present	63.6%	35.6%	0.8%
Pool Lift	Descent Depth	62.7%	0%	37.2%
Pool Lift	Seat with Armrests	43.2%	19.5%	37.2%
Pool Lift	Footrest	32.2%	30.5%	37.2%
Pool Lift	Controls Accessible on Deck	59.3%	1.7%	38.9%
Pool Lift	Operation w/o Grasping	50.8%	11.0%	38.1%
Pool Ramp	Ramp Present	11.9%	88.1%	0%
Pool Ramp	Ramp Width 3’	11.0%	0.8%	88.1%
Pool Ramp	Ramp Slope less than 8.3%	10.2%	1.7%	88.1%
Pool Ramp	Ramp Landings Level	11.0%	0.8%	88.1%
Pool Ramp	Ramp Landing Width	11.0%	0.8%	88.1%
Pool Ramp	Ramp Landing Length	9.3%	1.7%	88.9%
Pool Ramp	Handrails Present	10.2%	1.7%	88.1%
Pool Perimeter to Accessible Entry	< 300’ with 1 Accessible Entry	71.2%	5.1%	23.7%
Pool Perimeter to Accessible Entry	> 300’ with 2 Accessible Entries	55.1%	15.3%	29.7%
Transfer Wall	Transfer Wall Present	2.5%	97.5%	0%
Transfer Wall	Width 12-16”	2.5%	0%	97.5%
Transfer Wall	Height 16-18” above floor	2.5%	0%	97.5%
Transfer Wall	Surface Non-abrasive	2.5%	0%	97.5%
Entry Area Clear Space	5‘x 5’	85.6%	7.6%	6.8%
Slow Swimming Area	Area Provided	62.7%	36.4%	0.8%
Depth Markers	Visible Outside the Pool	84.7%	14.4%	0.8%
Lifeguards	Present & Able to Assist	95.8%	3.4%	0.8%

Table 3. AIMFREE Section L Item Analysis – Swimming Pools by Organization Type

Item Area	Item Content	CollegeUniversity Positive Response n = 51	Not-for-Profit Community Positive Response n = 67
Doors	Access without Doors	2.0%	1.5%
Doors	Power Assist	3.9%	3.0%
Doors	Threshold Height < 0.5”	84.3%	88.1%
Pool Ledge	Present for Holding	88.2%	88.1%
Deck Surface	Warning Texture at Edge*	70.6%	50.7%
Deck Surface	Clear Space 3’	92.2%	86.6%
Pool Access	Pool lift/Hoist	68.6%	61.2%
Pool Access	Wet/Dry Ramp	15.7%	9.0%
Pool Access	Zero Depth Entry	9.8%	22.4%
Pool Access	Transfer Wall	5.9%	0%
Pool Access	Stairs with Rails	78.4%	89.6%
Pool Access	Single Access Means	52.9%	53.7%
Pool Access	Dual Access Means	60.8%	70.1%
Pool Access	Access on Accessible Route	90.2%	95.5%
Pool Lift	Lift Present	68.6%	61.2%
Pool Lift	Descent Depth	66.7%	059.7%
Pool Lift	Seat with Armrests	47.1%	40.3%
Pool Lift	Footrest	33.3%	31.3%
Pool Lift	Controls Accessible on Deck	58.8%	59.7%
Pool Lift	Operation w/o Grasping	52.9%	49.3%
Pool Ramp	Ramp Present	15.7%	9.0%
Pool Ramp	Ramp Width 3’	13.7%	9.0%
Pool Ramp	Ramp Slope less than 8.3%	13.7%	7.5%
Pool Ramp	Ramp Landings Level	13.7%	9.0%
Pool Ramp	Ramp Landing Width	13.7%	9.0%
Pool Ramp	Ramp Landing Length	11.8%	7.5%
Pool Ramp	Handrails Present	11.8%	9.0%
Pool Perimeter to Accessible Entry	< 300’with 1 Accessible Entry*	58.8%	80.6%
Pool Perimeter to Accessible Entry	> 300’with 2 Accessible Entries	58.8%	52.2%
Transfer Wall	Transfer Wall Present*	5.9%	0%
Transfer Wall	Width 12-16”	5.9%	0%
Transfer Wall	Height 16-18” inches above floor	5.9%	0%
Transfer Wall	Surface Non-abrasive	5.9%	0%
Entry Area Clear Space	5‘x 5’	84.3%	86.6%
Slow Swimming Area	Area Provided	66.7%	59.7%
Depth Markers	Visible Outside the Pool	80.4%	88.1%
Lifeguards	Present & Able to Assist	96.1%	95.5%

**Pearson chi-square significant difference in response distribution, p < .05*

However, the Pearson chi-square analyses for these 37 items revealed only two individual items with positive and negative response distributions that were significantly different than expected. This included pool access via a zero-depth entry that was significantly greater for post-ADA construction at 29.8% compared with both pre-ADA construction at 5.3% and pre-ADA construction with post-ADA renovation at 4.8%, $\chi^2 = 12.99$, $p = .002$. The presence of at least two accessible entry modes for pools with over 300' of perimeter was the other identified item with significant differences, $\chi^2 = 9.78$, $p = .044$, with post-ADA construction yielding 63.2% positive response compared with pre-ADA construction at 42.1% and pre-ADA construction with post-ADA renovation at 50% positive responses.

Table 4. AIMFREE Item Analysis for Section L – Swimming Pools by Construction/Renovation Era

Item Area	Item Content	Pre-ADA Construction Positive Response n = 19	Pre-ADA Construction Post-ADA Renovation Positive Response n = 42	Post-ADA Construction Positive Response n = 57
Doors	Access without Doors	0%	0%	3.5%
Doors	Power Assist	0%	4.8%	3.5%
Doors	Threshold Height < 0.5"	73.7%	88.1%	89.5%
Pool Ledge	Present for Holding	78.9%	88.1%	91.2%
Deck Surface	Warning Texture at Edge	68.4%	45.2%	66.7%
Deck Surface	Clear Space 3'	89.5%	81.0%	94.7%
Pool Access	Pool lift/Hoist	63.2%	57.1%	68.4%
Pool Access	Wet/Dry Ramp	0%	9.5%	17.5%
Pool Access	Zero Depth Entry*	5.3%	4.8%	29.8%
Pool Access	Transfer Wall	0%	0%	5.3%
Pool Access	Stairs with Rails	73.7%	90.5%	84.2%
Pool Access	Single Access Means	52.6%	57.1%	50.9%
Pool Access	Dual Access Means	57.9%	59.5%	73.7%
Pool Access	Access on Accessible Route	84.2%	88.1%	100%
Pool Lift	Lift Present	63.2%	57.1%	68.4%
Pool Lift	Descent Depth	63.2%	54.8%	68.4%
Pool Lift	Seat with Armrests	42.1%	31.0%	52.6%
Pool Lift	Footrest	26.3%	19.0%	43.9%
Pool Lift	Controls Accessi-ble on Deck	57.9%	50.0%	66.7%
Pool Lift	Operation w/o Grasping	47.4%	40.5%	59.6%
Pool Ramp	Ramp Present	0%	9.5%	17.5%
Pool Ramp	Ramp Width 3'	0%	7.1%	17.5%

Item Area	Item Content	Pre-ADA Construction Positive Response n = 19	Pre-ADA Construction Post-ADA Renovation Positive Response n = 42	Post-ADA Construction Positive Response n = 57
Pool Ramp	Ramp Slope less than 8.3%	0%	9.5%	14.0%
Pool Ramp	Ramp Landings Level	0%	9.5%	15.8%
Pool Ramp	Ramp Landing Width	0%	9.5%	15.8%
Pool Ramp	Ramp Landing Length	0%	7.1%	14.0%
Pool Ramp	Handrails Present	0%	9.5%	14.0%
Pool Perimeter to Accessible Entry	< 300' with 1 Accessible Entry	73.3%	80.5%	61.7%
Pool Perimeter to Accessible Entry	> 300' with 2 Accessible Entries*	42.1%	50.0%	63.2%
Transfer Wall	Transfer Wall Present	0%	0%	5.3%
Transfer Wall	Width 12"-16"	0%	0%	5.3%
Transfer Wall	Height 16"-18" above floor	0%	0%	5.3%
Transfer Wall	Surface Non-abrasive	0%	0%	5.3%
Entry Area Clear Space	5' x 5'	89.5%	81.0%	87.7%
Slow Swimming Area	Area Provided	57.9%	64.2%	63.2%
Depth Markers	Visible Outside the Pool	78.9%	78.6%	91.2%
Lifeguards	Present & Able to Assist	100%	95.2%	94.7%

**Pearson chi square significant difference in response distribution, p < .05*

5. Discussion

The present findings suggest that the ADA has contributed to meaningful improvements in swimming pool accessibility, particularly among facilities constructed after its enactment. Consistent with prior research, the ADA appears to have served as an important catalyst for accessibility improvements across built environments (Vierling, 2005). However, the findings also indicate that compliance-driven progress has not eliminated significant accessibility barriers. Although post-ADA facilities generally demonstrated stronger accessibility outcomes than facilities constructed prior to 1990, accessibility remained inconsistent across many evaluated features. As a result, accessibility should be viewed not as a completed regulatory objective, but

as an ongoing component of inclusive facility design and management that better aligns with Universal Design principles.

Since its passage, the ADA has evolved through regulatory refinements, culminating in the 2010 Standards for Accessible Design, which provided more specific guidance regarding aquatic accessibility requirements (Long, 2012). While these standards established clearer expectations for facility operators and designers, the present findings suggest that implementation remains uneven. Thus, continued assessment of aquatic facilities remains important to determine not only regulatory compliance but also the degree to which facilities facilitate equitable participation and inclusion (French & Hainsworth, 2001).

The first research question examined whether accessibility differed between university pools and not-for-profit community recreation pools. Although no significant differences were identified, the practical implication is that accessibility challenges appear to be widespread across both sectors rather than concentrated within a particular organizational setting. These findings are consistent with previous literature documenting persistent accessibility barriers in recreational and sport environments (Arbour-Nicitopoulos & Ginis, 2011; Cardinal & Spaziani, 2003; Rimmer et al., 2017). Consequently, accessibility improvement should be viewed as a shared responsibility among aquatic facility providers regardless of organizational type.

The findings further suggest that many facilities continue to rely on a limited range of accessibility features rather than offering multiple avenues for independent participation. Greater implementation of zero-depth entries, ramps with handrails, transfer systems, and other inclusive access modalities may better accommodate the diverse mobility needs of users while advancing the broader objectives of accessibility standards. Taken together, these results underscore the need to move beyond minimum compliance toward more comprehensive and user-centered accessibility planning.

The second research question explored the influence of facility age and organizational type on swimming pool accessibility. Facility age emerged as a more influential factor than facility type, with post-ADA facilities generally demonstrating stronger accessibility outcomes than pools constructed before the legislation. This finding supports earlier work by Pike et al. (2008), which similarly identified accessibility advantages among post-ADA facilities. However, the continued presence of accessibility deficiencies in newer facilities suggests that compliance with evolving standards has not consistently translated into comprehensive accessibility.

One of the most meaningful findings was the limited accessibility advantage observed among pre-ADA facilities that underwent renovation after ADA implementation. Although renovation is frequently assumed to improve accessibility, these results suggest that retrofitting may be constrained by financial resources, existing structural limitations, and competing priorities. Renovation projects often focus on infrastructure upgrades, aesthetics, spectator amenities, or competitive enhancements rather than comprehensive accessibility improvements. As a result, accessibility outcomes may be influenced more strongly by inclusive design principles incorporated during original construction than by subsequent retrofit efforts. These findings reinforce the importance of integrating accessibility considerations during initial planning rather than relying on corrective modifications after construction.

Similarly, the stronger accessibility demonstrated by post-ADA university pools relative to older university facilities further supports the importance of designing for accessibility from the outset. Taken together, these findings suggest that construction era exerts a greater influence on accessibility outcomes than organizational setting. In practical terms, accessibility appears most

effective when embedded in original facility design rather than addressed through piecemeal renovation efforts.

For facility managers, these findings highlight the continued importance of aligning both facility design and operational practices with ADA expectations. While accessibility regulations provide an essential framework for equitable access, the observed gaps between regulatory standards and actual facility conditions suggest a need for stronger implementation, monitoring, and accountability. Accessibility should therefore be viewed as both a design objective and an ongoing management responsibility.

The third research question examined item-level performance across the 37 AIMFREE accessibility indicators. A consistent pattern emerged in which basic accessibility features were more frequently present than features intended to provide independent and varied forms of access. High-performing items generally reflected fundamental compliance-related requirements, whereas low-performing items were concentrated among features that facilitate autonomy and flexibility. This pattern suggests that many facilities have successfully addressed baseline accessibility expectations while falling short of broader inclusive design objectives.

One particularly noteworthy finding involved the near absence of door-free routes to pool areas. Although unrestricted access paths may provide the least restrictive environment for individuals with mobility impairments, aquatic facilities must simultaneously address legitimate safety and security concerns. Consequently, this finding highlights an important tension between accessibility and risk management. Controlled access points are often used to prevent unauthorized facility use and reduce drowning risks; however, excessive reliance on manual doors may unintentionally restrict independent access. Emerging technologies, including automated access systems, proximity-activated doors, wearable-access devices, and monitored entry controls, may provide opportunities to improve user autonomy while maintaining appropriate safety considerations.

The findings also illustrate that accessibility is influenced by both facility design and day-to-day management practices. Some AIMFREE indicators assess structural characteristics determined during construction, whereas others reflect ongoing operational decisions involving staffing, equipment placement, circulation routes, and facility maintenance. For example, accessible deck space may be reduced through the placement of starting blocks, benches, or storage equipment even when the original design met accessibility standards. Consequently, accessibility in aquatic settings should be considered an ongoing operational responsibility rather than solely an architectural concern.

Analysis of pool-entry modalities further reinforced this conclusion. Although stairs with handrails and seated lifts were relatively common, several alternative entry options, including zero-depth entries, ramps with handrails, and transfer walls, were substantially less prevalent. These findings support previous recommendations advocating for a more diverse range of aquatic access options to accommodate varying functional abilities and user preferences (Butzer et al., 2021; Rimmer et al., 2017). Collectively, the item-level findings suggest that many facilities continue to emphasize a narrow set of accessibility solutions rather than providing multiple pathways to participation.

The fourth research question examined item-level accessibility differences according to organizational type and construction or renovation era. Although overall accessibility patterns were broadly similar across facility settings, several item-level differences emerged. These findings suggest that organizations may achieve accessibility through different approaches even

when overall accessibility outcomes are comparable. Thus, evaluating facility accessibility solely through overall scores may obscure important differences in the specific features that facilitate or constrain participation.

More broadly, the findings indicate that accessibility should not be evaluated solely through the presence or absence of specific physical features. Rather, accessibility reflects the cumulative effect of design decisions, operational practices, and organizational priorities. Continued collaboration among facility operators, designers, accessibility specialists, and users with disabilities will be necessary to develop more comprehensive strategies for enhancing aquatic accessibility (Arbour-Nicitopoulos & Ginis, 2011; Archer, 2002; Becker, 2009; Borson, 2010; Broach & Dattilo, 2001; Calder & Mulligan, 2014; Conaster, 2007). Ongoing assessment and monitoring will likewise remain important for promoting continuous improvement and ensuring that accessibility efforts evolve alongside changing standards and user needs.

Overall, the findings suggest that swimming pool accessibility has improved during the ADA era but remains incomplete across both collegiate and community recreation settings. Future progress will depend not only on compliance with minimum standards, but also on greater attention to design quality, operational practices, and proactive accessibility planning. By emphasizing inclusion as well as compliance, aquatic facilities can better support equitable participation for individuals with disabilities. Viewed from a Universal Design perspective, these findings suggest that many facilities have successfully implemented baseline accessibility features while failing to provide the broader range of access options needed to accommodate diverse user preferences and abilities. Universal Design principles in general emphasize flexibility, equitable use, and independence, all of which remain areas for continued improvement within aquatic environments.

Several limitations should be considered when interpreting these findings. First, the study employed a cross-sectional observational design and therefore cannot establish causality. Second, facilities were sampled from eight states and may not represent aquatic facilities across the United States. Third, assessments relied on evaluator observations and did not include formal inter-rater reliability testing for the present study. Fourth, the investigation focused on environmental accessibility and did not incorporate direct perspectives from individuals with disabilities. Finally, actual user experiences were not assessed. Future research should incorporate mixed-method approaches and stakeholder perspectives to provide a more comprehensive evaluation of aquatic accessibility. Consistent with Watchorn et al. (2023), the present findings suggest that environmental audits alone may not fully capture the lived experiences of individuals with disabilities, underscoring the value of incorporating user-centered assessments within future aquatic accessibility research.

6. Conclusion

The inclusion of individuals with disabilities in physical activity is widely recognized as both a matter of equity and an important contributor to health and well-being (Petersen & Piletic, 2006; Riley et al., 2008). Regular physical activity plays a well-established role in disease prevention, functional health, and quality of life, and swimming pools are especially valuable because they provide an adaptable setting for rehabilitative and recreational exercise. For individuals with disabilities, the aquatic environment offers distinct advantages, including buoyancy, support, and reduced mechanical stress on the body.

This study contributes descriptive and analytical evidence on swimming pool accessibility across collegiate and not-for-profit community recreation facilities and highlights the continued relevance of ADA-related accessibility standards in aquatic settings. Although significant differences were observed by construction and renovation era, overall accessibility scores remained only moderate to low, indicating substantial room for improvement. Future efforts should focus on the specific barriers identified in the 37 items of Section L of the AIMFREE instrument, including door accessibility, deck space for transfer and circulation, and accessible pool entry and exit modes. Future investigations should also seek to incorporate the perspectives of aquatic facility users with disabilities to better understand how observed accessibility features influence participation, independence, and overall recreational experiences. As this may reveal accessibility barriers not identified through environmental audits alone.

While ADA standards provide an important regulatory baseline, Universal Design offers a broader framework for creating aquatic environments that support participation, independence, and inclusion for individuals with diverse abilities. Future facility construction and renovation projects should seek to move beyond minimum compliance toward more comprehensive inclusive design practices. Future research should also continue to incorporate the voices of individuals with disabilities and members of the disability community to better understand how accessibility features influence lived experiences and participation.

As a whole, these findings underscore the need for targeted strategies in facility design, renovation, and operational management to reduce barriers to aquatic participation. Expanding pool accessibility is essential to promoting more equitable access to the physical, rehabilitative, and psychosocial benefits of aquatic exercise.

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Beyond visual codes

Translating color through ambient haptics and passive multisensory architecture for the spatial justice of visually impaired in metro stations

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Abstract

Background: Public transport environments often communicate route and safety information through visual cues, which may create barriers to independent wayfinding for people who are blind. Integrating additional sensory information into the built environment may offer a complementary approach to accessible navigation.

Objective: This study explores “Ambient Haptics” as a conceptual approach to passive, architecture-integrated guidance and examines the potential of embedded neodymium–iron–boron (NdFeB) magnetic strips to support cane-mediated navigation along a simulated pathway.

Method: An exploratory mixed-methods study was conducted in Tehran, Iran, with 32 male participants with total blindness, aged 24–45 years, all of whom had experience using a white cane. Participants completed a 20-metre simulated pathway first without magnetic guidance and then with embedded magnetic strips interacting with the metal tip of their cane. A researcher recorded travel time, unintended stops, and navigation or collision errors. Questionnaire responses and qualitative interviews were also used to examine participants’ reported mobility experiences. The trial order was fixed, and the quantitative findings are interpreted descriptively.

Results: Mean travel time decreased from 60 to 45 seconds, representing a 25% reduction. Mean unintended stops decreased from 4.5 to 1.5, and mean navigation or collision errors decreased from 3.0 to 1.0, representing reductions of approximately 66.7% in both measures. On a five-point Likert scale, reported mobility anxiety decreased from 3.8 to 2.1, sensory trust increased from 3.3 to 4.2, and perceived path control increased from 2.9 to 4.0. These findings are descriptive; participant-level data and the original statistical output were unavailable for independent reanalysis. Conclusion: The findings provide exploratory evidence that embedded magnetic guidance warrants further investigation as a passive, architecture-integrated channel for supporting cane-mediated navigation. The proposed approach may complement established accessibility provisions, but its effectiveness, durability, surface safety, and applicability in operational metro stations remain to be established through further controlled and real-world testing.

Keywords: Spatial justice, Ambient haptics, blindness, magnetic guidance, Multisensory architecture, Inclusive design.

1. Introduction

Modern public transportation systems often rely on visual information to support orientation, wayfinding, and safety communication. In complex environments such as metro stations, coloured lines, signs, and contrasting surface markings may indicate routes, passenger movement, or potential hazards. Although these visual cues can facilitate navigation for sighted passengers, their effectiveness depends on users being able to perceive and interpret the information presented. Environmental design and spatial organisation are therefore important considerations when developing accessible wayfinding strategies for people with sensory impairments (Zali et al., 2026). For people who are blind, environments that communicate essential navigational information primarily through visual cues can create substantial barriers to independent mobility. Research on navigation in complex public environments has identified independent wayfinding as an important accessibility challenge for people with visual impairments (Guerreiro et al., 2019). From the perspective of spatial justice, accessible public architecture should therefore provide meaningful navigational information through channels that do not depend exclusively on vision (Fainstein, 2014; Zali et al., 2026).

Existing approaches include wearable haptic devices, electronic mobility aids, smart canes, and smartphone-based navigation systems that use auditory or other sensory cues (Elmannai & Elleithy, 2017; Kuriakose et al., 2020; Casanova et al., 2025; Pittet et al., 2026; Skulimowski et al., 2025). These technologies can assist users, although their capabilities and practical requirements vary. Some systems require users to acquire, carry, charge, or maintain individual devices, which may introduce practical or financial barriers to access (Elmannai & Elleithy, 2017; Casanova et al., 2025). An alternative, complementary approach is to incorporate navigational information into the built environment itself, allowing architectural elements to contribute to the guidance process rather than relying exclusively on personal electronic devices.

This study explores such an approach through the concept of “Ambient Haptics”, defined here as passive, architecture-integrated tactile guidance. Its central conceptual proposition is that the navigational function conveyed by a visual colour code may be represented through a distinguishable tactile signal. This does not imply that people who are blind directly perceive the colour itself. Rather, information conventionally communicated through colour in a particular environment could potentially be recoded into tactile cues that convey equivalent navigational meaning. Research on multisensory navigation demonstrates the relevance of alternative sensory cues to wayfinding, but it does not, by itself, establish a universal correspondence between particular colours and tactile responses (Casanova et al., 2025; Skulimowski et al., 2025). Accordingly, the interpretation of any cue would depend on a clearly defined mapping between the intended information and the corresponding tactile signal, rather than on an assumption that particular colours have universal psychological meanings.

The empirical component of this study investigates a specific aspect of this proposal: the use of embedded neodymium–iron–boron (NdFeB) magnetic strips along a simulated pathway to provide a potential tactile guidance channel through interaction with the metal tip of a white cane. The study evaluates navigation performance and self-reported experiences under standard and magnetic-guidance conditions. It does not independently establish that every visual colour code can be translated into a distinct tactile response, nor does it test the system in an operational metro station. By distinguishing the conceptual model from the intervention evaluated experimentally, the study seeks to contribute to further research on passive haptic guidance and spatial justice in public architecture.

2. Background and Theoretical Framework

Improving spatial justice for people who are blind requires reconsidering how architectural information is communicated, particularly where wayfinding depends on visual information. This section reviews ocularcentrism in architectural design, the distinction between active sensory-substitution technologies and passive haptic approaches, and the proposed role of magnetic guidance in translating navigational information into tactile form. It also considers how the proposed approach relates to established tactile walking surface indicators.

2.1. Ocularcentrism and the Limits of Active Sensory Substitution

The design of public infrastructure, including metro stations, frequently gives visual information a prominent role in wayfinding and safety communication. Coloured lines, illuminated signs, and contrasting surface markings can help sighted passengers identify routes and interpret environmental information (Pallasmaa, 2012). When equivalent information is not available through other sensory channels, these design strategies may create barriers for people who cannot access the visual cues. The resulting difficulties can affect navigation, perceived independence, and mobility-related anxiety (Casanova et al. 2025; Pittet et al. 2026)

Technological sensory-substitution systems seek to make information available through an alternative sensory modality. Examples include devices that convert visual information into auditory signals and systems that provide tactile or electrotactile stimulation. Such approaches demonstrate the potential to communicate information that would otherwise be inaccessible through vision alone (Kuriakose, Shrestha, & Sandnes, 2024). However, wearable and electronic solutions may require individual equipment, power, maintenance, training, and additional expenditure. They also place much of the technological burden on the user rather than embedding all guidance functions within the physical environment (Wazirali et al. 2025).

Ambient haptics explores a complementary approach: incorporating the means of conveying information into architectural materials and components. In principle, a route or warning could be represented through distinguishable physical cues that can be accessed through contact with a cane or, where appropriate, through other forms of tactile interaction. The intended benefit is not to reproduce colour perception itself, but to make the navigational function associated with a visual code available through a non-visual channel.

The correspondence between colour-coded information and tactile signals should not, however, be assumed to be universal. Colour meanings vary according to the conventions used in a particular environment, and the relationship between a colour and a psychological response cannot be generalised to all users or settings. In addition, people with congenital and acquired blindness may have different visual experiences and learned associations. Consequently, any proposed colour-to-haptic mapping should be defined in relation to the actual wayfinding information used in the target setting and evaluated with the intended users.

2.2. Interactive Architecture and the Transition to Passive Haptics

Interactive architecture considers how the built environment can support users' activities and communicate spatial information through its configuration, material properties, and sensory cues. Rather than treating architecture solely as a static setting through which users must navigate, this perspective recognises that spatial organisation and environmental features can influence orientation and accessibility (Heylighen & Herssens, 2014; Zali et al., 2026).

Within this broader framework, passive haptic guidance uses physical cues, such as detectable surface patterns or material differences, to convey information without requiring continuous electronic actuation. Tactile walking surface indicators provide an established example of environmental features designed to support wayfinding and identify hazards (International Organization for Standardization [ISO], 2019). The magnetic-strip arrangement examined in the present study represents a proposed extension of this environmental approach: directional guidance is intended to be conveyed through the interaction between embedded magnetic strips and the metal tip of a white cane. Unlike many electronic travel aids that rely on powered devices carried or worn by users, the proposed mechanism is integrated into the pathway itself (Casanova et al., 2025; Skulimowski et al., 2025; Pittet et al., 2026). However, this distinction describes the design approach rather than demonstrating superior effectiveness. Appropriate installation, inspection, and maintenance remain necessary, and integration into the built environment does not by itself establish universal accessibility or long-term reliability.

Table 1 summarises the conceptual differences between active haptic technologies and passive, architecture-integrated guidance. These differences describe the approaches in general terms and should not be interpreted as evidence that passive systems are necessarily more effective or safer in every environment.

Table 1. Comparison of active haptic systems and passive haptic approaches in architecture

Feature	Active Haptic Systems (wearables and electronic devices)	Passive Haptic Systems (Ambient Architecture)
Power Requirement	Often requires batteries or another source of electrical power.	May use inherent material properties, such as permanent magnetic fields, without continuous electrical power for the guidance mechanism.
User requirements	May require users to acquire, carry, operate, or charge equipment.	Intended to reduce reliance on user-owned electronic guidance equipment.
Maintenance	May require hardware repairs, charging, or software maintenance.	Requires inspection and maintenance of the integrated materials and finished surfaces.
Relationship with architecture	Guidance is commonly delivered through a separate device.	Guidance components are incorporated into the built environment.
Potential feedback mechanisms	Electronic vibration, electrotactile stimulation, and auditory cues.	Physical cues such as surface texture or magnetic interaction through a suitable cane tip.
Accessibility considerations	Access may depend on device availability, affordability, usability, and training.	May reduce the need for personal equipment, but accessibility and safety must be evaluated for the intended users and environment.

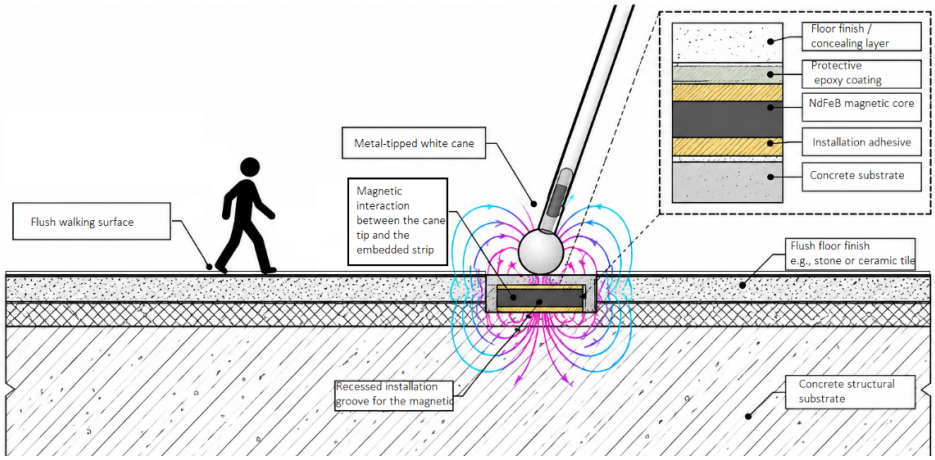
Passive haptic guidance should also be considered in relation to tactile walking surface indicators (TWSIs), including raised guiding patterns and truncated-dome warning surfaces. ISO 23599:2019 identifies guiding patterns and attention patterns as established forms of tactile walking surface indicators intended to support the safe and independent mobility of blind or vision-impaired people (International Organization for Standardization [ISO], 2019). Unlike these surface indicators, the magnetic concept examined here is intended to provide route information through magnetic interaction with a cane tip while keeping the walking surface visually continuous. The two approaches serve related but not identical functions: magnetic guidance may be investigated as a complement to established tactile indicators, not as a replacement for required warning surfaces or other accessibility provisions. Any proposed installation would need to meet applicable accessibility and safety requirements and be assessed for detectability, durability, and surface slip resistance.

The present study therefore examines a specific passive haptic intervention within a controlled simulated pathway. Broader claims about performance in crowded or noisy metro stations require further evaluation under operational conditions (Plikynas et al., 2020).

2.3. Neodymium Magnetic Guidance as a Sensory Translator

A key requirement for translating navigational information into a tactile form is that the resulting signals should be sufficiently distinguishable to convey the intended meaning. This study considers neodymium–iron–boron (NdFeB) magnetic strips as a means of providing pathway guidance through a passive physical interaction. Figure 1 illustrates the proposed integration of magnetic strips beneath the architectural floor finish.

Figure 1. Proposed integration of a neodymium magnetic strip beneath an architectural floor surface for cane-mediated guidance.



Note. The figure illustrates the proposed placement of an NdFeB strip beneath a protective floor finish. The system is intended to provide a potential tactile guidance channel through interaction with the metal tip of a white cane while maintaining a continuous floor surface. The use of an epoxy or other protective coating does not, by itself, establish adequate slip resistance, accessibility, or long-term durability; these properties require separate material and installation testing.

NdFeB is a permanent-magnet material known for its high magnetic energy density (Sagawa et al., 1984). In the proposed installation, magnetic strips are concealed beneath the floor surface and aligned with the intended route. The experimental arrangement used white canes with metal tips; no permanent magnet was attached to the cane. The effectiveness of the physical interaction depends on the magnetic properties of the tip and the installed configuration and should be evaluated for the materials used. The proposed arrangement is intended to provide tactile information through the cane without requiring electronic signal processing or continuous electrical power for the permanent-magnet guidance mechanism.

Table 2. Selected characteristics of neodymium (NdFeB) and standard permanent magnets for potential architectural integration.

Characteristic	Neodymium (NdFeB) Magnets	Standard Magnets (Ferrite / Alnico)
Magnetic Strength (Energy Density)	High magnetic energy density, potentially suitable for compact installations.	Magnetic performance varies by material and grade; larger dimensions or a different configuration may be needed for a comparable field.
Spatial Footprint	Can provide a relatively strong magnetic field in a compact component.	Required size depends on the selected material and the intended field strength.
Corrosion Resistance	Susceptible to corrosion in some environments; protection may be required depending on the grade and installation.	Corrosion resistance varies by material and grade.
Thermal Stability	Magnetic properties vary with temperature and magnet grade; performance under the intended environmental conditions must be verified.	Thermal behaviour also varies by material and grade.
Mechanical Durability	The material can be brittle and may require protection against damage during installation and service.	Mechanical durability varies by material and component design.
Cost and Implementation	Material and installation costs depend on grade, dimensions, floor construction, and protective measures.	Costs and installation requirements depend on the selected material and the performance needed.

Selected characteristics of NdFeB and standard permanent magnets are summarised in Table 2. Within the conceptual model, the function of colour-coded navigation is translated into differentiated tactile information rather than into the perception of colour itself. For example, where a particular wayfinding system uses a continuous coloured line to identify a route and a contrasting colour to indicate a warning, the associated functions could, in principle, be represented by different tactile signals. A continuous tactile cue might identify route continuity, while a distinct warning cue might indicate a decision point or hazard. Such signals would need to be specified and tested to ensure that users can distinguish them reliably.

The “Blue Line” and “Yellow Line” examples sometimes used to describe route flow and hazard warning are therefore illustrative of a possible mapping, not universal psychological rules. Blue does not inherently produce a reassuring response in every person or culture, nor does yellow necessarily trigger the same level of alertness in all settings. The proposed translation concerns the navigational meaning assigned to these colours by a specific environmental convention. The tactile alternatives must communicate that meaning through distinguishable and consistently applied cues, rather than relying on presumed universal colour–emotion associations.

The empirical component of the present study assessed a continuous magnetic-guidance pathway and compared navigation with and without the magnetic strips. It did not independently compare multiple colour-specific tactile codes or establish that participants could identify separate “blue” and “yellow” meanings through different haptic signals. The results should consequently be interpreted in relation to the navigation task that was tested, while the broader

translation of multiple visual codes into differentiated tactile patterns remains a topic for further experimental investigation.

Protective measures may be necessary to limit the environmental degradation of embedded magnets, particularly where moisture or repeated mechanical loading is present (Dobzhanskyi, 2022). However, protective coatings, low energy requirements, or a compact installation should not be taken as proof of long-term reliability, slip safety, or suitability for every public environment. These factors require verification as part of future material testing and field evaluation.

3. Methodology

This study adopted an applied, exploratory experimental design using a mixed-methods approach combining quantitative and qualitative data. It investigated whether passive magnetic haptic guidance integrated into an architectural pathway could support the navigation performance and perceived mobility comfort of people with total blindness. The intervention was designed as a low-cost, infrastructure-integrated approach that could potentially complement existing accessibility measures in public spaces. The experimental findings are interpreted in relation to the simulated pathway used in this study and are not assumed to demonstrate effectiveness in operational metro stations.

3.1. Research Design and Participants

The study included 32 male participants with total blindness, aged 24–45 years, who were purposively recruited through an association for blind people in Tehran, Iran. All participants had experience using a white cane. The distribution of participants with congenital and acquired blindness, the duration of visual impairment, the extent of mobility training, and the presence of additional mobility-related conditions were not documented in the available study records. These characteristics therefore cannot be reported or compared in the present analysis.

Each participant completed both experimental conditions: a standard pathway without magnetic guidance and the same pathway equipped with magnetic guidance. The standard condition was always completed first, followed by the magnetic-guidance condition. This within-participant design enabled comparison of the recorded navigation measures and questionnaire responses between conditions. However, because the order was not counterbalanced, practice and order effects cannot be ruled out.

The sample was selected purposively according to the study's participant criteria and access to the target population. No a priori sample-size calculation or statistical power analysis was conducted for the quantitative component. Theoretical saturation was considered in relation to the qualitative interviews only and was not used as a justification for quantitative sample adequacy. Accordingly, the quantitative findings should be interpreted as exploratory rather than as definitive evidence of effectiveness across the wider population of people with total blindness.

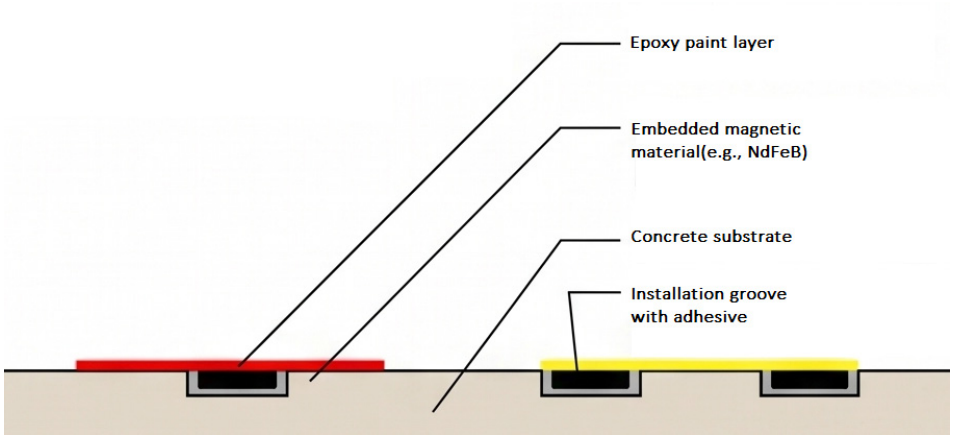
3.2. The Simulated Environment and Intervention

The experiment was conducted on a 20-metre simulated architectural pathway. Although the intervention was developed with potential applications in public environments such as metro stations in mind, the experimental pathway was not an operational metro station or a healthcare facility. It was a controlled route used to compare navigation with and without magnetic guidance.

Neodymium–iron–boron (NdFeB) magnetic strips were installed continuously beneath the designated route, aligned with the coloured directional lines used as visual guidance for sighted users. Participants navigated the pathway using their usual white canes with metal tips; no permanent magnet was attached to the cane. In the magnetic-guidance condition, interaction between the metal cane tip and the embedded magnetic strips was intended to provide tactile feedback through the cane, helping participants detect the pathway's direction and continuity.

Each participant first completed the route without magnetic guidance. Travel time, unintended stops, and navigation or collision errors were recorded by a researcher through direct observation. After a rest interval of approximately five minutes, the participant completed the same route with magnetic guidance, and the same performance measures were recorded. The questionnaire was administered separately after each condition: first after the standard route and then after the magnetic-guidance route. Semi-structured interviews were conducted after the trials to explore participants' experiences and perceptions of the guidance system. The fixed order of the trials is a limitation because possible practice effects cannot be separated from the effects of the intervention. Figure 2 illustrates the schematic cross-section of the embedded magnetic guidance strip.

Figure 2. Schematic cross-section of the embedded magnetic guidance strip.



Note. The schematic illustrates the proposed integration of NdFeB magnetic strips beneath a protective floor finish. The strips are intended to preserve the visible colour-coded route for sighted pedestrians while providing a potential tactile guidance channel through contact between the magnetic field and the metal tip of a white cane. The diagram represents the proposed construction arrangement and should not be interpreted as evidence of long-term durability or slip safety.

3.3. Data Collection and Analysis

Data collection combined direct observation of navigation performance, questionnaire responses, and qualitative interviews.

- Objective measures. The researcher manually recorded the time required to traverse the 20-metre pathway, the number of unintended stops, and the number of navigation or collision errors under each condition. These measures were based on direct observation rather than electronic motion tracking.
- Questionnaire measures. Participants completed a 20-item Persian questionnaire addressing spatial perception and mobility-related experiences. The questionnaire was informed by Loomis et al. (2001) and used a five-point Likert response scale ranging from 1 (strongly disagree) to 5 (strongly agree). The researcher read the items aloud in Persian and recorded participants' responses. The same questionnaire was administered after each route

condition, allowing comparison of self-reported outcomes between the standard and magnetic-guidance conditions.

The dimensions and Cronbach's alpha values reported in the original questionnaire table are presented in Table 3. These reliability coefficients are reproduced from the available records and could not be independently recalculated because the participant-level dataset and original statistical output were unavailable.

- Qualitative data. Interview notes were documented and coded manually to identify recurring experiences concerning route navigation, tactile feedback, perceived security, and path control. Theoretical saturation was judged in relation to the qualitative material. A separate quantitative sample-size justification was not inferred from this process.

The original manuscript reports that quantitative data were analysed using IBM SPSS Statistics, version 26, using descriptive statistics and mean-comparison procedures. However, the participant-level dataset and original SPSS output are no longer available. The analyses could therefore not be independently rerun, and the exact statistical procedures, assumptions, and inferential results could not be re-examined during this revision. The retained numerical results are consequently presented descriptively. Test statistics, degrees of freedom, exact p-values, standard deviations, confidence intervals, and effect sizes cannot be reconstructed reliably from the available summary values alone. Inferential claims that cannot be verified from the retained records are therefore not presented as independently confirmed results.

Table 3. Dimensions of the spatial perception and mobility questionnaire and reported internal consistency.

Questionnaire Dimension	Number of Items	Cronbach's Alpha (α)
Spatial Perception	3	0.78
Wayfinding	3	0.81
Path Control	3	0.74
Mobility Anxiety	3	0.85
Sensory Trust	3	0.80
Interactive Architecture /	3	0.82
Haptics technology	2	0.76
Total Questionnaire	20	0.89

4. Results and Discussion

The recorded observations and retained questionnaire summaries suggest differences between the standard pathway and the magnetic-guidance condition. Because the participant-level data and original statistical output are unavailable, the findings are presented descriptively and should be interpreted as exploratory evidence from a controlled, simulated route.

4.1. Objective mobility performance

The original results table reports a mean travel time of 60 seconds for the standard pathway and 45 seconds for the magnetic-guidance pathway. This corresponds to a descriptive reduction of 25%. The reported mean number of unintended stops decreased from 4.5 to 1.5, while the mean number of navigation or collision errors decreased from 3.0 to 1.0. Both changes correspond to reductions of approximately 66.7%.

These figures are descriptive comparisons of the values retained in the original tables. They do not, by themselves, establish statistical significance or demonstrate that the same reductions would occur in an operational metro station. The fixed order of the trials also means that the contribution of practice or route familiarity cannot be ruled out. The descriptive comparisons of these objective mobility measures are presented in Table 4.

Table 4. Descriptive comparison of objective mobility measures between the standard and magnetic-guidance pathways.

Mobility measure	Standard pathway (reported mean)	Magnetic-guidance pathway (reported mean)	Descriptive change
Travel time over 20 metres	60 seconds	45 seconds	25 % reduction
Unintended Stops	4.5 instances	1.5 instances	Approximately 66.7% reduction
Navigation/Collision Errors	3.0 instances	1.0 instance	Approximately 66.7% reduction

Note. Percentage changes were calculated from the means reported in the original table. The original participant-level records were unavailable for independent verification. No independently verified inferential statistics are reported.

4.2. Psychological outcomes and spatial perception

The retained questionnaire summaries indicate lower reported mobility anxiety and higher reported sensory trust and path control after the magnetic-guidance condition than after the standard pathway. Mobility anxiety decreased from a reported mean of 3.8 to 2.1, sensory trust increased from 3.3 to 4.2, and path control increased from 2.9 to 4.0 on the five-point Likert scale.

These changes are presented as descriptive differences between the two conditions. In the absence of participant-level responses and the original statistical output, their statistical significance and variability cannot be independently established. The reported percentage changes are based on the original means and should not be interpreted as independently verified estimates of treatment effect.

The qualitative interview notes described participants' experiences of the tactile guidance and their perceptions of route navigation. Such accounts may help contextualise the numerical summaries, but they do not establish that the system will produce the same outcomes in unfamiliar, crowded, or operational environments. The reported mean scores for these psychological and spatial-perception dimensions are summarised in Table 5.

Table 4. Reported mean scores for selected psychological and spatial-perception dimensions.

Psychological Dimension	Pre-test / Standard Path	Post-test / Magnetic Path	Percentage Change
Mobility Anxiety	3.8	2.1	Approximately 44.7% decrease
Sensory Trust	3.3	4.2	Approximately 27.3% increase
Path Control & Independence	2.9	4.0	Approximately 37.9% increase

Note. Scores use a five-point Likert scale. Percentage changes are calculated from the retained means and are descriptive only. The original participant-level responses were not available for reanalysis.

4.3. Technical limitations and implications for spatial justice

A passive tactile channel is introduced, which can be accessed using a white cane. Its potential accessibility benefit is that route information may be conveyed through the built environment rather than relying exclusively on visual signs or powered devices carried by users. However, the present experiment evaluated a 20-metre simulated pathway under controlled conditions; it did not test the system in an operational metro station or under sustained passenger traffic.

Several technical and practical issues require further investigation before real-world implementation. First, the magnetic properties of NdFeB materials vary with temperature and depend on the magnet grade and operating conditions (Constantinides & Gulick, 2004; Arnold Magnetic Technologies, n.d.). Manufacturer technical information reports a reversible temperature coefficient of remanent induction of approximately −0.12% per °C for representative NdFeB grades, while the temperature coefficient of intrinsic coercivity is a different material parameter (Arnold Magnetic Technologies, n.d.). These coefficients should not be interpreted as direct measurements of the guidance system's sensitivity. Accordingly, the previously stated 15% reduction in guidance sensitivity above 40°C should not be presented as an established result: it was not measured in the present study, and the available material-level data do not establish a 15% reduction in the performance of the complete installed system. The actual effect of temperature on cane-mediated feedback must be evaluated for the selected magnet grade and the complete installed assembly.

Second, long-term performance may be affected by the durability of the floor finish, moisture exposure, corrosion protection, repeated mechanical loading, and wear caused by pedestrian traffic. NdFeB magnets can be susceptible to corrosion, and protective coatings may be required depending on the magnet grade and environmental conditions (Arnold Magnetic Technologies, n.d.; Primc & Mozetič, 2024). The integrity of the protective epoxy layer and the condition of the finished surface would therefore require periodic inspection. Any raised edges, cracking, delamination, or changes in surface friction could create hazards for cane users and other pedestrians. Slip resistance and the safety of the finished surface must be assessed independently using appropriate test methods; the presence of a protective coating alone does not establish that the pathway is safe (European Committee for Standardization [CEN], 2021).

Third, the simulated route did not reproduce the full complexity of an operational metro station, including crowding, competing pedestrian flows, platform-edge hazards, background vibration, or the effects of prolonged use. The results should not be generalised to these conditions without further testing. Future research should examine different environmental temperatures, humidity conditions, surface wear, crowding, route configurations, and user characteristics, including differences in the onset of blindness and experience with mobility aids. A counterbalanced trial order, a larger and more fully characterised sample, and a prospective sample-size calculation for a defined primary outcome would strengthen subsequent evaluations.

Finally, magnetic guidance should be considered in relation to established tactile ground surface indicators, including guiding patterns and attention patterns, rather than as a demonstrated replacement for them. ISO 23599:2019 provides specifications and installation recommendations for tactile walking surface indicators intended to support the mobility of people who are blind or have low vision (International Organization for Standardization [ISO], 2019). The potential role of magnetic guidance is to complement existing accessibility provisions by conveying route continuity through interaction between a white cane's metal tip and embedded magnetic strips. Compatibility with applicable accessibility requirements, tactile paving, floor-surface safety, and emergency wayfinding would need to be assessed before implementation.

Within these limitations, the study provides exploratory evidence that a continuous, embedded magnetic pathway warrants further investigation as a passive architectural approach to accessible navigation. The findings support further controlled and real-world testing, rather than a definitive claim of effectiveness, long-term durability, or universal applicability.

5. Conclusion

This study investigated the potential of passive magnetic haptic guidance to support accessible navigation for people with total blindness. Through the concept of "Ambient Haptics", it explored how magnetic elements embedded within an architectural pathway could provide route information through tactile feedback transmitted via a white cane. The approach aims to incorporate an additional channel of navigational information into the built environment, potentially complementing existing accessibility measures without requiring users to carry powered electronic guidance devices.

The experimental evaluation involved 32 male participants with total blindness, aged 24–45 years, all of whom had experience using a white cane. Participants completed a 20-metre simulated pathway first without magnetic guidance and then with magnetic guidance. The values retained in the original results tables indicated a reduction in mean travel time from 60 to 45 seconds (25%), unintended stops from 4.5 to 1.5 (approximately 66.7%), and navigation or collision errors from 3.0 to 1.0 (approximately 66.7%). The reported questionnaire means also indicated a decrease in mobility anxiety from 3.8 to 2.1 and increases in sensory trust from 3.3 to 4.2 and path control from 2.9 to 4.0 on a five-point Likert scale.

These findings should be interpreted as exploratory descriptive evidence. The original participant-level dataset and SPSS output were unavailable for independent reanalysis; therefore, the statistical significance and variability of the reported differences could not be verified during this revision. Furthermore, all participants completed the conditions in the same order, so potential practice and order effects cannot be excluded. The findings do not establish the effectiveness of the system in operational metro stations or other complex public environments.

The proposed approach has potential as a passive, infrastructure-integrated complement to existing accessibility measures. However, practical implementation would require further evaluation of magnetic performance under relevant temperature and humidity conditions, durability under repeated pedestrian loading, the integrity of the protective floor finish, and the slip resistance and overall safety of the finished surface. The effects of environmental conditions on the complete installed system should be measured directly rather than inferred solely from the temperature coefficients of the magnetic material.

Future research should include larger and more fully characterised participant samples, prospective sample-size calculations based on defined primary outcomes, counterbalanced experimental conditions, and trials in operational environments. Further investigation should also examine how magnetic guidance can complement established tactile ground surface indicators and other accessibility provisions. Differences in users' mobility-training backgrounds and histories of blindness should also be considered in subsequent evaluations.

In conclusion, this study provides preliminary evidence that embedded magnetic strips warrant further investigation as a passive means of conveying route information through the built environment. Although the findings do not establish effectiveness across all settings, they identify a potential direction for more inclusive architectural wayfinding and support further evaluation of infrastructure-based haptic guidance as one component of accessible public-space design.

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Connecting UD theory to tool selection in the design process

Tool use as theory implementation.

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Abstract: This article reports on a five-phase study into communicating Universal Design theory so as to align tool use to UD design outcomes. It explains how to apply a method for strengthening the connection between UD and implementation: design tools and the data they gather are that connection. This study builds on research indicating that designers lack explicit UD justification for design tool selection. The study describes a teaching method for UD that encourages students to actively consider what elements of a design problem require direct user-involvement and what tools might be appropriate to achieve this end. The study shows that the process of categorization and organization of those categories raises awareness of design tools generally and user-centred design tools in particular. The study also indicates that educators in UD and design generally should be concerned about the number and type of design tools their students are aware of and use.

Keywords: Universal design, design tools, Inclusive Design, design process, design theory

1. Introduction

The aim of this research is to explore how to strengthen the linkage between universal design (UD) practice and the theory on which it is based. It develops research into the relation of UD theory to its application, an issue raised by Herriott (2023). The significance of theory here lies in the relation between it and data needed to define a product´s specification. The theory and data are linked by the "instruments of inquiry", the design tool (Dalsgaard, 2017) though not only by the design tool. The theory guides which design tool and what data are to be gathered and what that data might mean. Ideally, these should be as strongly-connected as possible (Fawcett, 1978; Wacker, 1998, p.362; Swanson & Holton, 2005, p.8; Van Maanen et al. 2007, p.1145; Sileyew, 2019, p.28). The worst case is that data collection tools are arbitrarily chosen. This work aims to explore a teaching approach that strengthens the theory-to-practice link. This happens by reducing the arbitrariness of UD tool selection so it is driven by UD theory. The use cases are a) in a commercial setting and b) in a class-room setting. This work, as noted above, does not work on the assumption that the class-room is a full proxy for the commercial setting.

Universal Design (UD) is a conception of design for accessibility and disability which is rooted in US legislation originating in the 1960s (Ostroff, 2011). In the literature there is interchangeable use of the terms Design for All, Inclusive Design and Universal Design (Stephanidis, 2001; Ostroff, 2011, p.3; Heylighen & Bianchin 2013, p.93, Persson et al., 2015 p.2, Zhu et al., 2020, p.2). For this article the term UD is used.

"Inclusive design was first coined as a term to promote social inclusivity towards the ageing and disability population" write Zhu et al., (2020). The name UD dates from 1985 (D`Souza, 2004, p.1).

Related work has been carried out in the UK where the field is known as Inclusive Design (ID). UD combines a blend of consumer-orientated responsibility and rights-based thinking (Heylighen & Bianchin, 2013; Heylighen, 2014). Herriott (2011) and Bianchin & Heylighen (2017) describe UD's relationship to themes of social justice. The general objective of UD is to discover detailed information about the physical, cognitive and emotional needs of users. Heightened regard is paid to disability, neurodiversity, ageing and inclusion. This last point then is what the method described here is trying to focus on: to convey to the designer that a suite of tools is required which will aim to cover information gathering requirements in relation to emotions, cognition and physical capability. When the tools are actively selected rather than selected by intuition this results in products and services which work for users with capability loss but which also are functionally and emotionally acceptable to mainstream users. By "actively selected" is meant that the tools are chosen consciously and with intention e.g. "I will choose this type of tools in relation to UD theory in order to get a defined set of data".

Preliminary research (Herriott, 2023), as stated above, suggests that the link from theory to the use of tools is not strong. Further research by Herriott (2024) reports "that the instance of explicit tool use can be found in a minority of articles. Those that do have articulated links between the tool of inquiry and theory are classed into four groups, a minority of which are based on UD theory". This means that only a minority of articles relating to UD make it clear why the tools used were chosen. If the reasoning was not arbitrary it is not made clear why it was not so. To remedy this, one could consider ways to focus on trying to make tool-use more deliberate and less arbitrary, or in other words to *deliberately choose a design tool based on definite grounds*.

1.1. About design theory.

It would be helpful at this point to have a basic understanding of theory as it is understood in this text. A short conception of theory outlined in Martin (2010: 71):

> *"A theory is made up of a number of generalisations, some of them typically referring to unobserved things postulated because they make for the best overall theory, plus a number of observation statements, typically from a variety of different contexts, which confirm the theory, which are consistent with it and which are best explained by the theory".*

Jones & Gregor (2007, p.312) state that a design theory consists of: 1) purpose and scope; 2) constructs; 3) principles of form and function 4) artifact mutability, 5) testable propositions, 6) justificatory knowledge (kernel theories), 7) principles of implementation 8) expository instantiation. In this article, the interest is focused on principles of implementation in the case of the classroom project. Application in a commercial setting is discussed in the Section 7.

In a study into the incidence of theory in UD research Herriott (2024) found that discussion of theory tended to be incomplete with respect to Jones & Gregor´s (2007) criteria. Principles of form and function were not often expounded. Implementation (i.e., how to practice the principles) tended to be neglected. Testable propositions were difficult to identify; a significant number of studies did not offer any. Overall, the bridge from theory to practice was often implicit or not dealt with at all. This is the first point to bear in mind: the weak connection that links theory and practice.

1.2. Design Tools

I now turn to the second item of research which is a study of the use of design tools (Herriott, 2023). Dalsgaard (2017) provides the terms of reference for the concept of design tools. Herriott (2023) explored in greater detail the use of theory to support tools use. Tools selection and use is an important part of how the theory is implemented. The database for the 2023 study was a two-decades long series of conference papers (the Cambridge Workshop on Universal Access and Assistive Technology). A priori, the implementation of Universal Design theory would seem to require that use of design tools was explicitly discussed on the way towards uncovering the kind of information needed for UD outcomes. However, confounding that expectation, Herriott (2023) found that 55 of 242 papers named design tools. Just 7 of the 55 used Universal Design theory (and related fields) as the basis for the use of the tool. This is in line with Beck & Stolterman (2016) who found "the question of how theory is used in design research is underrepresented in the literature".

As noted at the start, this present article aims to explore how to connect theory to practice by making explicit the justification of the use of tools of inquiry. Its practical consequence is that designers and educators will choose the design tools for Universal Design with a basis in UD theory and in so doing choose more user-centred design tools.

2. UD Pedagogy – a short review

This section is a brief overview of the previous work relevant to this study and will consider UD pedagogy. There are three main areas in which such research into UD can be divided. Watchorn et al., (2013) and Scott et al., (2018) direct attention to what they call strategies. These explain in general terms the sequence of steps that can lead to a UD outcome, without detail of the connection from UD theory to the final learning result. Watchorn et al., (2013) dealt with the context of teaching UD for architecture: "Online and face-to-face teaching methods were employed, including virtual and real-life simulation activities designed to provide students with a personal experience of impairment." They didn´t make explicit how this related to UD theory. The strategies Scott et al. discuss are 1) using guidelines as a spur for creativity and 2) engaging users in the design process. This was a set of case studies with implicit not explicit connection from theory to the outcome via the tool selection and data gathering stages. Moving to the second area, Majuri et al., (2018), Persson et al., (2015)and Rieger & Rolfe, (2021) consider the frameworks that support the teaching. These items deal with how to approach larger or smaller classes (in terms of numbers of students) and the array of methods for on-line or in-class teaching. The essence of these is how to present a conceptual structure appropriate for a classes of different sizes. There is not much linkage to UD theory, but rather these consider different types of content and the delivery mechanisms for these. The third category is design tools and the use of these which concern authors Wilson et al., (2019); Dong, (2010); and Olesen et al., (2018). Wilson et al., (2019) performed a review of design tools used in some courses in the UK. Dong (2019) focused on the persona as a design tool. There was not a very large array of material to be found on the design tools which accords with work done by Herriott (2024).

Absent from this sample is evidence that there´s much interest in the link from theory to practice or, in other words, from theory to instantiation. Theory is generally partially presented in UD design research (Herriott, 2024). That part of it which is most often absent, following Jones & Gregor´s schema is also absent in the papers cited above. These paper have strengths to be sure but the link from theory to implementation is not one of them. This then leaves a gap to be

explored which then takes us to the research question in the next section. As mentioned earlier, this concerns strengthening the linkage between (UD) practice and the theory on which it is based. Thus in the literature section the UD pedagogy was discussed because the approach selected has involved teaching. The operational goals of the study were to see if awareness of user-centred design tools (a UD need) could be increased. The method is a strategic one (per Watchorn et al., 2013 and Scott et al., 2018). With reference to Majuri et al., (2018), Persson et al., (2015)and Rieger & Rolfe, (2021), the teaching has been adjusted regarding size of class and also it is all in-person and not on-line. The work is intended to find out about design tool awareness (an understudied area, as mentioned above). As such, the operational goals (finding out about design tool use with respect to UD) are aligned with the operational goals of the theoretical basis of the study.

2.1. Structure

The article is structured as follows. The next sections consist of the research question, the method, the data from five phases of experiments, the analysis and discussion. In terms of organisational framework, it is explained to the reader UD generally what design theory consists of (Jones & Gregor, 2007) and thereafter how design tools (Dalsgaard, 2017) relate to this. With that as a start point, the method is explained. The method involves experiments exploring how to encourage the linkage to tool use to theory to achieve a UD outcome. There are five of these, with each experiment (or "phase") showing data indicative of how students make more use of design tools and user-centred design tools.

3. Research Question

The concepts of theory (Jones & Gregor, 2007) in design and what a design tool are (Dalsgaard, 2017) were explained in section 1.1 and 1.2 The background to UD and UD pedagogy were explained in section 2. In this section is articulated the way in which theory, content and the framework align across the design process by testing a pedagogical approach. How can the use of design tools, which depend on principles of implementation (Jones & Gregor, 2007), be encouraged via interventions in the structure of a design process?

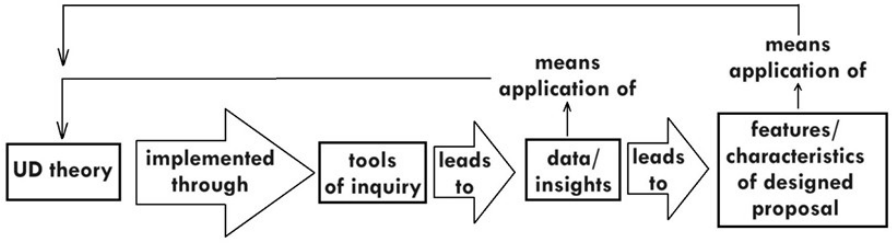
The hypothesis driving the research question is: the early identification, organizing and categorisation of the areas relevant to a design project will show where user involvement is required and which user-involvement design tools might be needed. The categorisation process involved indicating which topics required user involvement e.g. dimensions, usability. That supports the implementation of UD theory throughout the design process. Of interest is whether the identification and structuring of elements in a UD project improve designer´s awareness of which user-centred design tools to deploy in Universal Design projects. This was tested for in the class room-trials. This diagram (Fig. 1, below) represents the connection from theory to product features. Please notice the element "data/insights". To gather this data, the correct tools of inquiry are needed. The idea with this design method is to prime designers for which data types are required. The centre of this diagram is "tools of inquiry" (Dalsgaard, 2017)) which is why the experiments in sections 5.1 to 5.4 are focused on increasing awareness of tools in the UD design process.

Theory implementation depends on using design tools. Using design tools requires awareness of them. The study here proposes that recording students´ awareness is an indicator of the likelihood of using these tools. It is understood this is an imperfect measure but also it is not

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unreasonable to assume more awareness translates to some degree to some increase in the likelihood of the use of the tools.

Figure 1. The chain from theory to UD design features.



4. Methodology

The research question was formulated in Section 3 (above) and via this section the reader will move on to the experiments (5.1 to 5.4) guided by the methodology. Recall, as mentioned at the start, we are here seeing how to explore ways to strengthen the linkage between (UD) practice and UD theory. This is the theoretical bridge from the literature to the study: design tools represent implementation and the study focuses on implementation for which one needs awareness of the design tools and why they are chosen.

The methodological approach used here takes its cue from two elements. First is the general aim of UD, summarised as striving for a close fit between the broader mainstream of users´ physical, cognitive and emotional requirements and the product. This is to minimise design exclusion. The second is the set of design tools which could be used to gather and process information. We are focused on ensuring a through-line from theory to solution by implementation based on theory (Please see Fig. 1, above).

The class-room is the test environment in the following cases. One could have chosen a commercial setting also. But it is a complex environment and cross-comparisons would be difficult even if five different agencies could be found in time to complete the work. There are marked differences between the two settings so controlling the variables would be difficult. The experimental procedure described below this explores only ways to increase awareness students-as-designers within the framework of the pedagogical environment (please see Section 6 for more on this).

Recall that the literature (Herriott, 2024) showed that implementation of the theory was a weak point, namely that the use of tools and the reasoning for their use was lacking. This suggests that tool selection is not organised[1]. Given that a design tool is picked to get information, it would help to assess or scope in advance what the nature of the design case is so as to target the required information as comprehensively as possible. This then suggests that the method should support identifying the sub-parts of the design problem and which of these seem to need data related directly to the users.

The method used to scope the nature of the design cases (the class projects for the students) was derived from K/J Technique as described by Martin & Hanington (2009). In brief, the method

[1] For reasons of clarity and space, data itemizing which design tools were chosen in these experiments has been omitted. Generally, it showed that students chose from a narrow range of design tools chosen intuitively or, possibly, by default.

requires a group to name all the aspects of a situation they can think of, the pooling of the lists and the clustering of the groups into themes. In the revised versions (Phase 1 onwards) the participants are asked to identify which areas could require user-related data and what kind of data that is i.e. whether it is quantitative or qualitative. At the end of this process the students had a list of design categories that describe the task. This was divided into direct and indirect data gathering methods and general-purpose tools such as sketching and modelling.

The alternative to the collective way of identifying the categories of the design problem is either to not ask students to do this or to let them do it individually. If they did not undertake this task they would have missed a chance to identify user-related aspects of the problem. If they did it individually it would have reduced the opportunities to identify these aspects of the problem. A collective approach (the K-J approach) thus allows an opportunity to increase awareness of possible user-related issues to the largest extent allowed by the conditions.

Next, how to find out how aware of design tools the students were before and after? One approach would be to simply ask for a written list. That was rejected as it would be a list of out context of the process in which the design tools are embedded. Other approaches considered such as providing a menu or prompts might have artificially increased the number of tools names since people´s passive memory of such things is much larger than the active memory. Also, the students may have been inclined to check all the items listed at the start and at the end as was somehow expected of them. In the end, the method chosen was to ask for an annotated design-process diagram before and after the course.

Based on the model of Fig 1 (above), the steps in Table 1 (below) were followed to test how categorization and classification could support increased awareness of where user-centred design tools are be required. Students´ representations of the design process and tools used were compared before (Step 1) and after teaching (Step 6). The number and type of design tools were counted and compared before and after teaching. The teaching (not numbered) consisted of design lectures, supervision and project work.

Table 1. Stages in the Universal Design class teaching experiments. Step 5, naming a design tool also requires justification for its use: what the tool is and what information it gathers.

	Description	Comment
1	Visualising design process (“before”)	This is the first activity, prior to any teaching.
2	Universal Design Lecture, tools in design.	Theory and content of UD explained.
3	List of design concerns	Students make a list of the elements of the design problem
4	Grouped list of design concerns	Students organize the design concerns into themes.
5	Identify User-Related design issues	Students name a design tool to be used to gather the necessary information to tackle the design issue.
-	Teaching, supervision and project work.	
6	Visualise design process (“after”)	Students produce another diagram of their design process

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The following sections examine varying approaches to relating UD theory to the tools to be used. The five experiments were as follows. In the preliminary trial, the process was developed and adjusted in class. For Phase 1, it was refined and tested on a larger class (42 students). Students had project work between the preparation of the "before" and "after" diagram. Phases 2 and 3 produced more data and the procedure stabilised.

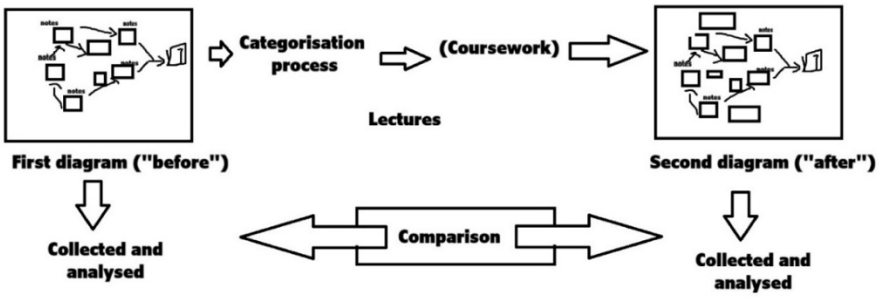
Table 2. The five stages of the experiments. In the table below the term "AC" means "accessory design". "ID" means "industrial design".

	Course name	Discipline	Tuition format	Year	Location	Date
Preliminary	Tools	ID and AC	Full length	BA-1	Denmark	Spring 2023
Phase 1	Transport Design	ID	Full length	BA-3	Turkey	Autumn 2023
Phase 2	Universal Design	ID	Full length	BA-2	Denmark	Spring 2024
Phase 3	Tools	ID	Full length	BA-1	Denmark	Spring 2024
Phase 4	Design Perspectives	ID, Clothing, Textiles, Communication	Short	MA-1	Denmark	Autumn 2024

The short version, (Phase 4 on Table 2) of the experiment explored what the effect would be of lectures on their own, without course work. The students heard about UD theory and about user-centred design tools. They were asked to consider their own previous work rather than a new project.

In all phases the students drew a design process diagram before other tuition and project work and then drew a second diagram at the very end of the course. The "before" diagram-drawing makes a baseline for the participants´ general awareness of user-centred design. The "after" diagram is a means to assess the student´s awareness of user-centred design tools after they have finished their project. Fig. 2 (above) shows the process in a simple form.

Figure 2. The experimental process (generic). Note: This diagram represents how students were asked before teaching to draw a design process diagram which was compared to a process diagram drawn at the end of course. The second diagram was expected to show increased awareness of user-centred design tools.



The process of analysing the data involved recording all design tools named on the *Before* and *After* process diagrams. Other approaches could have been doing qualitative interviews before and after the course. The pros and cons of qualitative approaches are discussed by Zawawi (2007) and Goertz & Mahoney (2013) among others. In this case, it was considered desirable to

focus on quantitative data for its immediacy while being aware of the missing subjective and interpretational richness provided by qualitative approaches. Students were not asked to provide a justification at any point in the process. The method (as explained) involved checking awareness of tools before and after. This is, to repeat, not a qualitative methods experiment. The author is also aware that some interpretation of the terms used by the subjects was involved. Other work using the same method (Herriott & Jackson, 2025) indicated the reliability of the process in terms of intersubjective agreement of interpretation of the analysis.

Now that the research question has been described (Section 3) and the method discussed, the next step is to look at the data from the experiments. Recall that, in terms of the organisational framework, the interest is in how to raise awareness of and increase use of design tools to gather user-related data to improve the UD outcome.

5. Data

The following tables show the results of the classroom experiments. The data consisted of the design tools named and recorded in the “before” and “after” process diagrams. Each participant submitted a numbered A3 sheet. The student used the same number for the “before” and “after” diagrams so they could be matched and compared.

The design process diagrams were collected after each phase. Instances of design tools were recorded. Instance of user-orientated design tools were noted. These included ideation, sketching, prototyping, modelling, mind-maps, brainstorming and CAD modelling, mood-boards, CMF boards. User-centred information gathering tools included interviews, focus groups, user-testing, questionnaires, co-creating, “co-design”. Some interpretation is required since there was not an agreed list of design tools and students appear to find it difficult to distinguish between tools and methods, as it seems that many researchers also do (Herriott & Akoglu, 2020).

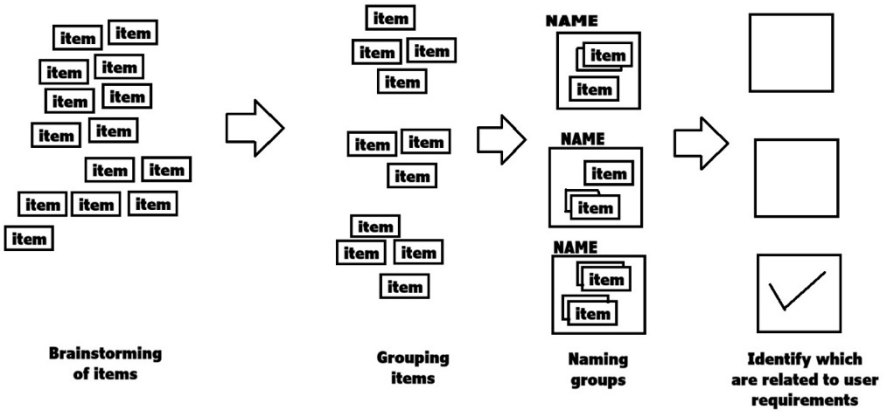
5.1. Phase Zero: BA-1 ID and accessory design (AC) students, Denmark

The class consisted of first year BA ID and accessory design (AC) students. It was a course on hand-held tool design The categorization process ran using a modified version of the K-J Technique (Martin and Hanington, 2009). The categorization process started as a class exercise with all students working in groups to identify the individual elements of which the design problem might consist. The collected list was organized in class and grouped into categories. These might be material, usability, functions, form-giving. The categories were divided into ones in which user data was required. This was further divided into those where indirect data would suffice and where direct user contact was required. An example of indirect user involvement data would be ergonomic data sheets or market research. An example of direct user involvement would be an interview, ethnography, or a focus group. Other tools such as drawing, analogue and CAD modelling and mood-boards were also identified. The process is shown schematically in Fig. 3 (below):

There were eleven diagrams collected and analysed for this phase. In the pre-course diagram, the average number of tools cited was 4.45 per person, skewed somewhat by Student #2 who listed 14. The average number of identified user-orientated tools was 1.5. The average ratio of user-related tools to general tools per person was 0.32 (the number of user-related tools divided by the total number of tools listed in each response). Martin & Hanington (2009) list 100 tools of

which 34 are user-centred. The ratio here of all tools to user-centred tools is thus 0.34, which is a point of reference for a ratio of user-centred design tools to all tools.

Figure 3. Left to right: naming design issues, grouping, naming the groups, identifying where user-centred design tools are need. Note: This diagram shows how, from left to right, students thought of elements that would be involved in their design project, then grouped those elements, named those groups and then identified which groups were related to getting user requirement data.



Six of the eleven responses did not list *any* design tools but did offer clear indications of a design process expressed in other terms. Those were, for example, a flow-chart with yes-no decision nodes or statements of the information required e.g. material, functions. The conclusion reached from this "before" diagram was that students were not very much integrating design tools into their conception of the design process. Usability/accessibility could not be said to be a strong element of their understanding given that under a quarter of the few tools named involved gathering information about the users.

In the "after" phase four weeks later, the average number of tools cited was 4.7 per person. The average number of identified user-orientated tools was 2.09. The average ratio of user-related tools to general tools per person increased to 0.51. The following table (Table 3, below) summarises the change in awareness of user-centred data gathering tools from this group.

Table 3. Preliminary Phase Zero. Industrial Design & Accessory Design BA-1 students, Denmark. Spring 2023.

	Named Any tools %	Named a user-related tool %	Average of all tools named (A)	Average no. of user-centred tools named (B)	Ratio of all tools to user-centred tools (B/A)
Before	81	63	4.36	1.6	0.36
After	100	81	4.72	2.27	0.48

5.2. Phase 1: 3rd Year ID students, Turkey.

The students were 3rd year industrial design students. The first activity of the class was to ask them to visualise a design process, bearing in mind the project they had started. That involved charging stations for electric vehicles. The class then had a four-hour tutorial during which they received a lecture on Universal Design and instruction on tools used to gather data in design. The next phase required the class to list the design concerns inherent in the project. The class had just finished their initial survey of the task as poster presentations. In the next phase class members were asked to list the design concerns for the entire class. This created a collective list of approximately forty areas of interest e.g. ergonomics, material selection, safety, graphics,

accessibility. The class were asked to individually turn this list into a set of clusters of related items. Penultimately, the class had to identify those areas on the clusters which required direct user involvement and what design tool might be appropriate to obtain that information or process it. Finally, the class were asked to draw a new diagram of the design process they envisioned would lead to a satisfactory design outcome. The students received 1:1 feedback during this work and, in particular, were encouraged to see the visualization of the diagram as a means to explain to a third party how this project would be completed. Having primed the students about a) design tools, b) user-centred design and c) Universal Design, the number of students who cited design tools increased and more of the tools required user involvement.

Table 4. Product Design (Transport Design course), BA 3 students, Turkey. Autumn 2023

	Named any tools %	Named a user related tool (%)	Avg. no. of all tools named (A)	Avg. no. of user-centred tools named (B)	Ratio of all tools to user-centred tools (B/A)
Before	89	30.7	3.26	0.41	0.126
After	91	78	6.65	2.51	0.377

The data is summarised in Table 4 (above). Awareness of any design tools increased to a little over 9 in 10 students. The number of students who named a user related tool reached nearly 80%, up from 30%. The number of tools named approximately doubled but there was a marked increase in the awareness of user-centred tools, from under 1 per person to 2.5 per person. So, general tool awareness went up but user-centred tool awareness increased even more (rather than increasing by the same amount).

5.3. Phase 2: B-ID 2 Universal Design course, Spring 2024, Denmark

The class consisted of 2nd year bachelor students, a course about Universal Design which ran over four weeks. The class size was 17 students. In the first diagram, before tuition, the average number of all tools named was 4.69 and the average number of user-related design tools was 1.8. At the end of the course (with only 10 students available to do a diagram), the average of all tools named was 7.2 per person and the number of user-related tools rose to 2.9 person. See Table 5 (below)

Table 5. B-ID 2 Universal Design, Spring 2024.

	Named any tools %	Named a user-related tool %	Avg. no. of all tools named (A)	Average no. of user-centred tools named (b)	Ratio of all tools to user-centred tools (B/A)
Before	93	75	4.69	1.8	0.33
After	100	100	7.20	2.9	0.40

In this iteration awareness of user-related tools increased from a high level, 75%, to 100%. The number of user-centered tools increased from 1.8 to an average of 2.9 per person. The ratio of all tools to user-centered tools increased but the difference was less than in the previous round.

5.4. Phase 3. "Tools" course. BA ID-1 students Denmark, Spring 2024.

This phase involved a class of 17 first year BA students. The course involved designing a hand-tool and also involved explicit instruction on Universal Design and the concept of user-centred design

tools. The categorization process was repeated. The course resulted in design proposals for hand tools including CMF, sketches, analogue and digital models. It ran for four weeks. The data is summarised in Table 6 (below).

Table 6. BA-ID 2 "Tools " course, Spring 2024.

	Named any tools (%)	Named a user-related tool (%)	Avg. no. of all tools named (A)	Avg. no. of user-centred tools named (B)	Ratio of all tools to user-centred tools (B/A)
Before	87.5	81	4.06	1.93	0.48
After	100	100	8.62	4.07	0.472

There was an initial high general awareness of tools reaching 100% in the "after" diagram. The number of tools cited doubled as did the number of user-centred tools. The ratio of all tools to user-centred tools was approximately the same (a very slight drop) which is more likely noise than signal.

5.5. Phase 4: MA-1, Design Perspectives, Autumn, 2024

The last part of the study, Phase 4, consisted of newly started first semester MA students on an introductory course called Design Perspectives. The students were from industrial design, accessory, fashion, communication and textiles lines. This version featured a shorter, half day lecture on UD. The project they carried out was not a UD project (meaning a UD project was optional). The course did have a strong focus on user-understanding and was aimed to promote equitable outcomes in a social design context. The students did not conduct the categorization exercise. So, they did receive UD tuition (lectures) but did not do the categorisation exercise that establishes where user-centred information is required. The data is summarised in Table 7 (below).

Table 7. MA-1, Design Perspectives, Autumn, 2024

	Named Any tools %	Named a user-related tool	Average number of all tools named	Average number of user-centred tools named	Ratio of all tools to user centred tools
Before	53	26	1.73	0.733	0.42
After	67	66	3.93	2.07	0.53

Before the tutorial, 53% of the class named one or more tools in their visualization. This increased to 67% after the tutorial. Before the tutorial, 26% named user-related tools which rose to 66% after the tutorial. Before the tutorial, the average number of all types of tools named was 1.733, skewed by student 15 who named 9. This rose to 3.93 after the tutorial. The average number of user-centred tools named per student was 2.07. The ratio of all tools to user-centred design tools increased by a fifth but the absolute average number was just over 2 per student.

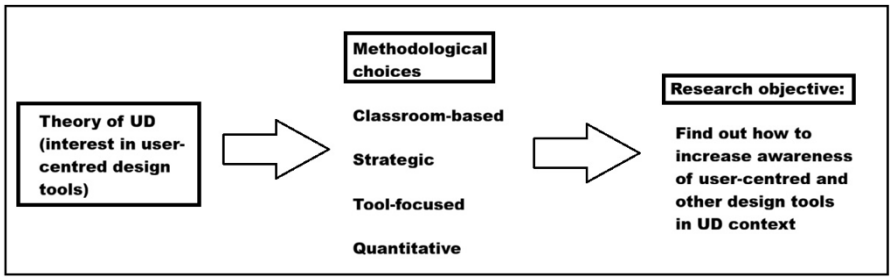
Regarding the organisation of this research, the reader has now been appraised of design theory, tools in design and the concept of UD. The studies have generated data showing how the awareness and therefore use of design tools was affected by different teaching approaches. In very general terms, these approaches to slightly varying degrees show increased awareness of design tools to gather data about the user so as to achieve UD design goals. The data is analysed below.

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6. Analysis

One question that must be briefly addressed is how the literature review covered in section 2 are related to the findings. The findings indicate a change in awareness in design tools and also add to the knowledge of strategic approaches discussed by Watchorn et al., (2013) and Scott et al., (2018). The findings also show how the conceptual work done by Jones & Gregor (2007) and Dalsgaard are translated into practical actions regarding design tool use. See Fig. 4 (below).

Figure 4. The diagram summarises the flow (left to right) from theory to research objective via methodological choices.



From a use case perspective, this process has been about seeing how the use case had demonstrated methodological feasibility. "A use case is an artifact that defines a sequence of actions that yields an observable result of value" (IBM, 2025). The sequence of actions was to use a categorisation process pooling participants´ knowledge so as to boost their ability to think about a design problem in terms of sub-tasks. This was the basis for identifying which areas would require user-centred information. And then this led to the question of what design tools would be needed to get that information. The effectiveness of the categorisation process was compared with an instance of only giving tuition (the final phase). The increase in the number of user-centred design tools was the smallest and the number of such named after tuition was the lowest.

Table 8: Summary of the change in awareness of user-centred design tools

Phase	Class	Named a user-related tool – before %	Named a user-related tool- after %
Preliminary	BA – 1 tools	63	81
1. Full prep.	BA – 3 Transport Design	30.7	78
2. Full prep	BA-2 Universal Design	75	100
3. Full Prep	BA – 1 Tools	81	100
4. No categorisation	MA 1 – Empathy & Equity	26	66

This is the summary (Table 8, above) of the changes in awareness of user-centred design tools in the five phases of the experiment.

Phase 4, without the categorization and without the design tools discussion ended with the lowest final awareness of user-centred design tools. If the application of UD theory depends on a fine-grained approach to data gathering then getting designers aware of the tools is a good start

to achieving a UD end. Categorisation and linkage to probable design tools would seem to support this.

Another point to discuss is that the qualitative data changed in the course of the experiments. Initial "before" diagrams tended more to be impressionistic e.g. abstract representations resembling the famous fuzzy-front end of Sanders & Stappers (2008). The "after" diagrams tended to be more structured and formalized, indicating that the student was representing something that they had done and in a way more communicable to others.

In general, there was very little change in the *diversity* of design tools named, of both types. Students tended to repeat the same tools rather than add new and different ones to the list. The inventory of design tools cited by students was not large. Ideation, sketching, prototyping, modelling, mind-maps, brainstorming and CAD modelling, mood-boards, CMF boards and the nebulous "desk research" were be the most frequently named. User-centred information gathering tools included interviews, focus groups, user-testing, questionnaires, co-creating, co-design (without further explanation), and observation. Role-play and "ergonomic data" were also named. Martin & Hanington (2009) list 100 tools for tackling design problems. There is a rich literature of design-tools created for UD. Herriott (2023) found 53 listed among the CWUAAT series of conferences papers. Almost none of them are cited by the participants in these investigations, whether or not there was accompanying literature to support the course.

Not unexpectedly, the group that received the least tuition and which did not do a project showed the least change, though also starting from a surprisingly small base. In mitigation, the Phase 4 participants on the MA design course had only started the first week of the first term and may have been "rusty" after a summer holidays. We can consider the Phase 4 as the baseline for what happens if one presents the theory of UD and no other tuition: awareness increases in the form of being able to cite a greater number of user-centred design tools but not by as much as when there is the categorization exercise.

7. Conclusion

The aim of this research, as stated at the start, was exploring how to strengthen the linkage between universal design (UD) practice and the theory on which it is based. The linkage was the use of design tools to gather qualitative and quantitative data. A bluntly formulated finding is that if one wants to teach UD, the students must understand the core idea of gathering detailed, fine-grained user data:

> *more user-centred tools, more often, more of the time, and chosen with justification.*

In section 4 I discussed the choice between a class-room or commercial setting. It would be highly interesting to see how to implement any aspect of this model under the rigorous conditions of a commercial setting. A priori, one might not have high hopes for much success. What one can hope is that the method described can at least encourage less opportunistic and intuition-based selection of design tools when the students find their seat in the design workplace.

The results here show improvements in the proxy for awareness. This means instances of user-centred design tools named increased but less than might be hoped for. One needs to do more than 1) explain the theory of UD, 2) carry out categorization processes and identify where user-centred data is required, 3) explain the value and use of design tools and also 4) run a design

project. Together these do raise awareness of design tools including user-centred design tools. They result in project work that is demonstrably UD in intention and outcome.

However, cause for concern remains. One is that three out of five times the awareness of the tools did not reach 100% despite explicit instruction. The last instance, of course, left out the coursework and categorization; basic tuition on UD alone does have some effect. But categorisation seems to increase awareness further.

Clearly, something more is needed to ensure that not only do students internalize the basic idea of more intensive user-centred tool use but can also show a raised awareness of the *variety* of design tools available. Note that the Hanington & Martin (2009) reference was listed as course material for Phases 0-4. Copies of the book were brought into the classroom and the contents discussed as a class exercise. Despite the evident value of this resource generally, and with regard to UD, the participants seemed not to reach for this book in the course of their project. One might have expected that explicitly and loudly highlighting the use of tools needed to get fine-grained data might have been a sufficient prompt to explore options beyond the standard menu of design tools. Apparently not.

Further work on this could involve analysing the projects that result from the teaching. It could be useful to compare this with a "standard" UD course. It might be possible to conduct interviews with students to examine what they mean by the diagrams they produce. Additionally, for UD courses, a way needs to be found to encourage critical engagement with design tools´ relation to UD theory. How this might be done is the next step in this research. At present the work shows that an assumed proxy for the awareness of UD theory has shown some change. Whether the students consciously link the tools to the theory requires further inquiry.

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AI disclosure. No AI was used in any way for any part of the creation of this document, including internet searches. AI use is antithetical to the goals of just and equitable society. There is no "reasonable use" of these tools as they depend on exploitation of labour and resources.

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An examination of students' metaphorical perceptions of universal design across different faculties

Bridging disciplinary knowledge and inclusive practice.

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Abstract: This study investigated the metaphorical perceptions of universal design among students from different faculties. Using a descriptive qualitative research design, 202 students were asked to complete an open-ended prompt: "Universal design is like... because..." The generated metaphors were analysed using content and descriptive analysis techniques to identify underlying themes and their alignment with the seven core principles of universal design. The findings reveal that students' perceptions are predominantly concentrated under the "Equitable Use" principle, highlighting a strong association between universal design and social justice or inclusivity. However, significant disciplinary variations were observed, suggesting that students' professional backgrounds (e.g., architecture vs. education) influence their focus on physical versus pedagogical accessibility. The study concludes that while students possess a foundational understanding of universal design, there is a need for more interdisciplinary integration in higher education to bridge the gap between theoretical principles and practical application.

Keywords: universal design, metaphorical perceptions, inclusive education, accessibility, equity.

1. Introduction

In recent years, approaches aimed at increasing inclusivity in education have become more prominent. Universal design (UD) is notable for its objective to create learning environments that accommodate all individuals, regardless of physical, mental, or cultural differences. Rather than treating differences as barriers, UD utilizes them to enhance instruction and promote the development of accessible, flexible learning spaces (Pobiner, 2016). UD is designed to address increasing student diversity and transform both the physical and pedagogical dimensions of education (Garcia-Huidobro et al., 2017).

Originating in architecture in the 1980s with Ronald L. Mace, UD focused on making environments more accessible for people with disabilities. This focus broadened to include age, language, learning styles, and culture, making UD a foundation for broader inclusivity (Zeyrek-Çepehan & Güller, 2020). The seven principles defined by the Centre for Universal Design at North Carolina

State University (Equitable Use, Flexibility in Use, Simple and Intuitive Use, Perceptible Information, Tolerance for Error, Low Physical Effort, and Size and Space for Approach and Use) capture the breadth of UD.

The Universal Design for Learning (UDL) and Universal Design for Instruction (UDI) models, developed based on universal design principles in educational settings, increase teaching flexibility and support diverse methods and materials suitable for different learning styles (Levey, 2018; Reyes, Meneses, Melián &, 2022). However, the implementation of these models remains limited because of specific structural and pedagogical barriers. Teachers' lack of knowledge and skills on the subject, the inflexibility of the curriculum, the inability of assessment systems to reflect diversity, and the lack of administrative awareness constitute significant obstacles to their application (Power, 2000; Shi et al., 2023; Zallio & Clarkson, 2023). The education system's focus on the normative student profile leads to resistance to differences, making it challenging to promote an understanding of inclusive education (Yu et al., 2024).

To bridge the practical challenges with conceptual understanding, it is essential to consider the theoretical frameworks that underpin the implementation of UD. A comprehensive understanding of these challenges requires consideration of the theoretical frameworks and approaches that inform the implementation of UD in educational contexts. Social justice principles, for instance, underscore the importance of providing equal opportunities for all learners.

Philosophical frameworks, including critical pedagogy, further support the transformative objectives of UD and UDL within inclusive education. These perspectives contribute to a deeper understanding of the potential societal impact of universal design. An expanding body of research examines the advantages and limitations of implementing UD in educational practice, thereby identifying areas for further investigation and highlighting specific disciplinary gaps. Analysing individuals' perceptions of a multidimensional concept such as UD elucidates both its practical and conceptual significance. The integration of UD across diverse disciplines has not become merely a technical adoption but a conceptual shift that requires a transformation in practitioners' mental models (Jones, 2014; Rose, 2001). Since UD principles are often perceived through the lens of one's primary field of study, whether the spatial focus of architecture or the pedagogical focus of education, a standard survey might fail to capture the nuanced, often subconscious disciplinary biases (Moore, 2007). Conceptual Metaphor Theory provides the necessary theoretical bridge here, positing that metaphors are not merely figurative speech but reflect the underlying cognitive structures through which students internalize and reformulate the 'abstract' ideal of inclusivity into 'concrete' professional practice (Lakoff & Johnson, 1980; Littlemore, 2001). Metaphors serve as effective cognitive tools for interpreting abstract concepts, as conceptual metaphor theory suggests that individuals structure complex phenomena through metaphors grounded in concrete experiences (Lakoff & Johnson, 1980; Landau, Barrera, & Keefer, 2017; Stamenković, Ichien, & Holyoak, 2020). By connecting theoretical perspectives with students' perceptions, metaphor analysis offers a practical lens for understanding how these concepts are internalized and applied. Moving from theoretical considerations to practical application, investigating students' descriptions of universal design reveals both their personal interpretations and the social and pedagogical contexts in which the concept is situated (Saban, Koçbeker, & Saban, 2006).

Perceptions of abstract, multidimensional concepts, such as universal design, offer insight into how they are positioned in educational practices. The metaphors used to make sense of such concepts are powerful linguistic and cognitive tools (Smedinga, Cienki, & Regt, 2023). Metaphor

analysis, based on Lakoff and Johnson, allows examination of the ways thought is shaped through language (Jensen, 2006; Lakoff & Johnson, 1980; Schmitt, 2005), revealing conceptual frameworks in education, teaching, and technology (Saban, 2006; Bagrıacık-Yilmaz, 2019; Balıkçı, Hayoğlu, & Alpsülün, 2024). As Freire noted, hearing students' voices is vital for educational democratization, and their metaphors for universal design reflect their expectations for liberation and inclusivity (Freire, 2000).

Recent academic research suggests that Universal Design extends beyond physical accessibility. In the context of higher education, it has evolved into a comprehensive framework that embraces neurodiversity and digital environments (Fernando 2026; Sousa, & Harb 2025). Meta-analyses indicate that effectively applying the three fundamental principles of UDL, engagement, representation, and action and expression, has a significant impact on student engagement and academic success (Almeqdad et al., 2023). Studies examining the views of neurodivergent students have highlighted that these learners often face challenges with conventional teaching methods. However, they prefer anonymous and adaptable interaction methods provided by digital platforms such as Quizizz and Padlet, as these tools help reduce social pressure (Durgungoz & Durgungoz, 2025; Harrison et al., 2024). In this scenario, investigating students' metaphorical understanding of universal design is essential, not only for conceptual analysis but also for understanding how neurodivergent needs are integrated into increasingly digital educational environments (Vincent et al., 2025).

Despite the recognized value of this approach, limited research has investigated students' metaphorical perceptions of UD, particularly across different faculties. Examining these perceptions helps bridge the gap between disciplinary knowledge and the practical implementation of inclusive design principles. Analysing these perceptions clarifies how discipline-specific knowledge shapes students' understanding and internalization of universal design. The findings of this study offer both methodological and theoretical foundations for developing accessible and inclusive teaching approaches and for integrating universal design principles into educational policies (Walters, 2010; Hofman & Kilimo, 2014). University students conceptualize UD differently across faculties, and these perceptions reflect specific core principles of UD; analysing their metaphorical expressions can reveal how disciplinary knowledge shapes students' understanding and interpretation of inclusive design. This study, therefore, investigates the relationship between students' metaphorical expressions and the core principles of UD, examining how these perceptions vary across faculties. In doing so, the research provides a more apparent connection between the theoretical underpinnings of UD and students' practical conceptualizations, thereby strengthening the rationale for an interdisciplinary approach. Additionally, it sought to conduct an interdisciplinary assessment based on faculty differences. Accordingly, the study explored the relationship between the metaphors generated by students and the core principles of UD, specifically investigating which UD principles are represented in students' metaphors and how these metaphorical perceptions vary across faculties.

2. Methodology

This research was designed as a qualitative study employing a phenomenological approach to explore students' experiences and perceptions of UD. Data were collected through open-ended questions, enabling participants to articulate their understanding of the concept. Participants conveyed their perceptions of universal design by generating written metaphors and providing explanatory rationales for their metaphorical expressions. The study was grounded in a phenomenological approach and informed by the principles of naturalistic inquiry (Blumer, as

interpreted by Athens, 2010), which emphasizes studying social phenomena in their natural context and allowing meanings to emerge inductively from participants' own interpretations.

2.1. Participants

The research involved students aged 18 and older from various faculties at Bolu Abant İzzet Baysal University, located in north western Türkiye between Ankara, the capital city, and Istanbul, the country's leading commercial and industrial centre. Situated between these two major cities, one in Central Anatolia and the other in the Marmara Region, the university occupies a geographically significant position that facilitates access for students from diverse regions. The institution admits students from across Türkiye and abroad, contributing to the diversity and inclusiveness of the student body. Participants were selected purposively, and data collection was voluntary. The demographic characteristics of the participants are presented in Table 1.

Prior to data collection, all participants were briefed on the study's objectives and the voluntary nature of their involvement. Informed verbal consent was obtained from all participants, ensuring they understood that their responses would remain anonymous and be used strictly for academic research purposes.

Table 1. Demographic characteristics of the participants

Variable	Category	n
Gender	Male	92
Gender	Female	110
Age	17-26	196
Age	27-36	2
Age	37-46	2
Age	47-50	2
Grade	First grade	59
Grade	Second grade	51
Grade	Third grade	45
Grade	Fourth grade	47
Faculty	Faculty of Theology	35
Faculty	Faculty of Communication	17
Faculty	Faculty of Science and Letters	26
Faculty	Faculty of Fine Arts	9
Faculty	Faculty of Architecture	23
Faculty	Faculty of Tourism	14
Faculty	Faculty of Engineering	26
Faculty	Faculty of Sports Sciences	25
Faculty	Faculty of Education	27

Two hundred two university students took part in the study. Among the participants, 110 were female, and 92 were male. The age distribution indicates that the overwhelming majority, 196 students, fall within the 17-26 age range. The breakdown by academic year shows 59 first-year students, 51 second-year students, 45 third-year students, and 47 fourth-year students. Participants are enrolled in various faculties, with the Faculty of Theology having the highest representation at 35 students. This is followed by the Faculty of Education, with 27 students, and both the Faculty of Engineering and the Faculty of Science and Letters, each with 26 students.

2.2. Data collection tool

Based on a comprehensive review of the relevant literature (Schmitt, 2005; Tannehill & MacPhail, 2012), the researchers determined that open-ended prompts of the form *"X is like … Because …"* are effective for eliciting participants' conceptual understandings through metaphorical expressions. The literature also emphasizes the importance of collecting demographic information and suggests that thematic content analysis is a suitable approach for analysing metaphor data. These insights informed the development of the data collection instrument used in this study.

2.3. Data collection procedure

The data were collected during the spring semester of the 2024–2025 academic year. Participants were asked to complete the open-ended prompt *"Universal Design is like … because …"* in a written form during class time. The instructions emphasized that there were no right or wrong answers and that students should express their own perceptions freely. Each response was coded anonymously to ensure confidentiality. The collected data were then compiled and prepared for qualitative analysis.

2.4. Data Analysis

The qualitative data obtained in this study were analysed manually using a thematic analysis approach. In line with the principles of naturalistic inquiry (Lincoln & Guba, 1985), the metaphorical expressions produced by the students were carefully examined, meaning units were identified, and each metaphor was interpreted within the framework of Universal Design principles. To ensure methodological rigour, the analysis followed a systematic process: (1) all 202 metaphorical expressions and their rationales were organized; (2) each metaphor was reviewed alongside its student-provided explanation to capture its true intent; (3) metaphors were cross-referenced with the operational definitions of the seven core principles of UD; and (4) researchers engaged in independent coding followed by consensus building to resolve any thematic ambiguities. The metaphors were categorized according to the seven core principles of Universal Design: Equitable and Fair Use, Flexibility in Use, Simple and Intuitive Use, Perceptible Information, Tolerance for Error, Low Physical Effort, and Appropriate Size and Access Space. Each metaphor was associated with the relevant principle(s), and metaphors reflecting similar themes were grouped. It is important to note that a fully inclusive approach was adopted, and no metaphors were excluded from the analysis to ensure that the diversity of all participants' voices was preserved. During this grouping process, the conceptual associations, verbal analogies, and metaphorical structures contained in the metaphors were evaluated collectively. Based on these groups, overarching themes were generated and interpreted. In this way, the students' mental representations of Universal Design and the meanings they attributed to the concept were systematically analysed and interpreted in accordance with qualitative data analysis principles

and naturalistic inquiry methodology. In line with Athens' (2010) interpretation of Blumer's framework, the data analysis followed the logic of naturalistic inquiry, consisting of three interrelated phases: exploration, inspection, and confirmation. The process concluded with the validation and refinement of themes through iterative reflection and discussion among the researchers, ensuring that the final thematic framework accurately represented participants' perspectives. To maintain full transparency and allow for independent verification, a comprehensive inventory of all metaphors is provided in the Appendices (Appendix 1 and 2), and the complete dataset supporting this research is publicly available in the Mendeley Data repository (Sivrikaya et al., 2025).

2.5. Reliability

To ensure inter-coder consistency in the study, coding reliability data were calculated. Coding reliability was determined by dividing the number of agreements between the two coders by the total possible number of agreements for the codes and then multiplying by 100 (Miles & Huberman, 1994). The inter-coder reliability was initially calculated at 94.5%, indicating agreement on 191 of 202 metaphors. For the remaining 11 metaphors with discrepancies (e.g., mother, scales, library, escalator), the researchers held a consensus-building session. During this session, the participants' written rationales for these specific metaphors were re-examined in detail to align the coding with the students' original intent. Through this iterative discussion, a 100% final consensus was reached on the categorisation of all metaphors. Furthermore, the Cohen's Kappa coefficient was calculated using the formula $K = \frac{P_o - P_e}{1 - P_e}$ (Cohen, 1960). The observed agreement (Po) was 0.945 and the probability of chance agreement (Pe) was 0.29 based on the marginal frequency distributions of the categories. The resulting Kappa value of 0.92 indicates an 'almost perfect agreement' according to the criteria established by Landis and Koch (1977), confirming the high objectivity and reproducibility of the categorical analysis. Having coding reliability above 90% is considered an accepted criterion (Saldana, 2015). In addition to inter-coder reliability, the overall trustworthiness of the qualitative findings was ensured through several strategies consistent with the principles of naturalistic inquiry (Lincoln & Guba, 1985; Athens, 2010). Credibility was enhanced through iterative reading and interpretation of the metaphors until conceptual saturation was achieved, while transferability was supported by providing detailed contextual information about the participants and the study setting. Dependability was ensured by maintaining an audit trail of analytical decisions and coding procedures, and confirmability was achieved by comparing and verifying the thematic structure between coders to ensure that interpretations were grounded in participants' actual expressions rather than researcher bias.

3. Findings

3.1. Findings on the relationship between students' metaphors and universal design principles

The students created 202 metaphors about universal design. Considering the metaphors and their justifications specified by the students, the metaphors were ranked from highest to lowest frequency and grouped into seven categories: "Equitable Use" (95 metaphors), "Perceptible Information" (39 metaphors), "Size and Space for Approach and Use" (25 metaphors), "Flexibility in Use" (25 metaphors), "Low Physical Effort" (7 metaphors), "Tolerance for Error" (8 metaphors),

and “Simple and Intuitive Use” (3 metaphors). When the categories are examined according to their constituent codes, the “Equitable Use” category is comprised of the codes universality/integrity/inclusivity, equality and fairness, balance/order, similarity and, sensitivity; the “Perceptible Information” category consists of the codes need, guide, reflectivity/expression, clarity, valuable, transparency, empathy, and hope; the “Size and Space for Approach and Use” category is made up of the codes infinity, accessibility, ideal and, existence/nonexistence; the “Flexibility in Use” category includes the codes diversity/relativity, individuality, difference, live-dynamic, imagination, complexity, and utopian; the “Low Physical Effort” category consists of the codes ease and happiness/well-being; the “Tolerance for Error” category includes the codes development-process and precaution; and the “Simple And Intuitive Use” category is comprised of the codes flexibility and simplicity. The analysis revealed 30 codes under the universal design principles. A comprehensive list of all metaphors associated with these codes and categories is provided in Appendix 1.

3.2. Findings on students’ metaphorical perceptions of universal design principles across faculties

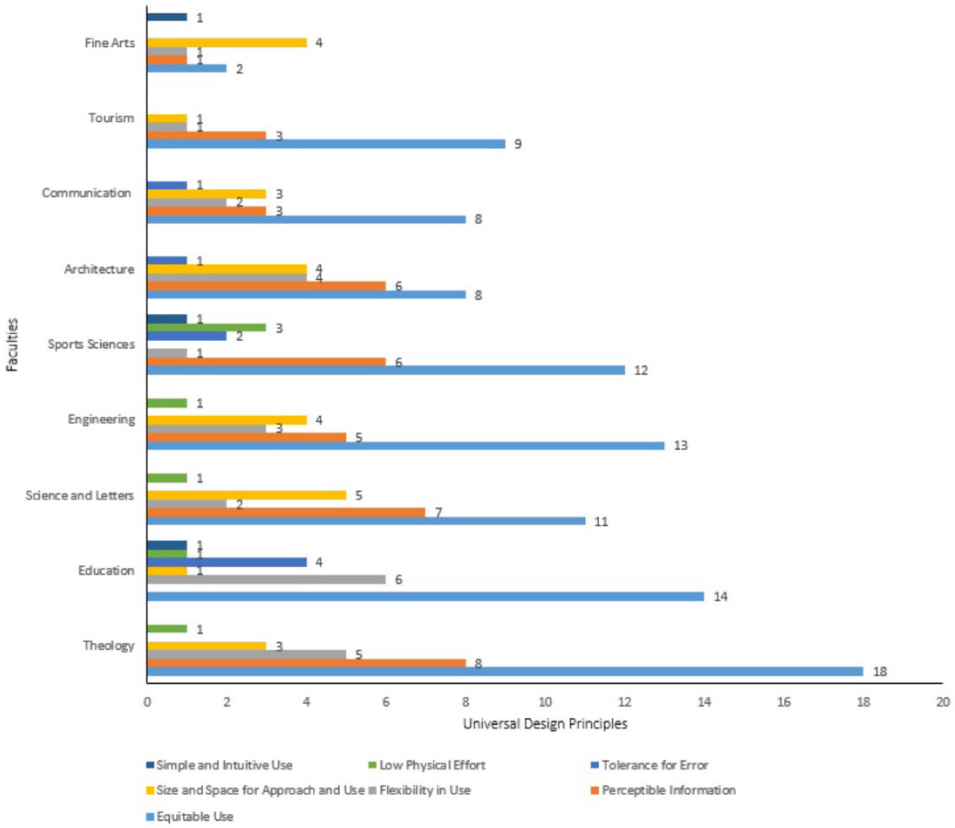
The metaphorical perceptions of students regarding UD principles were first analysed quantitatively to determine the distribution of themes across different academic disciplines. This comparative overview allows for a broader understanding of how various faculties prioritize different aspects of accessibility and design. Table 2 summarizes the frequency of metaphors produced by students from nine different faculties, categorized according to the seven fundamental principles of universal design.

As shown in Table 2, while "Equitable Use" emerged as the most frequently metaphorized principle across nearly all disciplines, significant variation was observed in other categories, such as "Perceptible Information" and "Flexibility in Use".

Table 2. Distribution of students’ metaphorical perceptions across faculties and universal design principles

Faculties	Equitable Use	Perceptible Information	Flexibility in Use	Size and Space for Approach and Use	Tolerance for Error	Low Physical Effort	Simple and Intuitive Use
Theology	18	8	5	3	0	1	0
Education	14	0	6	1	4	1	1
Science and Letters	11	7	2	5	0	1	0
Engineering	13	5	3	4	0	1	0
Sports Sciences	12	6	1	0	2	3	1
Architecture	8	6	4	4	1	0	0
Communication	8	3	2	3	1	0	0
Tourism	9	3	1	1	0	0	0
Fine Arts	2	1	1	4	0	0	1

Figure 1. Distribution of Universal Design Principles across faculties



As illustrated in Figure 1, a comparative analysis of metaphorical perceptions reveals that the principle of Equitable Use serves as a common conceptual core across all faculties, reaching its peak frequency in Theology (n=18) and Education (n=14). However, the graphical representation highlights significant disciplinary nuances: for instance, while Education students emphasize Tolerance for Error (n=4), students from Fine Arts and Science and Letters focus more on Size and Space for Approach and Use (n=4 and n=5, respectively). Conversely, principles such as Low Physical Effort and Simple and Intuitive Use exhibit the lowest frequencies across the board, suggesting a conceptual gap in these functional dimensions of Universal Design, regardless of students' academic background.

In addition to the numerical distribution in Table 2, a comparative word cloud analysis (see Figure 1) provides a qualitative synthesis of the metaphorical landscape across faculties. This visualization reveals distinct disciplinary leanings: while Theology and Education students gravitate towards metaphors of 'balance' and 'inclusion' (e.g., scales, puzzle), Architecture and Fine Arts students employ more spatial and structural metaphors (e.g., ocean, earth, buildings), reflecting a design-oriented perspective. The dominance of 'Equitable Use' is visually evident across all clouds, yet the secondary themes, such as 'Perceptible Information' in Engineering and 'Equitable Use' in Science and Letter, highlight how academic background nuances the conceptualization of Universal Design. This visual synthesis confirms that students do not perceive UD merely as a set of rules but as a diverse conceptual framework shaped by their specific fields of study.

To provide a more nuanced understanding of these perceptions, the qualitative data for each faculty, including specific metaphors and sample expressions, are detailed in the following subsections. Furthermore, Appendix 2 provides a comprehensive inventory listing all students' metaphors, their associated UD principles, and corresponding sample expressions.

Figure 2. Comparative Word Cloud Visualization of Metaphorical Perceptions across Different Faculties



The analysis of metaphors generated by students from different faculties demonstrates that UD is predominantly understood as a concept grounded in justice, inclusivity, and accessibility, though its interpretation varies across disciplinary perspectives. Across all faculties, the principle of Equitable Use emerged as the most frequently emphasized category, indicating a shared ethical core in students' conceptualizations of UD. Students consistently associated universal design with fairness, equality, and social harmony; however, the metaphors they employed revealed differences in the depth, focus, and functional orientation of this understanding (see Figure 2).

Faculties such as Theology, Education, Communication, Tourism, and Science and Letters framed universal design primarily within ethical, social, and philosophical dimensions. Theology students conceptualized UD through metaphors reflecting balance, divine order, and moral responsibility, positioning design as an extension of spiritual and social justice. Similarly, Education students emphasized inclusivity and equality, interpreting UD as a pedagogical tool that embraces all learners and sustains hope and continuity within inclusive education. Communication students extended this ethical framing by highlighting not only physical but also emotional and cognitive accessibility, portraying UD as a humanistic structure grounded in empathy and order. Tourism and Science and Letters students reinforced this perspective through metaphors of transparency, reflection, existence, and nonexistence, suggesting that UD is perceived as both a mirror of society and a fundamental requirement of human life. Collectively, these faculties approached universal design as a value-based construct, closely linked to social responsibility, moral awareness, and philosophical reflection.

In contrast, students from Engineering, Sports Sciences, Architecture, and Fine Arts placed greater emphasis on the functional, spatial, and aesthetic dimensions of universal design, while still grounding their interpretations in equitable use. Sports Sciences students predominantly evaluated UD on practicality, ease of use, and daily functionality, using concrete metaphors related to basic needs and physical accessibility. Engineering students, although expected to focus on technical aspects, instead favoured abstract and socially resonant metaphors, underscoring comprehensibility, shared values, and access to information rather than purely mechanical solutions. Architecture students demonstrated the most multidimensional

engagement with UD principles, integrating equity with flexibility, spatial accessibility, sustainability, and sensory–aesthetic considerations, reflecting a design-orientated and creative perspective. Fine Arts students uniquely prioritized the principle of Size and Space for Approach and Use, conceptualizing UD as limitless, accessible, and meaning-oriented through expansive and aesthetic metaphors such as the world, ocean, and art.

Despite these variations, certain principles, particularly Low Physical Effort and Tolerance for Error, were weakly represented across faculties. While some metaphors indicated partial awareness of sustainability, durability, and resilience, the limited number and depth of these metaphors suggest gaps in students' conceptual understanding of UD's functional dimensions. Overall, the findings indicate that although students share a strong ethical perception of universal design centred on justice and inclusivity, their understanding of its technical, functional, and error-tolerant aspects remains uneven and discipline-dependent.

4. Result

The analysis of 202 metaphors revealed that students' perceptions of universal design are predominantly organised around a limited number of core principles. Across all faculties, Equitable Use emerged as the most frequently represented principle, indicating a shared emphasis on justice, equality, and inclusivity in students' conceptualisations of universal design. This principle was consistently prioritised across disciplinary backgrounds.

Other principles, including Perceptible Information, Size and Space for Approach and Use, and Flexibility in Use, were represented at moderate levels and showed greater variation across faculties. These principles reflected differences in how students emphasised cognitive accessibility, spatial considerations, adaptability, and diversity across academic disciplines.

In contrast, the principles of Low Physical Effort, Tolerance for Error, and Simple and Intuitive Use were weakly represented in the metaphors generated by students from all faculties. These principles accounted for the lowest frequencies overall, indicating limited metaphorical engagement with the functional and error-related aspects of universal design.

Overall, the results show that while students across faculties share a strong orientation toward the ethical and social dimensions of universal design, the distribution of metaphors across principles varies by discipline, with some principles receiving consistently less attention than others.

5. Discussion

This study examined university students' metaphorical perceptions of UD across different faculties and found that students emphasized themes of justice, inclusivity, accessibility, and social equality. The findings both align with and diverge from the existing literature, enabling a multi-layered understanding of how students from various disciplines conceptualize UD.

The prominence of the "Equitable Use" category across all faculties indicates that students interpret UD within the axes of justice, equality, and inclusiveness. This finding reflects not only students' inherent valuation of fairness and accessibility but also aligns with theoretical frameworks emphasizing social justice and democratic participation in education (Nussbaum, 2011; Freire, 2000). By situating UD in the context of equity, the results suggest that students internalize broader societal and ethical dimensions of design, highlighting the importance of incorporating social justice considerations into both pedagogy and institutional policy.

Furthermore, this emphasis underscores that curriculum designers and educators can leverage students' perceptions to prioritize inclusivity and equitable access, ensuring that learning environments actively reflect these principles. This also has practical implications for teacher training programs, where modules can explicitly address inclusive and equitable design, guiding instructors to implement strategies that respond to the needs of diverse learners. This finding aligns with studies that define UD as a structure that serves social equality, democratic participation, and social justice (Zallio & Clarkson, 2023; Tang et al., 2022; Nussbaum, 2011). Zallio and Clarkson emphasized that inclusive and accessible design is a fundamental condition of UD, which aligns with the frequent emphasis on social justice in students' metaphors. In students' metaphorical expressions, social values also point to the ethical and philosophical dimensions of UD (Rawls, 1999; Freire, 2000). However, these emphases diverge from those in the study by Khalil, Ramzy, and Mostafa (2013), which addressed sustainability and equity-based design. Because Khalil et al.'s (2013) study did not directly focus on social justice or inclusion, only a limited connection can be made with the current study. This contrast highlights how students' metaphorical perceptions extend traditional UD frameworks by incorporating ethical, social, and philosophical dimensions that may not be emphasised in conventional design studies.

In particular, the evaluation of UD by students from the Faculty of Education and the Faculty of Arts and Sciences in terms of cognitive and emotional accessibility highlighted the importance of the "Perceptible Information" category. This suggests that UD is perceived not only as a physical design principle but also as a pedagogical approach that values cognitive inclusivity and equitable access in learning. By linking perceptible information to educational practice, this finding highlights that UD principles can inform curriculum design, instructional strategies, and learning technologies to support the needs of diverse learners (Dolmage, 2017; Meyer et al., 2014). Research, such as that by Super et al. (2020), suggests that UD has the potential to transform learning processes and highlights the importance of designs that cater to students' individual learning needs. In this context, students' metaphors align with the fundamental principles of the Universal Design for Learning (UDL) and Universal Design for Instruction (UDI) models (Levey, 2018; Reyes et al., 2022). However, factors such as teachers' lack of knowledge, rigid curricula, and administrative barriers pose severe limitations to the implementation of these models (Shi et al., 2023; Power, 2000). Thus, while students perceive UD positively, systemic and structural barriers continue to hinder its practical application, underscoring the need for policy-level and institutional support to fully realise its potential (Yu et al., 2024).

The metaphorical insights uncovered in this study reveal notable similarities with current debates in the literature concerning neurodiversity and digital accessibility. For instance, students' metaphors describing universal design as a 'liberating tool' or a 'supportive ecosystem' resonate with the aims of diminishing stigma and enhancing self-advocacy skills, as highlighted by Schuck and Fung (2024). According to Harrison et al. (2024), digital technologies are increasingly viewed not only as assistive resources but also as inclusive 'living spaces' that cater to the cognitive and emotional needs of neurodivergent students. However, as Karisa (2023) critically points out, the effectiveness of UDL strategies should extend beyond mere technical execution. As emphasized by Cole et al. (2024), it is crucial to consider the distinct needs of each student, especially neurodivergent individuals, when balancing flexibility with structured support in metaphorical reflection. Therefore, the differing perceptions across faculties confirm that universal design requires not only technical curriculum adjustments but also a comprehensive mind-set shift rooted in social justice (Espada-Chavarria et al., 2023; Priyadharsini & Sahaya-Mary, 2024).

One of the study's significant contributions is demonstrating how students perceive UD differently across disciplines. While architecture students tend to focus more on the aesthetic

and sensory aspects of design, engineering students emphasise the social functions and impacts of design. This disciplinary difference reveals that cognitive frameworks, epistemological foundations, and prior knowledge shape how students internalise multidimensional concepts like UD (Parpala et al., 2010; Singer & Smith, 2013). Understanding these differences can inform context-specific pedagogical interventions and curriculum development that align with disciplinary perspectives. In the study conducted by Wang et al. (2022), although the socio-political context of design in architectural education is highlighted, it does not directly overlap with the current research in terms of metaphorical analysis. Nevertheless, by offering a new perspective on students' interpretive practices, this study demonstrates the importance of metaphor analysis for understanding discipline-based differences in meaning-making. In this context, interdisciplinary perspectives contribute to a more comprehensive understanding of the pedagogical, social, and epistemological dimensions of UD (Lahti, 2023).

The relatively limited number of metaphors related to "Low Physical Effort" and "Tolerance for Error" suggests that students perceive these principles as secondary compared to other UD dimensions. Although the metaphors in these categories point to concepts such as sustainability, resilience, and functionality, which align with UD's understanding of long-lasting and effective design (Zallio & Clarkson, 2023; Tang et al., 2022), their overall scarcity suggests limited engagement with these functional aspects. This imbalance suggests that students may predominantly associate universal design with its ethical and social dimensions, such as equity and inclusion, while overlooking its functional and usability-related aspects. One possible explanation for this pattern is that universal design is often introduced in educational contexts primarily through the lens of accessibility and social justice, with less emphasis on technical principles related to usability, error tolerance, and efficiency (Nussbaum, 2011; Freire, 2000; Zallio & Clarkson, 2023; Tang et al., 2022).

In addition, these underrepresented principles may be less cognitively salient for students, as they require more concrete design experience and practical engagement to be fully understood. Unlike concepts such as fairness or inclusivity, which are socially visible and easily metaphorized, principles like "Tolerance for Error" or "Simple and Intuitive Use" are more abstract and embedded in design processes, making them less accessible for metaphorical thinking (Lakoff & Johnson, 1980; Landau et al., 2017; Stamenković et al., 2020). From a critical perspective, this finding may also indicate a gap in how universal design is taught across disciplines. The limited awareness of these principles suggests that current instructional approaches may not sufficiently address the full spectrum of UD, particularly its functional and user-experience dimensions (Meyer et al., 2014; Levey, 2018; Reyes et al., 2022; Shi et al., 2023). Therefore, a more balanced and comprehensive integration of all UD principles into higher education curricula is necessary to ensure that students develop a holistic understanding of UD.

The metaphor analysis method employed in this study provided detailed insights into how students make sense of UD, a concept that is abstract and multidimensional (Landau et al., 2017; Stamenković et al., 2020). By employing Lakoff and Johnson's (1980) conceptual metaphor theory, the study not only identified thematic patterns but also illuminated the cognitive and ethical dimensions embedded in students' interpretations. This method illustrates how metaphors serve as cognitive scaffolds, connecting abstract design principles to students' lived experiences and societal values (Saban, 2006; Jensen, 2006; Schmitt, 2005). Metaphors have been considered not only linguistic tools but also cognitive structures that shape individuals' conceptual worlds.

Beyond the cognitive structures identified by Lakoff and Johnson (1980), these metaphors must be interpreted within the context of modern Accessibility Theory. As Stevens (2019) articulates in the context of Hamraie's work, UD is not merely a neutral technical standard but a 'normative' project that shapes how future professionals perceive human variation and political belonging. In this study, metaphors that frame UD as a 'key' offer a dualistic interpretation. While a key suggests a facilitator role by providing a tool for entry, it simultaneously reflects what Hamraie calls 'access, knowledge', a conceptual framework that questions who holds the power to grant, possess, or restrict access.

Furthermore, as Titchkosky (2011) argues, when access is conceptualized only as a 'special' solution, much like a special key issued for a specific, segregated door, to accommodate a 'problematic body,' it creates a version of personhood that remains fundamentally excluded from the norm. This literal and symbolic reliance on 'special' access tools reinforces segregation rather than true inclusion. Such a perspective may hinder the broader implementation of UD by reducing it to a reactive, checklist-based adjustment or a secondary provision, rather than a proactive and universal design philosophy. Therefore, the disciplinary metaphors found in this research reveal the invisible 'epistemic' boundaries, the limits of what is known and practiced, that future practitioners may face. Bridging these metaphors with a critical disability perspective suggests that unless students' mental models shift from 'functional accommodation' to 'social justice' and symbolic belonging (Guffey, 2018), the actual implementation of UD will remain limited to physical compliance rather than holistic, meaningful inclusion.

The findings indicate that students assess UD not only in physical terms but also within cognitive, emotional, and social contexts. The prominence of justice and accessibility themes as common ground demonstrates that students recognise the ethical and pedagogical dimensions of UD, highlighting its relevance beyond mere technical design. By connecting UD principles to social justice and equity, students' perceptions provide actionable insights for curriculum development, instructional design, and policy formulation (Dolmage, 2017; Meyer et al., 2014; Nussbaum, 2011). However, the differences observed across disciplines indicate that UD education should be designed in a context-specific, discipline-sensitive manner. Instructors' interpretation of UD, aligned with their own disciplines' epistemological foundations, directly influences students' understanding (Parpala et al., 2010; Singer & Smith, 2013; Lahti, 2023). Future research should investigate how students' metaphorical perceptions of UD evolve and how these perceptions are reflected in their professional practices. In addition, analysing faculty members, administrators, and policymakers' metaphorical understanding of UD would be valuable for revealing how the concept is perceived at the institutional level. In conclusion, approaching UD as a concept of justice and access that encompasses not only individuals with disabilities but all individuals strengthen the inclusive and equitable nature of education, bridging theoretical understanding with practical application (Freire, 2000; Nussbaum, 2011; Rawls, 1999).

6. Limitations and Recommendations

The research was conducted only with university students from specific faculties and age groups, and the findings cannot be generalized to individuals of other ages or educational levels. Data were collected solely through open-ended questions; it is recommended that different methods be used for more in-depth analyses. Since the research was limited to a single university, cultural and regional differences were not taken into account. Although the study involved a significant sample of 202 students from various academic backgrounds, the distribution across faculties was not perfectly equal. Specifically, students from the Faculty of Theology (n=35), followed by the

Faculties of Education (n=27), Science and Letters (n=26), and Engineering (n=26), showed higher participation rates than those in other disciplines. This relative over-representation of certain academic fields may influence the overall metaphorical perceptions of universal design, as students' conceptualizations are often shaped by their specific disciplinary cultures. For future studies, it is recommended that more data be collected from individuals of different age groups, educational levels, and cultural backgrounds. Additionally, by ensuring a more balanced distribution of participants among faculties, metaphorical perceptions can be examined more comprehensively. For more in-depth analyses, data collection methods such as group work and focus group interviews should be employed. Ultimately, it is recommended that universal design be integrated into educational curricula to improve its effective implementation.

7. Conclusion

This study provides a comprehensive insight into how university students from different faculties conceptualize universal design through metaphors, revealing that UD is predominantly perceived as a framework grounded in justice, inclusivity, and accessibility. The findings demonstrate that, while students share a common ethical orientation toward equitable use, their metaphorical interpretations vary according to disciplinary perspectives, highlighting differences in emphasis on the cognitive, functional, spatial, and aesthetic dimensions of design. By employing metaphor analysis, the study contributes to the literature by illuminating the cognitive and value-based structures underlying students' understandings of UD, moving beyond purely technical interpretations. Overall, the results suggest that universal design is not merely a design principle but a multidimensional concept intertwined with social responsibility, educational equity, and human-centred values, underscoring the importance of discipline-sensitive, holistic approaches to UD education in higher education contexts.

To address areas of limited student awareness regarding certain UD principles, higher education curriculum designers should consider a more balanced integration of all UD dimensions. Courses could incorporate practical, hands-on design experiences that emphasize functional usability, error tolerance, and efficiency, alongside the more commonly taught ethical and social aspects, such as equity and inclusivity. Interdisciplinary collaboration across faculties can help students, link abstract UD concepts to concrete applications, while reflective activities, such as metaphor creation, case analyses, and design critiques, may strengthen students' understanding of less visible principles. By systematically embedding both technical and social-ethical aspects of universal design throughout curricula, universities can ensure that graduates develop a holistic understanding of UD, preparing them to create inclusive, effective, and human-centred designs in diverse professional contexts.

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Data availability statement. The dataset supporting this study is publicly available in Mendeley Data (*Sivrikaya et al., 2025).*

Ethics Statement. This research has been approved for ethical compliance by the Social Sciences Human Research Ethics Committee of Bolu Abant İzzet Baysal University with the decision dated 21.01.2025 and numbered 2025/01 (Protocol No.: 2025/05). Oral consent was obtained from the participants before the start of the research.

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Appendix 1. A qualitative comparison between students' metaphors for universal design and its principles

Table a1.1. A qualitative comparison between students' metaphors for universal design and its principles

Category		Code	Metaphors	Sample Expression
Equitable (95)	Use	Universality/ integrity/ inclusivity (43)	Tree (1), Mother (1), Escalator (1), Connecting (1), Simple and Intuitive Use (1), White (1), A Whole (1), A Kind of Object That Makes Our Lives Easier (1), Integrative Perspective (1), Nature (2), World (1), A Newborn Baby (1), A Puzzle Where Different Pieces Can Come Together (1), Sky and Sea (1), Everyone (1), Equality (1), A Book Everyone Should Read (1), Feelings (1), Illusion (1), Door (1), Common Language (1), Kebab (1), Book (1), Sphere (1), Mevlana (1), Meeting Needs (1), Clean Air (1), Pomegranate (1), River (1), Freedom (1), Statue of Liberty (1), Sharing (1), Respect (2), Social Media (1), Like a Mirror Held Up to Society (1), Puzzle (3), Puzzle Pieces (1), Creative Way of Thinking (1), Round Shape (1)	"It is like a puzzle. Because when the pieces come together, they form a meaningful whole." (S2)
Equitable (95)	Use	Being equal and fair (41)	Water (2), Scales (3), Escalator (1), Religion of Islam (1), Justice (1), Truthfulness (1), Living According to Religion (1), Cloud (1), Equality (1), Face (1), Equality and Design (1), A Dream That Must Come True (1), Paint Palette (1), Access (1), A Free Country (1), Equality (1), Life (1), Structures Dependent on Imagination (1), Wholeness (1), Equal Use and Flexibility (1), A Society Where Everyone is Equal (1), A World Where Everyone is Loved (1), Designing According to Everyone's Situation (1), Being Unique (1), Sky (1), Appealing to All Segments of Society (1), Gender Equality (1), Something That Should Be (1), Scales of Justice (2), School (1), Childhood (1), Oxygen (1), To Live (1), An Equal Environment (1), Water Accessible to All (1), Still Water (1), Tree Roots (1)	"It is like a scale. Because equality is its goal." (S44)

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Category	Code	Metaphors	Sample Expression
Equitable Use (95)	Balance/ order (9)	Scales (2), Religion (1), Life (1), Justice (1), Order Itself (1), Order within Chaos (1), Laws of Life (1), Chain Links (1)	"It is like order within chaos. Because reflecting the styles of people living in different geographies under a single roof in the world population demonstrates order amid chaos." (S81)
Equitable Use (95)	Similarity (1)	Emotions (1)	"It is like emotions. Because everyone feels similar things." (S150)
Equitable Use (95)	Sensitivity (1)	The Embodiment of Understanding (1)	"It is like the embodiment of understanding. Because it advises us to be more sensitive towards people." (S125)
Perceptible Information (39)	Need (16)	Tree (1), Water (3), House (2), Nature (1), Bread (1), A Rare Plant (1), Education (1), Breathing (1), Shelter (1), Emotions and Senses (1), Being Able to Eat (1), Car (1), Oxygen (1)	"It is like house. Because everyone needs shelter." (S71)
Perceptible Information (39)	Guide (11)	Mind (1), Library (1), Sun (2), Star (1), Being a Muezzin (1), A Free Bird (1), Audible Pedestrian Crossing (1), Guide (1), Key (2)	"It is like the sun. Because it sheds light on every subject." (S107)
Perceptible Information (39)	Reflectivity/ expression (5)	Tree (1), World of Imagination (1), Free Mindset (1), Imaginary Buildings (1), Mirror (1)	"It is like imaginary buildings. Because design is the reflection of what we have in mind. (S108)
Perceptible Information (39)	Clarity (3)	The Things We See When We Look Back (1), The Embodied Form of the Soul (1), Common Language (1)	"It is like a common language. Because it is understood in conversations." (S96)

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Category	Code	Metaphors	Sample Expression
Perceptible Information (39)	Valuable (2)	Treasure (1), Jewel (1)	“It is like a treasure. Because it is very valuable for humanity.” (S127)
Perceptible Information (39)	Transparency (2)	Water (1), Transparency (1)	“It is like transparency. Because inside and out it is the same.” (S112)
Size and Space for Approach and Use (25)	Infinity (10)	Sea (1), Space (2), Earth (1), Drowning in the Ocean (1), Ocean (2), Sky (3)	“It is like sea. Because it is endless.” (S1)
Size and Space for Approach and Use (25)	Accessibility (8)	Water (1), Information (1), Easy, Comfortable, Straight Path (1), Art (1), Easy Trends and Paths (1), Perceptible Information (1), World of Software (1), Accessibility for Everyone (1)	“It is like information. Because everyone can easily benefit from it.” (S31)
Size and Space for Approach and Use (25)	Ideal (4)	An Unknown Utopia (1), Keeping Imagination Alive (1), The Eye Opening to Reality (1), The Need for Nutrition (1)	“It is like an unknown utopia, because people believe in what they don't know.” (S9)
Size and Space for Approach and Use (25)	Existence/ nonexistence (3)	Nature (1), Extinction (1), Each Person's Private World (1)	“It is like nature. Because existence is fundamental to every individual. Nature is a unique part of it.” (S60)
Flexibility in use (25)	Diversity/ relativity (9)	It is a Confusion Where Everyone Derives Different Meanings (1), Class (1), Cloud (1), Imagination (1), World (2), Everyone Achieving Their Specific Desires (1), Creation (1), Universe (1)	“"It is a confusion where everyone derives different meanings. Because people's lives and understanding of life differ according to their way of seeing things from life.” (S18)

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Category	Code	Metaphors	Sample Expression
Flexibility in use (25)	Individuality (5)	Equal Art (1), Designed Shoes (1), Everyone Climbing Trees (1), Painting (1), Van (a city) (1)	"It is like a painting. Because every viewer gets a different meaning." (S196)
Flexibility in use (25)	Difference (4)	A Colorful Flower Garden (1), Functional and Aesthetic Design (1), Rain (1), Weather (1)	"It is like the weather because it contains various weather events and conditions." (S184)
Flexibility in use (25)	Live-dynamic (4)	Drinking Water (1), Water (1), Nature (1), Rubber (1)	"It is like drinking water. Because it is a living thing that gets refreshed as you drink it." (S3)
Flexibility in use (25)	Imagination (1)	Fairy tale (1)	"It is like a fairy tale. Because it is a product of imagination." (S104)
Flexibility in use (25)	Complexity (1)	Knot (1)	"It is like a knot because it is very complicated." (S110)
Flexibility in use (25)	Utopian (1)	Happiness (1)	"It is like happiness, because it is something that will never be perfect." (S137)
Low physical effort (7)	Ease (5)	Equal Accessibility (1), Telephone (1), Automatic Opening Door (1), Technological Devices (1), Flexibility and Simplicity in Use (1)	"It is like access to equal conditions because it allows a person to meet their needs more easily." (S63)
Low physical effort (7)	Happiness/ well-being (2)	Chocolate (1), Sunny Sky (1)	"It is like chocolate. Because it is happiness." (S10)

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Category	Code	Metaphors	Sample Expression
Tolerance for Error (8)	Development-process (4)	Sustainability (1), It Is Not as Easy to Do As One Might Think (1), The Way to Happiness (1), Stream (1)	"It is like sustainability because it preserves and transforms the ordinary." (S109).
Tolerance for Error (8)	Precaution (2)	Social Media (1), Box (1)	"It is like social media. Because we can quickly access the information we want and determine whether it is safe or not." (S195)
Tolerance for Error (8)	Empathy (1)	Build Empathy (1)	"It is like building empathy. Because in order for everyone to understand, one must first understand the other person." (S52)
Tolerance for Error (8)	Hope (1)	Fenerbahçe (1)	"It is like Fenerbahçe. Because it is the never-ending belief that one day you will become a champion." (S202)
Simple and intuitive use (3)	Flexibility (2)	Library (1), Air (1)	"They can easily access the information they want.." (S194)
Simple and intuitive use (3)	Simplicity (1)	Main Purpose (1)	"It is like the main purpose. Because it makes it easier for everyone to understand." (S85)

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Appendix 2. Comprehensive inventory of students' metaphors on universal design principles by faculty

Table a2.1. Metaphors of faculty of theology students on universal design and its principles

Category	Code	Metaphors	Sample Expression
Equitable Use (18)	Being equal and fair (10)	Water (1), Scales (1), Escalator (1), Islam Religion (1), Justice (1), Truth (1), Living on Religion (1), Cloud (1), Equity (1), Face (1)	"It is like an escalator. Because everyone goes up or down in the same way and at the same time." (S21)
Equitable Use (18)	Universality/ integrity/ inclusiveness (5)	A Kind of Item That Makes Our Life Easier (1), World (1), Statue of Liberty (1), Puzzle (1), Pieces of puzzle (1)	"It is like the World. Because it is a design that includes everyone." (S30)
Equitable Use (18)	Balance/order (3)	Scales (1), Religion (1), Life (1)	"It is like a scale. Because the universe was created on balance." (S6)
Perceptible information (8)	Guide (6)	Mind (1), Library (1), Sun (1), Star (1), Being a Muezzin (1), A Free Bird (1)	"It is like the mind. Because it leads to truth for those who can use it." (S5)
Perceptible information (8)	Need (1)	House (1)	"It is like the house. Because it is necessary for life." (S35)
Perceptible information (8)	Reflection / expression (1)	World of Imagination (1)	"It is like the World of Imagination. Because it reveals what is deep within the mind." (S16)
Flexibility in use (5)	Diversity/ relativity (3)	It is a Confusion Where Everyone Gets Different Meanings (1), Class (1), Imagination (1)	"It is like a classroom. Because it brings together all kinds of perceptions." (S20)
Flexibility in use (5)	Live-dynamic (2)	Drink Water (1), Water (1)	"It is like water. Because it is constantly flowing and extends everywhere." (S4)

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Category	Code	Metaphors	Sample Expression
Size and Space for Approach and Use (3)	Accessibility (1)	Information (1)	"It is like information. Because everyone can easily benefit from it." (S31)
Size and Space for Approach and Use (3)	Ideal (1)	An Unknown Utopia (1)	"It is like an unknown utopia. Because people believe in what they don't know." (S9)
Size and Space for Approach and Use (3)	Infinity (1)	Sea (1)	"It is like the sea. Because it is endless." (S1)
Low physical effort (1)	Happiness/ well-being (1)	Chocolate (1)	"It is like chocolate. Because it is happiness." (S10)

Note. *S refers to student; the number indicates the participant code.*

Table a2.2. Metaphors of faculty of education students on universal design and its principles

Category	Code	Metaphors	Sample Expression
Equitable Use (14)	Universality/ integrity/ inclusiveness (8)	Tree (1), A Puzzle Where Different Pieces Can Fit Together (1), Feelings (1), Book (1), Freedom (1), Respect (1), Social Media (1), Puzzle (1)	"It is like a tree. Because it appeals to living things both above and below ground." (S199)
Equitable Use (14)	Being equal and fair (6)	Sky (1), Scales of Justice (1), Equal Environment (1), Water Accessible to Everyone (1), Still Water (1), Tree Roots (1)	"It is like an equal environment. Because everyone has equal rights in an equal environment, regardless of their situation." (S177)
Flexibility in use (6)	Individuality (3)	Everyone Climbing Trees (1), Painting (1), Van (a city) (1)	"It is like everyone climbing a tree. Because the notion of caring about someone's inner world is not prevalent in this society. Design, while individual and not universal, is a blessing for all societies." (S183)

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Category	Code	Metaphors	Sample Expression
Flexibility in use (6)	Diversity/ relativity (2)	World (1), Universe (1)	"It is like the world. Because it has so many different features and diversity." (S185)
Flexibility in use (6)	Difference (1)	Weather (1)	"It is like the weather. Because it contains various weather events and conditions." (S184)
Tolerance for error (4)	Caution (2)	Social Media (1), Boxing (1)	"It is like boxing. Because it is trying to protect yourself against a punch that you don't know where it will come from." (S200)
Tolerance for error (4)	Development-process (1)	Stream (1)	"It is like a stream. Because it both brings traces from where it comes and leaves traces where it flows." (S197)
Tolerance for error (4)	Hope (1)	Fenerbahçe (1)	"It is like Fenerbahçe. Because it's the never-ending belief that one day you will become a champion." (S202)
Simple and intuitive use (1)	Flexibility (1)	Library (1)	"It is like a library. Because they can easily access the information they want." (S194)
Low physical effort (1)	Ease (1)	Flexibility and Simplicity in Use (1)	"It is like flexibility and simplicity in use. Because we hold on to things that make our lives easier, they are simple and easy." (S178)
Size and Space for Approach and Use (1)	Infinity (1)	Sky (1)	"It is like sky. Because it is endless and has no beginning or end, everyone can see it." (S192)

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Table a2.3. Metaphors of faculty of science and letters students on universal design and its principles

Category	Code	Metaphors	Sample Expression
Equitable use (11)	Being equal and fair (7)	Water (1), Equality and Design (1), A Dream to Come True (1), Paint Palette (1), Access (1), A Free Country (1), Equality (1)	"It is like equality and design. Because it shows and realizes that everyone is designed to be used equally." (S53)
Equitable use (11)	Universality/ integrity/ inclusiveness (4)	Means Everyone (1), A Book Everyone Should Read (1), Mevlana (1), Creative Thinking Style (1)	"It means everyone. Because to be universal, it has to be suitable for everyone." (S72)
Perceptible information (7)	Need (5)	Water (1), Home (1), A Rare Plant (1), Education (1), Breathing (1)	"It is like breathing. Because everyone needs it." (S78)
Perceptible information (7)	Comprehensibility (1)	Things We See When We Look Back (1)	"It is like the things we see when we look back. Because the universe consists of things we can see and interpret." (S65)
Perceptible information (7)	Reflectiveness / expression (1)	Free Mindset (1)	"It is like a free mindset. Because when people do something without any obstacles or fear, it makes them more comfortable and free." (S67)
Size and Space for Approach and Use (5)	Existence/ extinction (3)	Nature (1), Extinction (1), Each Person's Private World (1)	"It is like extinction. Because extinction is the inevitable end of everyone." (S61)
Size and Space for Approach and Use (5)	Ideal (1)	Keeping Imagination Alive (1)	"It is like keeping the imagination alive. Because people want to keep their dreams alive." (S70)
Size and Space for Approach and Use (5)	Infinity (1)	Drowning in the Ocean (1)	"It is like drowning in the ocean. Because only the gods have the power to do this." (S55)

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Category	Code	Metaphors	Sample Expression
Flexibility in use (2)	Diversity/ relativity (1)	Achieving Everyone's Desired Special Wishes (1)	"It is like everyone achieving their own special wishes. Because everyone's special wishes are different." (S76)
Flexibility in use (2)	Difference (1)	A Colorful Flower Garden (1)	"It is like a colorful flower garden. Because all the flowers in the flower garden are more beautiful than each other." (S73)
Low physical effort (1)	Ease (1)	Equal Accessibility (1)	"It is like access to equal conditions. Because it allows a person to meet their needs more easily." (S63)

Note. *S refers to student; the number indicates the participant code.*

Table a2.4.Metaphors of faculty of engineering students on universal design and its principles

Category	Code	Metaphors	Sample Expression
Equitable use (13)	Being equal and fair (5)	Scales (1), Appealing to All Segments of Society (1), Gender Equality (1), Something That Should Happen (1), Scales of Justice (1)	"It is like appealing to every segment of society. Because every person is equal." (S133)
Equitable use (13)	Universality/ integrity/ inclusiveness (5)	Equality (1), Common Language (1), Clean Air (1), Pomegranate (1), River (1)	"It is like equality. Because it should be for everyone." (S131)
Equitable use (13)	Similarity (1)	Emotions (1)	"It is like emotions. Because everyone feels similar things." (S150)
Equitable use (13)	Balance/ order (1)	Justice (1)	"It is like justice. Because both sides of the scale must be equal." (S138)

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Category	Code	Metaphors	Sample Expression
Equitable use (13)	Sensitivity (1)	The Embodiment of Understanding (1)	“It is like the embodiment of understanding. Because it advises us to be more sensitive towards people.” (S125)
Perceptible information (5)	Valuable (2)	Treasure (1), Jewel (1)	“It is like a jewel. Because its value increases as it is processed.” (S134)
Perceptible information (5)	Need (2)	Water (1), Eating (1)	“It is like water. Because it is an important part of life.” (S126)
Perceptible information (5)	Guide (1)	Key (1)	“It is like a key. Because it helps everyone open their doors.” (S140)
Size and Space for Approach and Use (4)	Accessibility (3)	Perceptible Information (1), World of Software (1), Accessibility for Everyone (1)	“It is like the world of software. Because it recognizes no obstacles and is easily accessible.” (S143)
Size and Space for Approach and Use (4)	Infinity (1)	Sky (1)	“It is like the sky. Because it is a magnificent thing with no limits.” (S146)
Flexibility in use (3)	Individuality (1)	Equal Art (1)	“It is like equal art. Because everyone has different interpretations, there's only one drawing.” (S144)
Flexibility in use (3)	Utopian (1)	Happiness (1)	“It is like happiness. Because it is something that will never be perfect.” (S137)
Flexibility in use (3)	Live-dynamic (1)	Rubber (1)	“It is like rubber. Because it is flexible in use.” (S141)

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Category	Code	Metaphors	Sample Expression
Low physical effort (1)	Happiness/ well-being (1)	A Sunny Sky (1)	"It is like a sunny sky. Because it makes you feel peaceful and happy." (S130)

Note. *S refers to student; the number indicates the participant code.*

Table a2.5.Metaphors of faculty of sport sciences students on universal design and its principles

Category	Code	Metaphors	Sample Expression
Equitable use (12)	Universality/ integrity/ inclusiveness (6)	Simple and Intuitive Use (1), Pomegranate (1), Sharing (1), Respect (1), Puzzle (1), Escalator (1)	"It is like an escalator. Because it is something everyone uses in common." (S160)
Equitable use (12)	Being equal and fair (4)	School (1), Childhood (1), Oxygen (1), Living (1)	"It is like school. Because every individual has the right to study." (S153)
Equitable use (12)	Balance/ order (2)	Scales (1), Chain Links (1)	"It is like a scale. Because it is important to keep balance on both arms." (S172)
Equitable use (12)	Universality/ integrity/ inclusiveness (6)	Simple and Intuitive Use (1), Pomegranate (1), Sharing (1), Respect (1), Puzzle (1), Escalator (1)	"It is like an escalator. Because it is something everyone uses in common." (S160)
Perceptible information (6)	Need (4)	Tree (1), Water (1), Car (1), Oxygen (1)	"It is like water. Because it is a necessary substance." (S152)
Perceptible information (6)	Guide (1)	Key (1)	"It is like a key. Because it opens every door and provides convenience." (S164)
Perceptible information (6)	Reflectiveness/ expression (1)	Tree (1)	"It is like a tree. Because you reap what you sow." (S151)

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Category	Code	Metaphors	Sample Expression
Low physical effort (3)	Ease (3)	Telephone (1), Automatic Door (1), Technological Devices (1)	"It is like a telephone. Because it makes life easier. (S154)
Tolerance for error (2)	Development-process (2)	It is Not As Easy As It Seems (1), The Path to Happiness (1)	"It is like the path to happiness. Because everyone can only be happy by following a certain path." (S171)
Simple and intuitive use (1)	Flexibility (1)	Air (1)	"It is like air. Because it is simple and accessible." (S156)
Flexibility in use (1)	Individuality (1)	Designed Shoes (1)	"It is like a designed shoe. Because everyone designs the shoes they love." (S157)

Note. *S refers to student; the number indicates the participant code.*

Table a2.6. Metaphors of faculty of architecture students on universal design and its principles

Category	Code	Metaphors	Sample Expression
Equitable Use (8)	Universality/ integrity/ inclusiveness (6)	Feelings (1), Illusion (1), Door (1), Kebab (1), Book (1), Sphere (1)	"It is like a sphere. Because there is sphericity everywhere in the universe." (S89)
Equitable Use (8)	Being equal and fair (2)	Life (1), Imaginative Structures (1)	"It is like life. Because universal design is a right for everyone." (S101)
Perceptible information (6)	Clarity (2)	The Incarnation of the Spirit (1), Common Language (1)	"It is like the soul incarnated in a body. Because it concretizes something abstract." (S90)
Perceptible information (6)	Need (2)	Nature (1), Emotions and Senses (1)	"It is like emotions and senses. Because it appeals to human life." (S91)

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Category	Code	Metaphors	Sample Expression
Perceptible information (6)	Guide (1)	Sun (1)	“It is like the sun. Because it sheds light on everything.” (S107)
Perceptible information (6)	Reflectiveness/ expression (1)	Imaginary Buildings (1)	“It is like imaginary buildings. Because design reflects what we think. (S108)
Flexibility in use (4)	Diversity/ relativity (1)	Creating (1)	“It is like creating. Because each person's work is unique to the person.” (S94)
Flexibility in use (4)	Difference (1)	Rain (1)	“It is like rain. Because the drops are shaped according to the cold.” (S105)
Flexibility in use (4)	Dreaminess (1)	Fairy Tale (1)	“"It is like a fairy tale. Because it is a product of imagination." (S104)
Flexibility in use (4)	Complexity (1)	Knot (1)	“"It is like a knot. Because it is very complicated." (S110)
Size and Space for Approach and Use (4)	Accessibility (2)	Water (1), Easy Trends and Paths (1)	“It is like water. Because it is the most accessible thing everyone needs.” (S99)
Size and Space for Approach and Use (4)	Ideal (1)	Nutritional Needs (1)	“"It is like the nutritional need. Because every living thing has needs." (S103)
Size and Space for Approach and Use (4)	Infinity (1)	Ocean (1)	“It is like the ocean. Because it is an endless, limitless infinity.” (S106)

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Category	Code	Metaphors	Sample Expression
Tolerance for error (1)	Development-process (1)	Sustainability (1)	“It is like sustainability. Because it preserves and transforms the ordinary.” (S109).

Note. *S refers to student; the number indicates the participant code.*

Table a2.7. Metaphors of faculty of communication students on universal design and its principles

Category	Code	Metaphors	Sample Expression
Equitable Use (8)	Universality/ integrity/ inclusiveness (6)	Mother (1), Building a Connection (1), White (1), Nature (1), Kebab (1), Like a Mirror Held Up to Society (1)	“"It is like mother. Because it means the same thing everywhere." (S39)
Equitable Use (8)	Being equal and fair (1)	Scales (1)	“It is like the scale. Because equality is its goal.” (S44)
Equitable Use (8)	Balance/ order (1)	The Order Itself (1)	“It is like order itself. Because everything in the universe is the result of an order.” (S51)
Perceptible information (3)	Guide (2)	Audible Pedestrian Crossing (1), Guide (1)	“It is like an audible pedestrian crossing. Because it serves as assistance and therapy for visually impaired people.” (S36)
Perceptible information (3)	Need (1)	Bread (1)	“It is like bread. Because it is the most basic nutritional element.” (S45)
Size and Space for Approach and Use (3)	Infinity (2)	Space (2)	“It is like space. Because it has no end.” (S50)

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Category	Code	Metaphors	Sample Expression
Size and Space for Approach and Use (3)	Accessibility (1)	Easy, Comfortable, Straight Path (1)	“It is like an easy, comfortable, straight path. Because it is suitable for individuals to progress easily.” (S38)
Flexibility in use (2)	Diversity/ relativity (2)	Cloud (1), World (1)	“It is like the world. Because design is different for everyone, just like people in the world.” (S47)
Tolerance for Error (1)	Empathy (1)	Build Empathy (1)	“It is like building empathy. Because everyone needs to understand the other person in order to understand.” (S52)

Table a2.8. Metaphors of faculty of tourism students on universal design and its principles

Category	Code	Metaphors	Sample Expression
Equitable Use (9)	Being equal and fair (6)	Integrity (1), Equal Use and Flexibility (1), A Society Where Everyone Is Equal (1), A World Where Everyone Is Loved (1), Designing for Everyone's Situation (1), Being Unique (1)	“"It is like equal use and flexibility. Because everyone is a part of an equal life." (S114)
Equitable Use (9)	Universality/ integrity/ inclusiveness (2)	Mevlana (1), Meeting the Needs (1)	“"It is like meeting needs. Because it is about creating a design that suits everyone." (S119)
Equitable Use (9)	Balance/ order (1)	Laws of Life (1)	“It is like the laws of life. Because people live in an order.” (S116
Perceptible information (3)	Transparency (2)	Water (1), Transparency (1)	“It is like water. Because it is transparent.” (S121)

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Category	Code	Metaphors	Sample Expression
Perceptible information (3)	Reflection/ expression (1)	Mirror (1)	"It is like a mirror. Because in front of the mirror, our reflection appears; it is our equal, our twin." (S123)
Flexibility in use (1)	Live-dynamic (1)	Nature (1)	"It is like nature. Because there is life in it." (S115)
Size and Space for Approach and Use (1)	Infinity (1)	Sky (1)	"It is like the sky. Because it has no end." (S124)

Note. *S refers to student; the number indicates the participant code.*

Table a2.9. Metaphors of faculty of fine arts students on universal design and its principles

Category	Code	Metaphors	Sample Expression
Size and Space for Approach and Use (4)	Infinity (2)	Earth (1), Ocean (1)	"It is like the earth. Because it is endless." (S80)
Size and Space for Approach and Use (4)	Accessibility (1)	Art (1)	"It is like art. Because it reaches the masses." (S83)
Size and Space for Approach and Use (4)	Ideal (1)	The Eye Opening to Truth (1)	"It is like an eye opening to the truth. Because human beings reflect their dreams with what they see." (S87)

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Category	Code	Metaphors	Sample Expression
Equitable use (2)	Universality/ integrity/ inclusiveness (1)	Integrative Perspective (1)	"It is like a holistic perspective. Because every person can adopt the same mindset." (S84)
Equitable use (2)	Balance/ order (1)	Order within Chaos (1)	"It is like order within chaos. Because reflecting the styles of people living in different geographies within the world's population under a single roof demonstrates order within chaos." (S81)
Perceptible information (1)	Need (1)	Accommodation (1)	"It is like accommodation. Because it is something everyone builds and uses according to their needs." (S82)
Simple and intuitive use (1)	Simplicity (1)	Main Purpose (1)	"It is like the main purpose. Because it makes it easier for everyone to understand." (S85)
Flexibility in use (1)	Difference (1)	Functional and Aesthetic Design (1)	"It is like functional and aesthetic design. Because individuals with physical, mental, and emotional differences need to have a comfortable design." (S79)

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University entrance exams for students with special educational needs

Analysis by Spanish autonomous communities

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Abstract: Access to university for students with special educational needs remains a major challenge for inclusive education in Spain. Structural, regulatory and social barriers, along with territorial inequalities, hinder equity. This study analyses the procedures for processing and resolving requests for adaptations in university entrance exams, as well as the types of measures adopted. Data were gathered from 16 Spanish regions through an open-ended questionnaire and analysis of information published on institutional websites. The results show great heterogeneity in admission criteria, required documentation, and adaptations granted, both in terms of material and human support, as well as the measures applied during the administration and correction of the exams. This lack of regulatory harmonisation creates inequalities that compromise equitable access to higher education. The study concludes by highlighting the urgent need to establish common national criteria to ensure fair, accessible, and inclusive assessment processes.

Keywords: Access, Higher education, Special Needs, Students with Disabilities, Inclusion, Spain.

1. Introduction

The concept of inclusive education can be confusing (Echeita & Ainscow, 2011) or have different interpretations (Dyson & Millward, 2000; Muñoz, 2012). Essentially, it seeks to defend the right of all people to learn in a standardised system that considers their circumstances and support needs (Ainscow, Slee, & Best, 2019). In other words, it is a process that promotes learning to live with differences (López-Melero, 2011) by identifying and eliminating barriers or factors that may limit access to and participation in education for all people (Florian, 2019). In line with the principles of Universal Design for Learning (UDL), ensuring inclusion involves anticipating and removing barriers that may limit access, participation, and learning by designing flexible and accessible educational environments that recognize and respond to diversity (King-Sears, et al., 2023).

For inclusive education to be viable in practice, it requires the support of different governments, public authorities, and educational and social administrations to generate genuine political

conviction concerning it and provide sufficient resources at different levels (economic, social, and cultural) (Arnáiz, 2019). For this purpose, it is essential to bear in mind what is happening both within and outside educational institutions and within the system as a whole; that is, an ecological perspective on equity is necessary (Ainscow, Dyson, Goldrick, & West, 2013; Echeita, 2022). The implementation of an inclusive education system guarantees both the right to education and the construction of fairer and more sustainable societies (Medina, 2019). However, inclusive higher education is still more of a policy objective than an established reality (Solís-García, Barreiro-Collazo, Rodríguez-Correa, Delgado-Rico, & Real-Castelao, 2025). In this regard, a recent study found that while UDL shows significant potential for promoting inclusive education, systemic barriers and teachers' perceptions continue to pose significant challenges (Muzdalifah, et al., 2026).

Various international organisations, such as the United Nations Educational, Scientific and Cultural Organisation (UNESCO, 1994; UNESCO, 2009; UNESCO, 2011; UNESCO, 2015a; UNESCO, 2015b), the UN (UN, 2015) with Sustainable Development Goal (SDG) 4 of its 2030 Agenda, the Organisation for Economic Co-operation and Development (OECD, 2020) and the European Agency for Special Needs and Inclusive Education (Donnelly & Watkins, 2021), have sought to contribute to the promotion of more inclusive educational policies, procedures and instruments. The last body includes among its current priorities the need for greater collaboration between agencies, services and institutions to contribute to the transition of students across schools/stages of education, as well as to entry into higher education and the labour market. The UN (UN, 2015) seeks to create partnerships for sustainable development (SDG 17) with a view to inclusive education (SDG 4).

Some authors (Heleta & Bagus, 2021) assert that, in fact, no work is being done in this area at the international level, which means that certain population groups face restrictions in accessing and participating in higher education. Other authors have pointed out that students' social background or rural origins may also contribute to inequality in academic selection processes (Deng, 2024). In other contexts, authors have found that university websites are significantly inaccessible, which could constitute a major barrier to higher education access (Rahmatizadeh & Valizadeh-Haghi, 2018). These situations of disadvantage interact with other variables, such as socioeconomic status, becoming cumulative and creating barriers to access to higher education (Lambrechts, 2020). Given this situation, the variables that favour permanence and continuity in studies must be promoted. In this sense, having specific and sufficient individualised support can prevent school dropout among different groups (Cage & McManemy, 2022; Sahli, Brandenberg, Ganz, & Wüthrich, 2022). Therefore, education systems, and particularly universities for this study, must strengthen the guarantee of equal access and participation processes. When discussing special educational needs (SEN), particularly disability, prior planning is required to consider support needs and solutions to break down structural barriers (Langørgen & Magnus, 2020), thereby contributing to improved academic and social support and thus equalising opportunities (Cage & McManemy, 2022; Weiss, Lerche, Muckenthaler, Heimlich, & Kiel, 2019). Only in this way can educational success be assessed in terms of students' progress in developing their capacities and skills (Pujolàs, 2012). Furthermore, the students themselves highlight the structural barriers to inclusion in higher education, which not only hinder access to study but also affect their academic journey (Ed-dali, 2024).

In the case of Spain, the Constitution (Constitución Española, 1978) recognises the right to education for all (Art. 27). In the context of higher education, Royal Decree 1791/2010, of 30 December, approving the University Student Statute (Real Decreto 1791/2010), recognises the right of students who meet the established requirements to apply for admission to degree

programs at any Spanish university. Likewise, Organic Law 2/2023, of 22 March on the University System (Ley Orgánica 2/2023), declares the right of access to university education, guaranteeing equal opportunities and conditions in the exercise of this right for all (Art. 31.1), without discrimination based on racial or ethnic origin, sex, sexual orientation, gender identity, disability, illness, socioeconomic status, language, etc. (Art. 37.1). In addition, universities must promote inclusive curricular structures to ensure an inclusive, accessible and adaptable university education, on an equal footing with the rest of the student body, making reasonable adjustments, both curricular and methodological, to teaching materials, teaching methods and the assessment system (Art. 37.2). In this regard, the National Agency for Quality Assessment and Accreditation (ANECA) (2024) proposes an institutional and process-oriented approach to evaluating university policies and practices regarding the inclusion of students with disabilities and special needs. This framework involves reviewing the actions taken throughout the academic journey—from access and admission to teaching, learning, assessment, and participation in university life— to identify barriers and improve institutional inclusion processes (Nyssen, 2023).

Royal Decree 534/2024, of 11 June, regulating the requirements for access to official university degree programmes, the characteristics of the entrance examination and the basic rules governing admission procedures (Real Decreto 534/2024), provides for a quota of up to 5% of places for students with officially recognised disabilities or SEN related to disability. However, although the trend is rising, there is still a long way to go to reach the stipulated percentage, and early twenty-first-century statements (Pérez, 2004) remain valid. In other words, there are still a small number of students with disabilities at university. Although SEN covers different cases, in addition to disability, it is the most regulated and studied. Based on data provided by 56 universities for the 2021-2022 academic year (Fundación Universia, 2023), students with disabilities represented only 1.6% of the total university student population.

In addition to underrepresentation, students with disabilities face various difficulties in the university environment associated with deficits in different resources and procedures: lack of adapted public transport; lack of technical aids; inaccessibility of some centres and faculties; communication barriers; lack of sign language interpreters and/or teaching assistants; lack of teacher training; etc. In fact, around 70% of students with disabilities were not provided with any kind of adaptation in accessing university, and up to 20% suffered discrimination in accessibility, curriculum adaptation, exams, relations with teachers, or certain bureaucratic aspects (Fundación Universia, 2023). Consequently, there is a gap between the level of education attained by the general population, with up to 38.6% receiving higher education, compared to the population with disabilities (19.1%) (Huete-García, Morales-Romo, Otaola-Barranquero, & Jiménez-Lara, 2023).

University entrance exams in Spain are regulated by Organic Law 3/2020, of 29 December (Ley Orgánica 3/2020). This regulation establishes the obligation to pass a specific entrance exam (Art. 38.1), which is added to the grades obtained in the previous educational stage. It is the responsibility of the Spanish Government, after consultation with the autonomous communities, to define the basic characteristics of this exam (Art. 38.3). Likewise, the LOSU grants the Government the power to establish the basic rules for admission to universities (Art. 31.2). The state procedure for access to higher education is set out in Royal Decree 534/2024 (Real Decreto 534/2024), which regulates the processes and criteria for admission to the university system. Concerning students with SEN, this royal decree assigns the organising committees of the exams the responsibility of implementing the necessary measures to guarantee equal opportunities, non-discrimination and universal accessibility (Art. 21.1). These measures may include

adaptations of time, exam formats, material and human resources, as well as specific products and support (Art. 3.2).

Despite the existence of a state regulatory framework that seeks to harmonise procedures throughout the territory, the territorial structure of the Spanish state —composed of 17 autonomous communities with transferred powers in the area of education— leads to considerable diversity in the practical application of these regulations. This diversity must also coexist with the principle of university autonomy, which grants each university the capacity for self-government through its bodies. As a result, there are significant variations in the implementation of educational measures, including the provision of support for students with SEN. In this regard, previous studies have shown that the segregation of students with disabilities into special education centres does not always respond to pedagogical criteria linked to their needs but is mediated by factors such as gender or the autonomous community of residence (Ramos & Huete-García, 2016).

This context has a greater impact on students with SEN. According to the LOMLOE (Ley Orgánica 3/2020), students with SEN face barriers that limit their access, attendance, participation or learning, resulting from disability or serious behavioural, communication and language disorders (Art. 73.1). It also states that the education system will have the necessary resources to enable them to achieve the objectives set for all students in general, providing them with the necessary support (Art. 73.2) so that they can continue their schooling at all pre- and post-compulsory education levels, including the adaptation of the conditions for taking the established exams (Art. 73.5). Concerning the configuration of the spaces where the exams are carried out, the trend is to incorporate spaces with support (mainly human) within the ordinary commissions, although there are specific commissions for students with SEN who have greater support needs or whose health conditions prevent them from attending shared spaces.

The inclusion of people with SEN in the university context has been a topic of recent research interest in Spain (Díaz-Jiménez, Yerga-Míguez, Relinque, & Granados-Martínez, 2025; Serrano & Viguera, 2024). However, the mechanisms for accessing the university system have not been studied extensively. Given this situation, it seems relevant to understand how university entrance exams are adapted in Spain, from the moment of application to the marking of the exams, to assess the possible existence of differences between autonomous communities in terms of promoting inclusive education. Given the above, the objective of this study is to analyse the procedures related to the processing and resolution of applications for adapting university entrance exams in different Spanish autonomous communities, as well as the types of measures to be adopted. Specifically, it aims to answer the following research questions (RQs):

- What are the prerequisites for accessing exam accommodation? (RQ 1)
- What documentation must accompany the request for exam accommodation? (RQ 2)
- Which agents and institutions are involved in the process of processing and resolving requests for exam accommodation? (RQ 3)
- What are the different measures to be taken before and during the exams? (RQ 4)
- What are the different measures to be taken when marking exams that have been adapted? (RQ 5)

2. Material and Methods

To answer the research questions posed, two sources of information were used. First, a questionnaire was designed and administered to members of the regional committee responsible for university entrance exams. Subsequently, an analysis was conducted of the websites of the different Spanish autonomous communities whose representatives had completed the questionnaire.

2.1. Instruments, participants/sample and data collection

The initial data collection was carried out using a questionnaire designed and validated by four experts in education and social work, who discussed the clarity and relevance of the items according to the RQs and resolved discrepancies until agreement was reached on the final version. The instrument (Appendix), which was approved by the four experts, consists of 10 open-ended questions referring to procedures related to: the presentation and processing of requests for exam accommodation, the accommodations to be applied during the exams, and their correction.

The questionnaire was transferred to Google Forms and sent by email by the delegate of the Interuniversity Commission of Galicia, who requested the collaboration of all the autonomous communities in gathering information. Sixteen of the seventeen possible members of the committee responsible at the state level (comprising delegates from all Spanish autonomous communities, except the Community of Madrid) for university entrance exams completed the questionnaire. The members represented their autonomous communities at the 5th CRUE Conference on Access and Admission to Spanish Public Universities held in Las Palmas de Gran Canaria.

To enrich the information obtained through the questionnaires, an analysis was carried out of the information available on the website regarding adaptations to university entrance exams in the sixteen autonomous communities that had completed the questionnaire. The protocol for analysing the websites followed the procedure proposed in another study (Mosteiro, Espiñeira, Muñoz, & Porto, 2025):

1. Search and registration of websites that included information on the procedures for adapting university entrance exams in the different participating autonomous communities.
2. Access to various websites, downloading, and reading documents related to the adaptation of university entrance exams.
3. Creation of a computerised registration form to record the information under the following headings: name of the autonomous community, pre-registration procedures (requirements and necessary documentation), processing of applications (location, services/human resources involved), conduct of the exams (content of the reports with the type of adaptations to be applied during the exams and location) and correction (information transferred to the evaluation committee and existing protocols).

Considering that the website analysis served as a complement to the delegates' responses, the authors did not consider conducting follow-up interviews or requesting further clarification. The information gathered from both sources was considered sufficient to address the RQs proposed.

2.2. Data analysis

The raw data obtained from the questionnaire questions and the web pages were integrated and organised according to the previously posed research questions (RQs). Next, a content analysis of the information was conducted using an essentially inductive approach.

The 1st-level categories were established based on the RQs and are: prerequisites, defined as criteria for access to exam adaptation; documentation accompanying the application for adaptation to the university entrance exams; agents, institutions and services involved in the accreditation process, submission, reception and assessment of applications; adaptations, defined as the typology of measures to be applied in the course of the exam concerning the extension of times, adaptations in the examination, material and human resources available, accessibility and other aspects to be considered; and correction, which are aspects intended to correct university entrance examinations with adaptations.

In general, the 2nd-, 3rd-, and 4th-level subcategories emerged from the analysis of the raw information following an inductive process. However, in the case of adaptations, the 2nd- level categorisation from Royal Decree 534/2024 (Real Decreto 534/2024) was complemented in the 3rd and the 4th-level from the raw information (Table 1).

Table 1. 1st-, 2nd- and 3rd-level categories and subcategories of information analysis

1st level categories	2nd level subcategories	3rd level subcategories
Prerequisites	Percentage disability	
Prerequisites	Previous adaptations	
Prerequisites	Medical certificate	
Prerequisites	Depending on the need	
Documentation	Psychopedagogical report	
Documentation	Medical report	
Documentation	Disability certificate	
Documentation	Other	Inspection report
Documentation	Other	School certificate
Documentation	Other	Registration census
Agents, institutions and services	Accreditation	Health service
Agents, institutions and services	Accreditation	Educational service
Agents, institutions and services	Accreditation	Combination
Agents, institutions and services	Accreditation	Depending on the need
Agents, institutions and services	Presentation	Educational centre
Agents, institutions and services	Presentation	Student/legal tutoring
Agents, institutions and services	Reception	University commission
Agents, institutions and services	Reception	School guidance service
Agents, institutions and services	Reception	Other
Agents, institutions and services	Evaluation	Competent service

1st level categories	2nd level subcategories	3rd level subcategories
Agents, institutions and services	Evaluation	Professional profile
Adaptations	Time	Exam
Adaptations	Time	Breaks
Adaptations	Exam	Instructions
Adaptations	Exam	Format
Adaptations	Resources	Material
Adaptations	Resources	Human
Adaptations	Accessibility	Information
Adaptations	Accessibility	Physical
Adaptations	Space	Specific
Adaptations	Space	Ordinary
Correction	Criterion	Presentation
Correction	Criterion	Written expression
Correction	Criterion	Spelling mistakes
Correction	Subject	Foreign language
Correction	Subject	Spanish language
Correction	Subject	Other language
Correction	Protocol	Dyslexia
Correction	Protocol	Dysgraphia
Correction	Protocol	Dysorthographia
Correction	Protocol	Hearing impairment
Correction	Protocol	Visual impairment
Correction	Protocol	Attention Deficit Disorder/ Attention Deficit Hyperactivity Disorder
Correction	Protocol	Autism Spectrum Disorder

The analytical procedure and initial coding scheme were agreed from the outset. Once the analyses had been completed, the researchers jointly reviewed and discussed any discrepancies identified during the coding process. This procedure helped strengthen the reliability of the findings.

For each subcategory, relative and absolute frequencies were calculated using the MAXQDA software. For the categories 'adaptations' and 'correction', frequencies of the total number of code occurrences were calculated. For the remaining categories, the results are given over the number of participants (n=16). Furthermore, it should be noted that in the category 'documentation', in some cases, there was a multiple response, so that the sum of the frequencies exceeds the total number of representatives. To enrich the information, textual quotations have been extracted from the web analysis and translated into English to illustrate the

situation of some of the participating autonomous communities concerning the different aspects analysed.

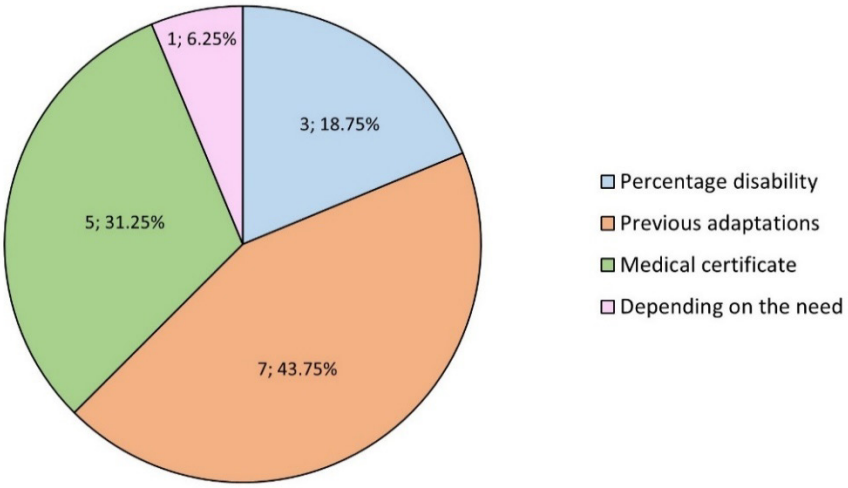
3. Results

The findings have been grouped into two content blocks considering the research questions (RQs) on: the application procedure for adaptation of university entrance examinations (RQ 1, 2 and 3) and the typology of adaptations to be applied during the examinations and specific procedures for the adaptation of marking criteria (RQ 4 and 5).

3.1. Application process for university entrance exam accommodations: Preliminary aspects, procedures and resolution (RQs 1, 2 and 3)

In terms of the criteria used to make decisions to identify students eligible for exam adaptations, the most frequently used requirement is that the applicant student has received previous adaptations due to learning difficulties (accredited through a psycho-pedagogical report) or that supervening health circumstances prevent them from taking the exam in an ordinary context (accredited by medical certification) (Figure 1). The following is a representative excerpt: "The educational measures with which they studied Baccalaureate (methodological and access adaptations, specialised personal support resources and technical aids) will be indicated" (Universidad de Oviedo, 2024, p. 3).

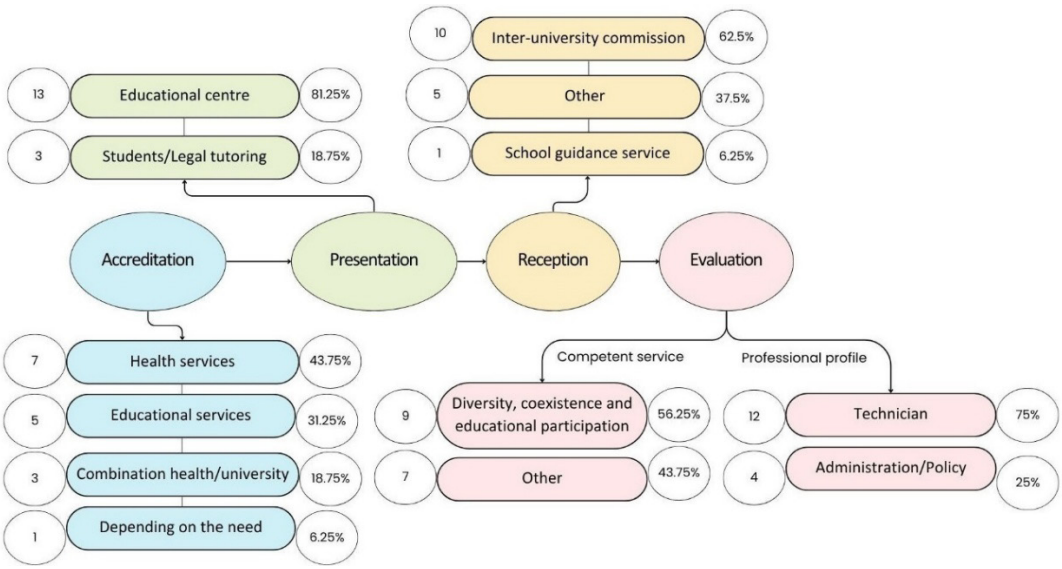
Figure 1. Student eligibility requirements for exam accommodations



The application for adaptation to the entrance examinations must be accompanied, in most cases, by a psycho-pedagogical report issued by the Guidance Department (7 out of 16 autonomous communities; 43.5 %). In some of them, additional documentation such as a medical report (4 out of 16; 25 %) or an official disability certificate (2 out of 16; 12.5 %) is also required. In addition, five autonomous communities (31.25 %) require other types of additional documentation, including reports from the education inspectorate, certificates from the institutional register of students with special educational support needs or documents issued by the school management. For example, in the case of Castilla y León, it is stated that "for students with educational needs linked to health and social-health circumstances, Annexe II shall be sent, duly completed, together with a copy of the medical report" (Junta de Castilla y León, 2024, p. 5).

Different institutions, services and actors involved in the application procedure have been identified (Figure 2). The institutions or services mainly responsible for the accreditation of the need for adaptation are part of the health system. This is followed by services/institutions of an educational nature. To a lesser extent, respondents report mixed formulas for accreditation or state that it depends on the type of need.

Figure 2. Agents, institutions and services involved in the processing and assessment of applications



Applications must be submitted mainly by the educational institution and are received by the universities. The results show some diversity in the type of university services responsible for reception. In most cases, applications are received by the committee organizing the examinations. In other cases, university services with specific competences in this area, such as the Disability Service, are chosen. The university guidance service, which varies in name and structure depending on the university, is an anecdotal example. In some cases, it is a service attached to the Vice-Rector's Office for Students and in others to the Academic Management Service.

Concerning who carries out the assessment or decision-making on exam adaptations and the implementation of support elements, in three-quarters of the cases, the responsibility falls on a technical profile; specifically, the competent services in this matter are university services responsible for attention to diversity, coexistence and educational participation, involving technical professionals in disability from the fields of psychology, psychopedagogy or social work. In the remaining situations, decisions are taken by political or administrative profiles in general, by the coordination or presidency of the Exam Organising Committees or the Student Attention Unit. An extract on the process of submission and resolution of applications is presented:

Applications will be submitted through the Minerva Web platform, where the management teams of the centres will give access to the staff of the guidance departments or units to process these applications (...). The Organising Committee of the exam, in its resolution, will establish the type of adaptation in each case, following current legislation and the documentation presented in the applications. (Universidad Politécnica de Cartagena, 2024, pp. 2-3).

3.2. Typology of accommodations to be implemented during the examinations and specific procedures for the adaptation of assessment criteria (RQs 4 and 5)

The findings have revealed the most frequent types of adaptations made during the exams for students with SEN in the different autonomous communities (Table 2). Adaptations focused on available resources are the most frequently reported type of adaptation measure (52/136 codes; 38.23%). More specifically, material resources stand out (37/52; 71.15%), with technical or digital aids being the most frequently mentioned type of adaptation. To a lesser extent, various human resources are identified (15/52; 28.85%), including assistants.

Table 2. Typology of adaptations during the exams in students with SEN

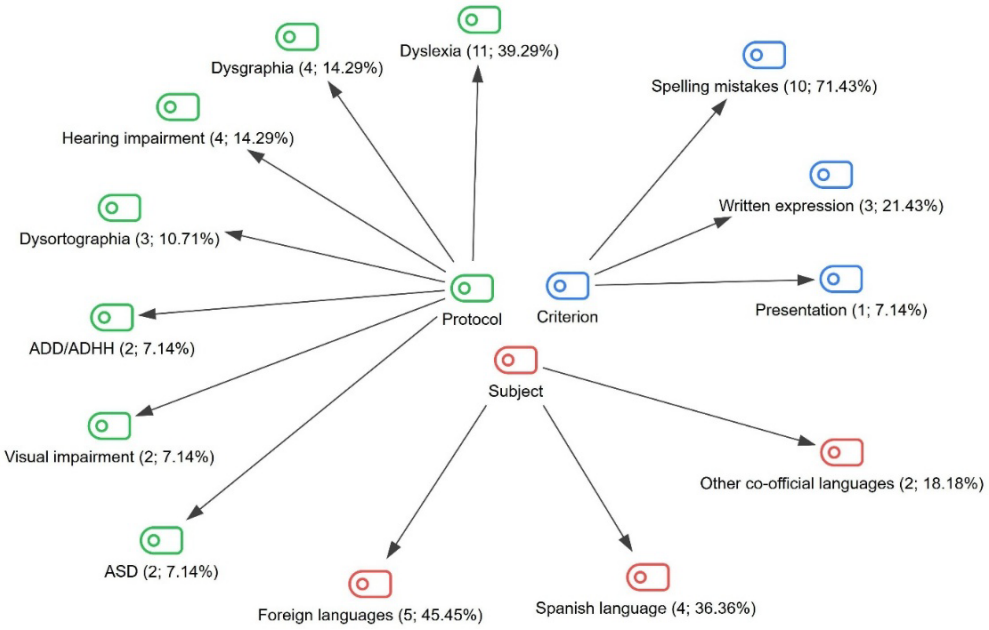
2nd level subcategories	3rd level subcategories	4th level subcategories	Frequency	Percentage
Resources	Material	Technical/digital aids	29 out of 37	78.38 %
Resources	Material	Reference materials	8 out of 37	21.62 %
Resources	Human	Assistants	9 out of 15	60 %
Resources	Human	Technical personnel	3 out of 15	20 %
Resources	Human	Interpreters	2 out of 15	13.33 %
Resources	Human	Counselors	1 out of 15	6.67 %
Exam	Instructions		21 out of 37	56.76 %
Exam	Format		16 out of 37	43.24 %
Time	Exam		25 out of 28	89.29 %
Time	Breaks		3 out of 28	10.71 %
Space	Ordinary		12 out of 19	63.16 %
Space	Specific		7 out of 19	36.84 %
Accessibility	Physical		12 out of 18	66.67 %
Accessibility	Information		6 out of 18	33.33 %

The adaptations associated with the content and format of the exam itself (37/136 codes; 27.21%) aim to provide general and specific instructions for taking the exam, as well as modifications to the format (font size and type, enlargements, etc.). As for the time available to take the exams (28/136 codes; 20.59%), a generalised adaptation is to extend the time available (in general, an extra 30') and, consequently, also to increase the breaks to be taken between each exam.

The space in which the exams are conducted appears to be referred to, in some cases, proceeding to a specific location within the ordinary classroom and in others, opting for referral to a designated classroom. In this respect, the responses of those responsible sometimes reflect the lack of operationalised criteria for deciding on referral to these commissions. Another adaptation refers to the availability of support for accessibility (18/136 codes; 13.23%) to the physical space where the student will take the exam, as well as to the information, including both the instructions provided and the content of the exams themselves.

Adaptations in the process of marking exams may cover different subjects and include the incorporation of specific criteria or protocols for teachers' marking, depending on the type of SEN (Figure 3). In terms of the subjects concerned, these adaptations are applied almost exclusively to linguistic subjects. Analysis of the correction criteria established by the different autonomous communities reveals a predominant focus on linguistic aspects, such as spelling, increasing the margin of permissible errors. Among the specific protocols, dyslexia is the need that appears most frequently. For example, in the case of Galicia, the protocol aimed at students with dyslexia includes specific guidelines related to spelling correction, such as penalising only one out of five accentuation errors or not applying penalties for certain spellings in foreign languages such as French or English (Comisión Interuniversitaria de Galicia, 2019).

Figure 3. Subjects, specific criteria and protocols for marking the exams



Note: ADD= attention deficit disorder, ADHD= attention-deficit/hyperactivity disorder, ASD= autism spectrum disorder.

4. Discussion

The requirements demanded of students to apply for adaptations in university entrance examinations in Spain reveal a series of relevant aspects that deserve attention. In this regard, Royal Decree 1791/2010, of 30 December, of 30 December, approving the University Student Statute (Real Decreto 1791/2010) recognises the right of students who meet the established legal requirements to access and apply for admission to official degree programmes at any Spanish university. However, differences across autonomous communities in the prerequisites for accessing exam adaptations, the documentation required, the agents and institutions involved in processing and resolving requests, the measures implemented before and during the exams, and the criteria used to mark adapted exams may raise concerns regarding equal opportunities and fairness in a competitive university admissions system.

Firstly, the documentation required varies significantly from one autonomous community to another. Thus, while in some regions a psycho-pedagogical report is required, in others, medical or disability certificates or other supporting documents are also necessary. This disparity reflects a predominantly medical-rehabilitative orientation, focused on identifying the deficit, rather than a rights-based approach. The latter promotes an understanding of students' needs geared

towards the provision of personalised and flexible supports (Taneja-Johansson, 2024), in line with the principles of inclusive education (Ainscow, Slee, & Best, 2019). Reliance on diagnostic criteria can pose an additional barrier to equitable access by making the educational response contingent on formal accreditation of a condition, rather than addressing the actual needs of the student.

The diversity of institutions, services and actors involved in the procedure for requesting accommodations reveals the prominence that, once again, is given to medical services. This approach does not seem consistent with the logic of the education system, given that the identification of SEN and the implementation of the associated adjustment measures are responsibilities that, in practice, fall mainly on professionals in the field of education. This discrepancy is particularly evident when compared to other European contexts, such as Sweden, where decisions related to educational accommodations are primarily dealt with in the school setting, without requiring external medical validation (Taneja-Johansson, 2024).

It is necessary to rethink the services responsible for assessing and managing adaptation requests from an educational perspective, incorporating a perspective that is more coherent with the principles of inclusion. To this end, autonomous communities should have university services made up of technical profiles from the socio-educational field, such as professionals in Social Work (Asamoah, Tam, & Cudjoe, 2023) or Psychopedagogy, who can receive and assess the support needs of students with SEN in accessing university in a specialised and comprehensive manner. This type of service would help to ensure that entrance examinations are carried out under conditions of fairness and equal opportunities, preventing them from becoming barriers to inclusion (Nieminen, Moriña, & Biagiotti, 2024). Furthermore, it is essential to highlight the role of the inter-university commissions in charge of organising entrance examinations in autonomous communities where several universities coexist. Although in these cases, the central role of the university in receiving applications for exam adaptations has been highlighted, its role should be further strengthened to promote equitable policies, accessible environments and support for the employability and international mobility of university students with disabilities (Díaz-Jiménez, Yerga-Míguez, Relinque, & Granados-Martínez, 2025).

Regarding the measures implemented for adaptations during university entrance exams, the prevalence of material support over personal support stands out. However, in addition to having material resources (Cifuentes-Faura & Faura-Martínez, 2024), it is essential to have qualified support staff who can offer direct support to students, as shown by the results of a study carried out in Croatia (Babic & Dowling, 2015). Along these lines, recent recommendations (Riobóo-Lois, Frieiro, González-Rodríguez, & Verde-Diego, 2024) advocate the systematic incorporation of personal assistance in education systems, which can contribute to reducing this gap, a practice that is already being implemented in some Spanish regions (Ros, 2020).

The supports identified in exam adaptations focus mainly on providing clearer instructions and modifying the presentation format of the exams, considering that many materials are not adapted to SEN (Fernández-Batanero, Montenegro-Rueda, & Fernández-Cerero, 2022). Additional time for exam-taking is also envisaged. Although it has been shown that this extra time makes it easier for students with disabilities to perform assessment tasks, it can also be counterproductive in certain cases, such as for students with dyslexia (Tai, et al., 2023). In line with the UDL approach, these measures must be considered in advance to ensure equitable assessment from the outset (Nieminen, Moriña, & Biagiotti, 2024), contributing to ensuring accessibility, both physical and cognitive, in higher education (Serrano & Viguera, 2024).

Measures to make the marking of exams for SEN students more flexible focus mainly on quantitative criteria, such as increasing the number of spelling mistakes allowed, in line with the

regular assessment system. However, a study conducted at Portuguese universities highlights the usefulness of implementing qualitative assessments to provide more enriching feedback to students (Pereira, Flores, Simão, & Barros, 2016). Furthermore, the correction criteria and protocols detected focus predominantly on linguistic aspects. Thus, other common needs in higher education, such as dyscalculia (Kuriakose & Amaresha, 2024), should receive more attention, considering the particular challenges it can pose in STEM disciplines.

According to the review of institutional websites, only specific criteria for dyslexia are identified. In this cases, the main difficulties are related to the reading and writing process (Tops, et al., 2023), a situation similar to that faced by deaf students (Alamargot, Morin, & Simard-Dupuis, 2018; Albertini, Marschark, & Kincheloe, 2016; Coelho & Borges, 2022). It is therefore essential to develop remediation criteria and protocols tailored to each student's specific needs to promote genuinely accessible assessment. To this end, UDL and learner-centred design can serve as guiding principles to remove barriers and enable flexible and personalised adaptation (Manresa-Yee, Muntaner, & Sanz, 2012).

5. Conclusions and practical implications

The analysis carried out has revealed a lack of harmonisation of adaptations in university entrance exams across the different Spanish autonomous communities. This fact results in greater discrimination and a lack of guarantees of equal opportunities for students with specific educational support needs. This lack of uniformity is the main weakness in the application of adaptations in the Spanish university access system. However, other aspects need to be addressed to guarantee a fairer and more equitable procedure, such as the requirements to be considered as a student eligible to receive support or adaptations, the process of accreditation and assessment of the measures required, or the type of actions to be applied during the exam and its subsequent correction. These weaknesses and their impact on students with SEN have significant consequences for access to higher education insofar as the existence of a single university district allows students from an autonomous community to apply for access to any university in the Spanish public education system. Therefore, this circumstance is generating situations of significant inequality and disadvantage.

Considering the different measures adopted by the Spanish autonomous communities in the process of processing and carrying out university entrance examinations for students requiring adaptations, a series of aspects are proposed that make up a unified proposal. This initiative seeks to contribute to the promotion of inclusive education in the context of adaptations to university entrance exams for students with disabilities or SEN. The key aspects to consider are:

- The applicant student must present difficulties that interfere with the learning process or the performance of the assessment exams, ascertained through adaptations in previous years (at least the two years of Baccalaureate, except in the case of supervening health situations).
- In the case of difficulties that interfere with the learning process or the performance of the exams, a detailed report should be provided by the guidance department; and in the case of supervening causes, a report from the health service. These reports will allow the technicians (social workers or guidance counsellors) to assess whether the student should be referred to:
  - Ordinary commissions, in cases requiring low-medium support and low context adaptations or no context adaptations.

- Specific commissions, in cases requiring high support and high contextual or specific adaptations.

To promote equal opportunities throughout Spain, it is essential to establish a common framework across all the Spanish autonomous communities, ensuring equal support to SEN students. Likewise, university entrance exams should be designed in accordance with UDL guidelines, incorporating accessibility principles from the outset and thereby reducing the need for region-specific adaptation protocols. In addition, common assessment and correction criteria should be established to ensure consistency and fairness across regions, while allowing for the adjustments required to accommodate SEN.

6. Limitations and prospects

This study has several limitations that should be acknowledged. Firstly, the information collected through the questionnaires was based on self-reported data provided by regional delegates, which could introduce some variability in responses due to differences in how questions were interpreted and in respondents' knowledge of the procedures. Furthermore, the lack of triangulation with other perspectives, particularly those of SEN students, limits the extent to which institutional information can be compared with the experiences of those receiving these measures. Although the analysis of institutional websites made it possible to complement the questionnaire responses, no direct observation techniques were employed to examine how these measures are implemented in practice. Regarding the website analysis, the absence of information on certain measures does not necessarily mean that they do not exist or are not implemented; rather, they may not be publicly documented or easily accessible. Therefore, the findings should be interpreted considering the potential limitations of the publicly available institutional information. In addition, the absence of data from one autonomous community prevents a fully comprehensive overview of the Spanish university system.

Future research should broaden the range of information sources by incorporating the perspectives of SEN students and other stakeholders involved in the management and implementation of accessibility measures. Interviews, focus groups, and direct observations would make it possible to gain deeper insights into students' experiences and compare institutional provisions with their actual implementation. Furthermore, website analysis could be complemented by additional documentary sources and data collection methods to identify potential discrepancies between published measures and those implemented in practice. Finally, including data from the Community of Madrid would complete the geographical analysis and provide a more comprehensive overview of assessment accessibility measures across the Spanish university system.

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Appendix. Questionnaire

1. Concerning the application process for exam adaptation and its context
    a. What are the requirements of the beneficiaries?
    b. Who accredits the needs?
    c. What kind of documentation accompanies the application?
    d. Who submits the application?
2. Concerning the process of processing and resolution of the request for exam adaptation and the context of the request for adaptation
    e. Which unit or service receives the documentation? Please indicate which administration is responsible for this service.
    f. Which unit or department carries out the assessment or study? Please indicate which administration is responsible for this service.
    g. Which professional profile carries out the acceptance of proposed measures?
    h. How is it decided which cases are referred to ordinary committees with minimal adaptation measures (e.g., time available) and which cases are referred to specific delegated committees?
3. Concerning the type of adaptation measure and incorporation of support resources (personal and material)
    i. What type of measures are carried out to make adaptations in university entrance examinations?
4. Concerning the existence of protocols or criteria linked to the correction of the exam
    j. Does your community have adaptations of assessment criteria or protocols for different types of needs? If so, please indicate for which ones and specify the adjustment measures.

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Comprehension without load, engagement without persistence

Measuring whether generative AI is accessible to disabled learners

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Abstract: Generative artificial intelligence (GenAI) tools are increasingly offered to disabled learners to make learning accessible. Accessibility is usually evaluated by conformance: checking an interface against the success criteria of a technical standard such as WCAG 2.2. Such checks show that content can be reached, not how much effort using it requires. This systematic analysis of 92 studies (2023 to March 2026) examines whether research measures how much mental effort GenAI-supported learning demands of disabled learners, whether individual learners keep using these tools across repeated sessions or stop, and whether their confidence as learners grows. Seventeen outcome constructs were coded against Cognitive Load Theory, the Technology Acceptance Model and Self-Determination Theory. Studies mostly measured immediate responses: comprehension (57.6%), engagement (53.3%) and attitudes (48.9%). Few measured the processes that decide whether these results last: cognitive load (10.9%), disengagement (4.3%) and self-efficacy (17.4%), giving asymmetries of 5.3:1, 12.3:1 and 2.8:1. Only 27.2% of studies followed learners beyond a single session. A second coder agreed poorly with the original coding and judged that 16 of 23 sampled studies did not meet all inclusion criteria, so these figures are upper estimates. Cognitive load is defined as the demand a task places on working memory; only the load that arises when the output format does not match a learner's way of accessing information is treated as an accessibility issue. A three-axis framework adds evidence from use to conformance-based evaluation.

Keywords: accessibility, universal design, disabled learners, cognitive load, generative artificial intelligence, technology-mediated learning.

1. Introduction

About 15% of the world's population lives with some form of disability (World Health Organization, 2011). Disabled students often meet barriers that make ordinary learning materials harder to process, slower to use or impossible to access. Generative artificial intelligence (GenAI) tools, especially large language models such as ChatGPT, Gemini and Claude, are now offered to these learners as a response. They can simplify a text on request, explain a concept again without social cost and give help at the moment a difficulty arises. The expectation is that a learner who could not access a text before can now understand it, and that this understanding will last. Research on the topic has grown quickly: 96.7% of the 92 studies examined here were published in 2024–2026, a pace that mirrors the wider growth of AI research in higher education (Zawacki-Richter et al., 2019).

This growth has not yet produced a detailed account of the learner. The studies show which tools exist, which disability populations have been studied and where the research took place. They show much less about what happens to a disabled learner's thinking, behaviour and motivation when learning is mediated by these tools. Most studies observe learners at one moment, when the tool appears to work, and few follow them afterwards. Comprehension is measured in 57.6% of studies, but cognitive load, which indicates how much effort that comprehension required, in only 10.9%. Engagement is measured in 53.3%, but disengagement (learners reducing or stopping their use of the tool) in only 4.3%. Attitudes towards the tool are measured in 48.9%, but self-efficacy, the learner's belief that they can use the tool successfully on their own, in only 17.4%. This pattern is referred to here as measurement asymmetry: studies regularly measure early, visible successes and rarely measure the processes that decide whether those successes last.

An example shows why this matters. A blind student who uses a screen reader receives a long, unstructured answer from a GenAI tool. She understands it, and a comprehension test records a success. The test does not record the extra effort the format required: a screen reader presents text in sequence, so she has to keep the earlier parts of the answer in mind while listening to the rest (Sweller et al., 2011). If this happens in every session, the tool comes to feel difficult, and perceived ease of use is a key predictor of whether people continue to use a technology (Davis, 1989). Repeated difficulty can then weaken her belief that she is able to learn with the tool, a belief that motivational theories identify as a condition for sustained, self-directed use (Bandura, 1977; Deci & Ryan, 2000). She may conclude that the problem lies with her rather than with the design, and stop using the tool. In the current literature, almost none of the steps after the first is measured. Because disabled learners often have fewer alternatives, the cost of this gap falls unevenly on them.

This is an accessibility question that conformance-based evaluation cannot answer on its own. WCAG 2.2 (W3C, 2023) and the design-for-all tradition set out what makes an interface perceivable, operable, understandable and robust. A GenAI tool can meet these criteria and still be hard to use in practice for the learner it was meant to serve. GenAI output is generated anew in each interaction, so its length, density and structure change from one response to the next. Conformance testing checks the interface that displays the output; it cannot check every response the model produces. W3C guidance on cognitive accessibility also notes that it addresses barriers for people with cognitive and learning disabilities that are not included in the current WCAG success criteria (W3C, 2021). Knowing whether GenAI is accessible to disabled learners in practice therefore also requires evidence from use: about effort, about whether learners keep using the tools and about their confidence. Few studies have collected this evidence.

This review asks what the existing evidence allows researchers to know about disabled learners who use GenAI. RQ1: Which aspects of disabled learners' cognition, behaviour and affect do the included studies measure? RQ2: Within each of these three domains, which theoretically important learner processes are measured, and which are not? RQ3: Do the study designs (for example, follow-up over time or measurement in several domains) make it possible to trace how a learner's experience develops? RQ4: Do these measurement patterns differ across disability populations? The article makes three contributions. It describes how disabled learners are represented in GenAI research and what this representation leaves out. It uses three established theories to specify how GenAI-mediated learning can succeed or fail for these learners over time. It proposes a three-axis framework, with practical guidance for researchers, reviewers and funders, for measuring this process.

1.1. Key terms

The following terms are used throughout the article.

- Conformance-based accessibility evaluation: checking whether a digital product meets the success criteria of a technical standard, such as WCAG 2.2, usually by inspecting the interface.
- Cognitive load: the demand that a learning task, as presented, places on working memory, the limited system that holds and processes information during learning (Sweller et al., 2011).
- Accessibility-related load: the part of design-related (extraneous) load that arises when the format of the content does not match the way a learner accesses information (Section 2.1).
- Disengagement: a learner reducing or stopping their use of a tool over time.
- Self-efficacy: a learner's belief that they can successfully carry out a task (Bandura, 1977).
- Asymmetry ratio: the number of studies that measure a visible outcome divided by the number that measure the related process (for example, comprehension compared with cognitive load).

2. Theoretical framework

Three theories from the learning and motivation sciences describe what happens inside a learner when instruction is mediated by technology. Each points to a process that visible outcomes do not show. Together they define the three coding axes of this review and the standard against which the studies' account of disabled learners is assessed.

Cognitive Load Theory (CLT) starts from the fact that working memory has a limited capacity and that learning depends on how this capacity is used (Sweller, 1988; Sweller et al., 2011). In this article, cognitive load means the demand that a learning task, as presented, places on the learner's working memory. CLT distinguishes two main sources of load (Sweller, 2010; Kalyuga, 2011; Sweller et al., 2019). Intrinsic load comes from the complexity of the material itself, that is, from how many elements must be processed together; it depends on the task and on the learner's prior knowledge, and it cannot be removed without changing what is learned. Extraneous load comes from the way information is presented, for example from unclear structure, unnecessary information or a confusing interface; it does not contribute to learning and can be reduced through better design. Germane load, a third type in earlier accounts, is now usually described as the working-memory resources a learner devotes to intrinsic load rather than as a separate source (Kalyuga, 2011; Sweller et al., 2019). Because the same comprehension score can be reached with little or with great effort, comprehension measured alone cannot show whether learning was efficient or came at a cost the learner cannot repeat (Paas & van Merriënboer, 2020).

The Technology Acceptance Model (TAM) explains technology use through two beliefs: perceived usefulness and perceived ease of use (Davis, 1989; Venkatesh & Davis, 2000). When users find a technology difficult, they are less likely to adopt it or to keep using it. Meta-analytic evidence confirms that both beliefs predict technology adoption in education (Scherer et al., 2019). Studies that measure engagement but not disengagement only observe learners who remain users. This creates a survival bias: the learners who gave up, as TAM predicts some will, are not seen. For disabled learners this matters because a student may engage with a chatbot tutor while finding it hard to use; without a measure of disengagement, a study cannot show whether that engagement continues as barriers accumulate.

Self-Determination Theory (SDT) holds that self-directed (autonomous) motivation depends on meeting three basic needs: competence, autonomy and relatedness (Deci & Ryan, 2000; Ryan & Deci, 2000; Niemiec & Ryan, 2009). Self-efficacy, a learner's belief that they can organise and carry out the actions a task requires (Bandura, 1977), is closely linked to the need for competence and helps explain whether a positive attitude turns into sustained effort. A study that measures attitudes but not self-efficacy can show that learners like a tool without showing whether they feel able to use it for their own goals.

2.1. Task load, design load and accessibility-related load

Cognitive load is not, in itself, an accessibility barrier. Some load is necessary: a learner who studies a complex topic must process many related elements, and removing this intrinsic load would mean removing the content to be learned. Other load comes from poor design and affects all learners. This review therefore distinguishes three sources of effort.

- Intrinsic load (task load): effort required by the complexity of the learning content itself, given the learner's prior knowledge. It is part of learning and should be supported, not removed.
- Extraneous load (design load): effort caused by the way content or the interface is designed, for example long, unstructured or redundant responses. It affects all learners and can be reduced by better design.
- Accessibility-related load: the part of extraneous load that arises when the format of the output does not match the way a particular learner accesses information. A long answer without headings makes a screen-reader user listen to it in sequence and keep earlier parts in mind; dense written text demands more decoding effort from a learner with dyslexia; and for a deaf learner whose first language is a sign language, complex written text is processed in a second language. **(Galasso, 2026)** The same response can therefore create little extra effort for one learner and a great deal for another.

Only the third source is treated here as an accessibility variable. It is the mechanism through which content that conforms to accessibility standards can still be difficult to use in practice: two learners who receive the same output do not receive the same access. Universal design aims for environments that the widest possible range of people can use without adaptation (Rose & Meyer, 2002; CAST, 2018). Accessibility standards check this at the level of the interface; accessibility-related load arises at the level of the content the interface delivers, which in GenAI changes with every response. Design for all can be confirmed in use only if this load is measured. The distinction also has a methodological consequence. Many cognitive load measures, such as the NASA-TLX (Hart & Staveland, 1988), record overall effort and cannot separate these sources. Separating them requires instruments that distinguish intrinsic from extraneous load (e.g., Leppink et al., 2013) and designs that compare the same content in different formats, or across learners with different access needs. As Section 4.5 shows, the included studies did neither, so the load they recorded cannot be attributed to any one source.

The three theories lead to a shared account of successful technology-mediated learning. Learning succeeds not when a learner understands something once, but when understanding is reached at a cost the learner can sustain, with a tool the learner continues to choose, and with growing belief in their own capability. The theories also predict how these processes interact. Accessibility-related load makes a tool feel difficult, which TAM identifies as a barrier to continued use. Repeated difficulty weakens the learner's sense of competence, which SDT identifies as a condition for autonomous motivation. A learner overloaded by the format of the output

(cognitive axis) may come to see the tool as too effortful (behavioural axis) and herself as unable to use it (affective axis). Studies that measure only immediate outcomes, or only one axis, cannot observe this sequence. The three axes are therefore used both to code the studies and to describe how GenAI-mediated learning can fail for disabled learners, a failure that may be wrongly attributed to the learner rather than to the design.

3. Methodology

This review is a secondary, theory-driven analysis of how outcomes are measured in 92 studies on generative AI, disability and education published between 2023 and March 2026.

3.1. Relationship to the parent study

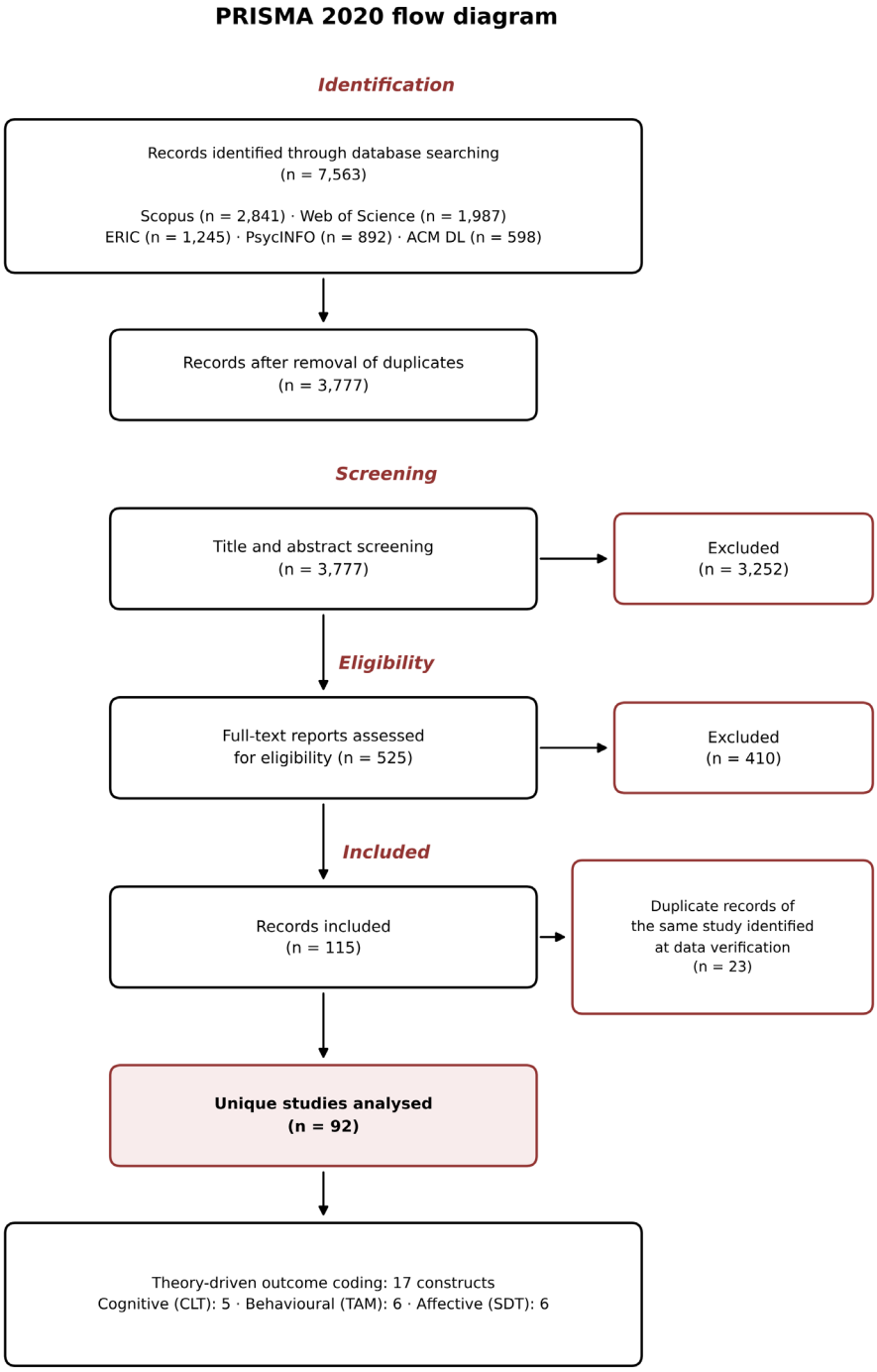
The corpus was first assembled for a companion descriptive review by the author, which has not been published. That review mapped the field: for each study it extracted, with a structured extraction form, the GenAI tool, the disability population, the country, the educational level and the type of technology, and it summarised these variables with frequency counts (population categories were assigned from a fixed list of 13 categories, such as visual impairment, autism or dyslexia, according to the population each study reported; a study could receive several categories). It did not code outcome measures. The present study re-analyses the studies included in that review to answer a different question: not what the field studies, but what it measures. The re-analysis followed four steps. First, the full texts of all included studies were retrieved again. Second, a new codebook of 17 outcome constructs was developed from the three theories (Appendix C). Third, each study was coded with this codebook, independently of the parent review's extraction (Section 3.3). Fourth, the disability population recorded in the parent review was linked to each study, solely to report results by population (Section 4.6). Apart from this population variable and bibliographic identifiers, no data from the parent review were reused. The two studies therefore use the same publications but extract different data to answer different questions.

3.2. Systematic search and corpus formation

The corpus was formed through a PRISMA-compliant systematic search (Page et al., 2021; Tricco et al., 2018; see Figure 1) executed in March 2026 across five databases: Scopus, Web of Science Core Collection, ERIC, PsycINFO, and the ACM Digital Library. A three-block Boolean strategy combined generative-AI terms (e.g., "generative AI," "ChatGPT," "large language model," "Copilot," "Gemini," "Claude"), disability and inclusive-education terms (e.g., "disabilit*," "special education," "accessibility," "autism," "dyslexia," "universal design for learning"), and educational-context terms; complete database-specific strings are available from the author on request. The search identified 7,563 records, reduced to 3,777 after deduplication; title/abstract screening excluded 3,252 records; full-text assessment of 525 reports excluded 410 against seven inclusion and seven exclusion criteria, yielding 115 records. During data verification, 23 of these records were found to duplicate another record of the same study (identical or truncated titles); they were merged, leaving 92 unique studies, which form the analytic corpus. Inclusion required a genuine generative-AI focus (not traditional or rule-based AI); an explicit, named disability population rather than general usability; an educational context; original empirical data; English language; and peer-reviewed status. The temporal distribution was concentrated: 3.3% (2023), 20.7% (2024), 62.0% (2025) and 14.1% (January to March 2026; percentages do not sum to 100

because of rounding), reflecting the field's emergence after the public release of ChatGPT in late 2022.

Figure 1. PRISMA 2020 flow diagram of the systematic search and screening process.



Note. Search conducted in five databases in March 2026. Duplicate removal before screening: 3,786 records.

3.3. Theory-driven outcome coding

Each study was coded for the presence or absence of 17 outcome constructs in three theory-aligned domains: cognitive (cognitive load, comprehension, learning gains, transfer and working memory), behavioural (adoption/intention, engagement, disengagement, persistence, self-

regulation and help-seeking) and affective (self-efficacy, motivation, satisfaction, attitudes, anxiety and frustration). Coding followed a fixed sequence: locating all named outcome measures in the Methods or Procedure section; checking the Results for further outcomes; assigning each outcome to the 17-construct taxonomy; and recording design features (longitudinal, pre-post, experimental) and, where reported, sample size. Only Methods and Results were coded, so that constructs mentioned only in an introduction were not counted. The threshold was deliberately inclusive: any construct named in Methods or Results was coded as measured. Because an inclusive threshold raises the counts of all constructs, the prevalence figures are upper estimates; the second-coder check (Section 3.4) shows that it raised the counts of the visible constructs most. Under this threshold, a construct was coded as measured when it was named as an outcome in Methods or Results, including outcomes reported by teachers or assessed on the output of the tool. The cognitive load code recorded any measure of mental effort; because no study used an instrument that separates intrinsic from extraneous load (Section 4.5), the code could not distinguish the three sources of load described in Section 2.1. The main results are prevalence percentages and asymmetry ratios. An asymmetry ratio is the number of studies that measure a visible outcome divided by the number that measure the related process on the same axis; because both counts share the denominator of 92, the ratio is computed from the counts.

For RQ4, each study was assigned to the disability population recorded in the parent review. The parent review assigned each study one or more categories from a fixed list of 13 population categories (for example, visual impairment, deaf or hard of hearing, autism, ADHD or dyslexia), plus “not identified”, according to the population the study reported. For this analysis, these categories were grouped into 11 groups (Table 2): dyslexia was grouped with general learning disabilities, and the general, multiple and neurodivergent (general) categories were grouped together. Because 64 of the 92 studies involve more than one category, a study can appear in several groups, and results by population are therefore reported as counts and are not tested statistically.

3.4. Coding reliability, quality appraisal and ethics

The author coded all 115 records. Intra-coder consistency was checked first on a calibration subset of 15 studies (13% of the 115 records), coded twice 72 hours apart, with 91% agreement across the 17 constructs; most disagreements concerned the boundary between satisfaction and attitudes and were resolved by refining the operational definitions. The full set of records was coded in four batches (30, 30, 30 and 25), each followed by a consistency check against earlier coding decisions.

To assess inter-coder reliability, a second coder with experience in inclusive education, who had not taken part in the original coding, independently coded a random subsample of 23 of the 92 unique studies (25%), drawn with a fixed random seed, using the codebook in Appendix C, without access to the first coder’s decisions. Agreement was assessed for each construct with percentage agreement and Cohen’s kappa (Cohen, 1960). Because kappa can be low for rare constructs even when agreement is high (Feinstein & Cicchetti, 1990), Gwet’s AC1 (Gwet, 2008) and positive agreement are also reported. Percentage agreement averaged 77.2% across the 17 constructs, but agreement corrected for chance was low (pooled Cohen’s kappa = 0.06; pooled AC1 = 0.71). The disagreements were systematic rather than random. Across the 391 construct decisions in the subsample, the first coder recorded 89 constructs as measured and the second coder 10, and the two coders agreed on 5 of these. The second coder recorded a construct only when it was measured as an outcome of the learners themselves, whereas the first coder had also recorded constructs assessed on AI outputs, reported by teachers or clinicians, or described

qualitatively. Full texts were not available to the second coder for four studies, which were coded from their abstracts; excluding them did not change the result (pooled kappa = 0.07). Positive agreement, the share of "measured" codes on which both coders agreed, was 0.10. The second coder also judged that 16 of the 23 studies did not meet at least one of four inclusion criteria (generative AI, a named disability population, an educational context and original empirical data). The prevalence figures reported in this article therefore rest on the first coder's inclusive threshold and should be read as upper estimates. Construct-level results are given in Appendix D, and the full construct-level statistics in the repository (see Data availability).

No formal appraisal of the methodological quality of the included studies was conducted, and this decision follows from the research questions. Appraisal tools such as the Mixed Methods Appraisal Tool (Hong et al., 2018) judge how far a study's findings can be trusted. This review does not synthesise findings: it records whether a construct was measured at all. A weaker study that measured cognitive load and a stronger study that did not are both correctly coded, and excluding or weighting studies by quality would change the description of the field rather than make it more accurate. PRISMA-ScR also treats critical appraisal as optional when the aim is to map how a field is studied (Tricco et al., 2018), which is the aim here. Three study characteristics that bear on measurement were nevertheless coded and are reported with the results: study design (longitudinal, pre-post, experimental), the reporting of sample size, and, for cognitive load, the use of validated instruments. Section 4.5 also tests whether the asymmetries hold in the methodologically stronger subsets of longitudinal and experimental studies.

The verification also bears on eligibility. Besides the second coder's judgements reported above, the parent review recorded no disability population for 8 of the 92 studies. These checks indicate that the corpus includes studies outside the stated inclusion criteria. It is therefore best read as a map of research at the intersection of generative AI, disability and education, rather than as a set of studies that all meet those criteria. The studies were not removed, because a full re-screening of the corpus was beyond the scope of this study; this is listed as a limitation.

The protocol was registered retrospectively on OSF; because registration followed completion, deviations cannot be checked against a pre-specified plan, although all protocol details are documented. As a secondary analysis of published, publicly available articles involving no human participants or personal data, the review did not require institutional ethical approval.

4. Results

4.1. Overall coverage

Across the 92 studies, cognitive outcomes were measured in 76.1% (n = 70), behavioural outcomes in 66.3% (n = 61) and affective outcomes in 75.0% (n = 69); 51.1% (n = 47) measured all three domains. At first sight, the field therefore seems to attend to the whole learner. Within each domain, however, measurement is strongly uneven (Table 1; Figure 2).

4.2. Cognitive axis: comprehension without load

Most cognitive codes concerned what disabled learners understood: comprehension in 57.6% (n = 53), learning gains in 40.2% (n = 37) and transfer in 26.1% (n = 24). Few measured what this understanding cost them: cognitive load in 10.9% (n = 10) and working memory in 5.4% (n = 5). For every study that measured cognitive load, 5.3 measured comprehension (5.3:1). Studies

usually recorded that a learner succeeded, but not how much effort the success required or whether the learner could repeat it.

4.3. Behavioural axis: engagement without persistence

Most behavioural codes concerned learners while they were using the tool: engagement in 53.3% (n = 49) and adoption or intention to use in 35.9% (n = 33). Few measured learners who stopped: disengagement in 4.3% (n = 4) and persistence in 9.8% (n = 9). Help-seeking, which shows that a learner is struggling and may need support or an accommodation, was measured in a single study (1.1%). The engagement-to-disengagement ratio is 12.3:1. As a result, the abandonment that TAM predicts when barriers outweigh benefits, and the learners for whom the tool did not work, remain largely unobserved.

4.4. Affective axis: attitudes without self-efficacy

Most affective codes concerned how learners felt about the tool: attitudes in 48.9% (n = 45) and satisfaction in 46.7% (n = 43). Fewer measured whether learners came to feel capable of using it: self-efficacy in 17.4% (n = 16) and frustration in 7.6% (n = 7). The attitudes-to-self-efficacy ratio is 2.8:1. Studies thus recorded learners' opinions of the tool more often than their confidence in using it independently.

4.5. Measurement depth and study design

The measures that would reveal a learner's difficulty while it is happening were the rarest. Help-seeking was measured in one study (1.1%), frustration in seven (7.6%), persistence in nine (9.8%) and working memory in five (5.4%). Each of these constructs was measured in fewer than 10% of the studies.

Measurement was also shallow. Only 27 studies (29.3%) reported their sample size (median 33; range 1–1,000; total N = 3,240), which points to mostly small, exploratory studies rather than confirmatory designs. Most studies (65 of 92) did not report a sample size at all, which also raises the question of whether all of them report original empirical data. None of the 10 studies that measured cognitive load used a validated cognitive load instrument such as the Leppink et al. (2013) scale or the NASA-TLX (Hart & Staveland, 1988); the instruments recorded for them were general questionnaires, rating scales or tests. None of these studies could therefore separate intrinsic, extraneous and accessibility-related load. Instrument quality was not coded for the other constructs, so the depth of measurement of self-efficacy or self-regulation, for example, cannot be assessed from the dataset. The asymmetry therefore concerns which constructs are measured and, for cognitive load at least, also how they are measured.

The pattern is not explained by weak study designs. Longitudinal designs, which are needed to test whether outcomes last, were used in 27.2% of studies (n = 25), pre-post designs in 15.2% (n = 14) and experimental designs in 22.8% (n = 21). Of the 25 longitudinal studies, 16 (64.0%) measured all three domains, more than the corpus average of 51.1%. Within each axis, however, the asymmetries remained in both stronger subsets. Among the 25 longitudinal studies, 14 measured comprehension and 3 cognitive load, 16 engagement and 3 disengagement, and 15 attitudes and 7 self-efficacy. Among the 21 experimental studies, the corresponding counts were 8 and 2, 11 and 2, and 10 and 4. In the original coding, measurement asymmetry therefore runs through the whole corpus and does not appear to be simply a sign of weaker studies.

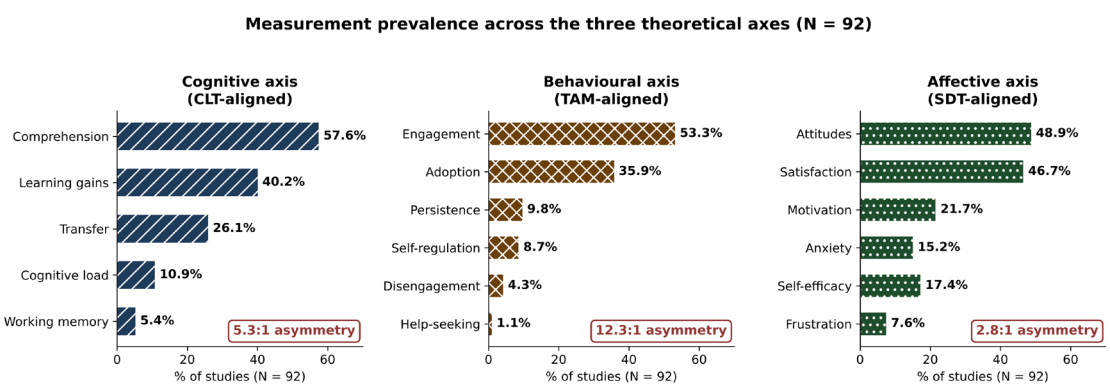
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DOI: https://doi.org/10.17411/jacces.v16i2.788

Table 1. Measurement prevalence across the 92 unique studies, by theoretical axis.

Construct	n	% of N = 92
Cognitive outcomes (total)	70	76,1
Comprehension	53	57.6
Learning gains	37	40.2
Transfer	24	26.1
Cognitive load	10	10.9
Working memory	5	5.4
Behavioural outcomes (total)	61	66,3
Engagement	49	53.3
Adoption/intention	33	35.9
Persistence	9	9.8
Self-regulation	8	8.7
Disengagement	4	4.3
Help-seeking	1	1.1
Affective outcomes (total)	69	75,0
Attitudes	45	48.9
Satisfaction	43	46.7
Motivation	20	21.7
Anxiety	14	15.2
Self-efficacy	16	17.4
Frustration	7	7.6
Design characteristics (total)	70	76,1
Multi-domain (all three)	47	51.1
Longitudinal	25	27.2
Pre-post	14	15.2
Experimental	21	22.8

Note: N = 92 unique studies. Percentages are of the full corpus; constructs are not mutually exclusive.

Figure 2. Measurement prevalence across the three theoretical axes (N = 92).



4.6. Results by disability population

Table 2 reports the measurement pattern for each disability population. The asymmetry appears in every group: in all ten groups other than "no population identified", more studies measured comprehension than cognitive load, engagement than disengagement, and attitudes than self-efficacy. For example, among the 26 studies involving deaf or hard-of-hearing learners, 13 measured comprehension and 2 cognitive load, and none measured disengagement. This gap matters because many deaf signers read GenAI output in a second language, and text-based interaction with these tools assumes written language as the default channel (Galasso, 2026). Disengagement was not measured in any study involving deaf or hard-of-hearing learners, learners with intellectual disability, learners with physical or motor disability, or learners with speech or language disability. Self-efficacy was measured most often in studies involving visually impaired learners (11 of 38). For 8 studies, the parent review identified no disability population; this is discussed in Section 3.4.

Table 2. Measurement of paired constructs by disability population (number of studies).

Population group	n	Compr.	Load	Engag.	Diseng.	Attit.	Self-eff.
Visual impairment	38	23	7	22	2	19	11
Deaf or hard of hearing	26	13	2	13	0	12	3
Autism	32	20	4	19	1	16	5
ADHD	23	17	2	13	1	11	3
Dyslexia and specific learning disabilities	33	27	5	22	2	17	6
Intellectual disability	17	10	1	11	0	6	1
Physical or motor disability	17	9	2	8	0	7	1
Speech or language disability	17	9	2	7	0	5	1
Mental health conditions	25	14	4	12	2	11	3
General, multiple or unspecified disability	45	31	6	29	3	23	6
No population identified	8	5	0	4	0	5	0

Note: n = number of studies involving the group. Populations as recorded in the parent review. Studies involving more than one population appear in several rows, so rows do not sum to 92. Compr. = comprehension; Load = cognitive load; Engag. = engagement; Diseng. = disengagement; Attit. = attitudes; Self-eff. = self-efficacy.

5. Discussion

The main finding concerns how disabled learners are represented. Across 92 studies, disabled learners are observed at the point where GenAI appears to work for them, and seldom afterwards. Studies record what learners understood but not what the understanding cost them; that they engaged, but not whether they came back; that they liked the tool, but not whether they came to trust their own ability to use it. This section discusses why this pattern exists, what it costs disabled learners and how it can be corrected.

5.1. Why surface outcomes dominate

Comprehension, engagement and attitudes are easier to measure, need shorter studies and tend to produce the positive results that publication rewards. Measuring cognitive load requires

specialised instruments and controlled conditions; measuring disengagement requires following learners over time and being willing to report negative results; and measuring self-efficacy requires domain-specific scales rather than general satisfaction items. Researchers therefore tend to measure what is easiest to measure, and publication incentives reinforce this. The field is also very new (96.7% of the studies were published in 2024–2026), and shared measurement practices have not yet developed. Similar patterns have occurred before. Early research on computer-assisted instruction focused on performance outcomes such as test scores and completion rates, and only later did research syntheses show the importance of cognitive and motivational processes (Mayer, 2009). Research on assistive technology long measured adoption without the psychological and social factors that predict abandonment (Lazar et al., 2017). Research on GenAI and disability may repeat these errors. The problem also reflects a wider concern in the psychological sciences: constructs are often measured without evidence that the measures capture what they claim to capture (Flake & Fried, 2020).

5.2. What the asymmetry costs disabled learners

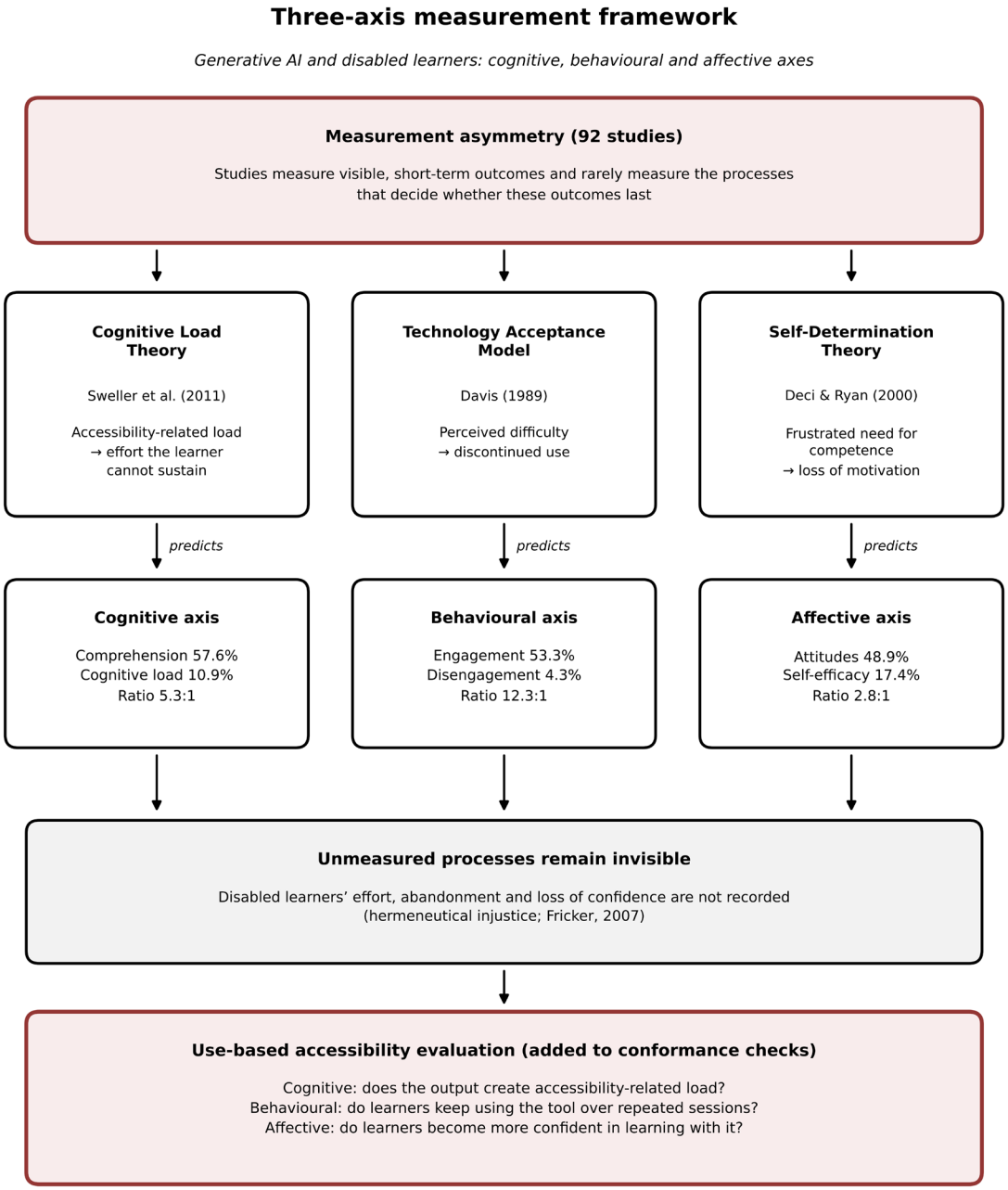
The asymmetry has direct consequences for learners. When comprehension is measured without load, a student who understands a GenAI explanation easily and a student who understands it only through great effort receive the same score, although theory predicts that the second is more likely to stop using the tool; the included studies cannot test this. When engagement is measured without disengagement, studies describe the learners who stayed and say little about those who left, who may be the very learners the tool was meant to help. When attitudes are measured without self-efficacy, a learner who enjoys a tool cannot be distinguished from one who has become able to use it independently. These gaps also reflect a long-standing tendency to measure what is convenient for researchers and designers rather than what matters to disabled people (Oliver, 1990; Shakespeare, 2006). Fricker (2007) uses the term hermeneutical injustice for a situation in which a group lacks the shared concepts needed to make its experience understood. When learners' effort, abandonment and loss of confidence are not measured, their experience of GenAI-mediated learning remains largely invisible to research and practice. The practical consequences are concrete. An institution that relies on this evidence when buying GenAI tools will find measures of comprehension, attitudes and engagement, but almost no measures of effort, abandonment or long-term motivation. Procurement decisions, accessibility evaluations and teaching recommendations will therefore rest on incomplete data about the learners they affect. The pattern is the same across disability populations (Section 4.6). For deaf or hard-of-hearing learners, for example, only 2 of 26 studies measured cognitive load and none measured disengagement, although many deaf signers read GenAI output in a second language.

5.3. Towards observing the learner

The three-axis framework (Figure 3) proposes three changes in measurement. On the cognitive axis, studies should pair comprehension measures with a validated cognitive load measure that distinguishes types of load (e.g., Leppink et al., 2013). Where possible, they should compare the same content in different output formats (for example, structured and unstructured responses) or across learners with different access needs, so that accessibility-related load can be separated from the load of the task itself. On the behavioural axis, studies should measure disengagement, non-adoption and persistence explicitly, rather than treating them as the absence of engagement, and should use longitudinal designs to test whether engagement continues after the first sessions. On the affective axis, studies should treat self-efficacy as a core outcome and measure it with scales suited to the task and population rather than with general satisfaction

ratings. These changes do not require new theories. They require applying established theories and instruments (CLT with differentiated load scales, TAM with measures of continued use, and SDT and self-efficacy theory with validated self-efficacy scales) to outcomes that are currently left unmeasured.

Figure 3. Three-axis measurement framework for generative AI and disability research.



5.4. Implications for theory, accessibility evaluation and practice

For theory, the concept of measurement asymmetry applies beyond this field. It reflects a distinction found across the learning sciences between measuring the visible products of instruction and measuring the processes that decide whether those products last. CLT separates performance from learning (Sweller et al., 2011), SDT separates compliance from autonomous engagement (Deci & Ryan, 2000), and universal design for learning emphasises sustained

engagement over one-off completion (Rose & Meyer, 2002; CAST, 2018). All three imply that understanding instructional effectiveness requires measuring processes as well as products. For accessibility evaluation, the implication is more specific. Current approaches to judging whether a GenAI tool is accessible are conformance-based and focus on the interface: they ask whether assistive technology can reach the output, not what using it costs. This is necessary but not sufficient. A design-for-all evaluation of a GenAI tool should add three questions based on use to the conformance checklist. Does the output create accessibility-related load, that is, more effort for learners who access it through a different route, such as a screen reader, than for other learners (cognitive axis)? Do learners keep using the tool over repeated sessions, or do they stop (behavioural axis)? Do learners become more confident in their ability to learn with it (affective axis)? For research practice, future studies should: (a) include at least one validated cognitive load measure alongside any comprehension assessment; (b) track disengagement, non-adoption and persistence over several sessions; (c) measure self-efficacy with scales suited to the task and the population; (d) use longitudinal or repeated-measures designs that can show whether early outcomes last, decline or reverse; and (e) report results separately for each disability population. Journal reviewers, funders and procurement bodies can use these criteria to encourage better measurement.

5.5. Limitations

Several limitations should be noted. First, the corpus is limited to peer-reviewed studies in English from five databases; grey literature, preprints and studies in other languages may show different patterns. Second, the presence/absence coding is inclusive, so the prevalence figures are upper estimates, and it cannot distinguish central from peripheral measures or judge the quality of instruments. Third, inter-coder reliability was assessed on a 25% subsample and was low (pooled kappa = 0.06), and the second coder judged that 16 of the 23 sampled studies did not meet at least one inclusion criterion. The prevalence figures are therefore upper estimates under an inclusive threshold, and the corpus includes studies outside the stated criteria; a full re-screening and double coding of the corpus is needed to confirm the findings. Fourth, no formal quality appraisal was conducted, so the findings describe how the field measures outcomes, not how strong its evidence about effects is. Fifth, because no included study used an instrument that separates types of load, the review cannot estimate how much of the reported load was accessibility-related. Sixth, several disability populations are represented by few studies, so comparisons between populations are descriptive. Seventh, the field is very new (96.7% of the studies were published in 2024–2026), so the asymmetries are best read as a baseline against which future progress can be measured. Finally, the review does not test whether better measurement would improve outcomes for learners; that would require experimental evidence beyond its scope.

6. Conclusions

The main conclusion of this review is that studies of GenAI for disabled learners mostly measure short-term comprehension, engagement and attitudes, and rarely measure whether these early results can be sustained. Across 92 studies, cognitive load was measured in 10.9%, disengagement in 4.3% and self-efficacy in 17.4%. In other words, more than 82% of the studies say nothing about whether disabled learners' confidence in their own ability changes when they learn with a GenAI tool. These gaps are not random: they fall on the processes that Cognitive Load Theory, the Technology Acceptance Model and Self-Determination Theory identify as

decisive for whether technology-mediated learning lasts. These figures are upper estimates (Section 3.4). In the original coding, the direction of the gap is the same in every subset examined, and the few constructs the second coder recorded point the same way. In the original coding, the asymmetry holds in every disability population examined. Closing these gaps does not require new theory. It requires applying existing theories and instruments to disabled learners: measuring the load that instruction imposes with scales that separate types of load, such as that of Leppink et al. (2013); recording which learners stop using a tool, when they stop and why, as studies of continued use do (Bhattacherjee, 2001); and measuring self-efficacy with validated scales (e.g., Compeau & Higgins, 1995) as an outcome in its own right. Journal editors and reviewers should expect at least one measure on each theoretical axis; funders should support the longitudinal designs (currently 27.2% of studies) that can follow learners beyond first use; and researchers should develop instruments suited to specific disability populations rather than relying only on general scales. Until then, the field cannot say whether GenAI makes learning more accessible for disabled learners in practice, or only at first contact.

7. Acknowledgements

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Ethics. The study is a secondary analysis of published, publicly available research. No human participants or personal data were involved, and institutional ethical approval was not required.

Data availability. The coding protocol, the coding dataset (including the disability population of each study), the second coder's reliability data and the analysis materials are openly available in an Open Science Framework repository: https://doi.org/10.17605/OSF.IO/TMXG6.

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Appendix A. Systematic search strategy

The corpus was assembled through a PRISMA-compliant systematic search executed in March 2026 across five databases: Scopus, Web of Science Core Collection, ERIC (EBSCOhost), PsycINFO (EBSCOhost), and the ACM Digital Library. The search combined three Boolean blocks with the AND operator; within each block, terms were combined with OR and truncation (*) was used to capture morphological variants. Database-specific field tags and syntax were adapted to each platform (e.g., TITLE-ABS-KEY in Scopus; TS in Web of Science).

Block A — Generative-AI terms (21 terms). “generative AI” OR “ChatGPT” OR “GPT-4” OR “large language model*” OR “LLM” OR “Copilot” OR “Gemini” OR “Claude” OR “AI chatbot*” OR “conversational AI” (among 21 terms).

Block B — Disability and inclusive-education terms (45 terms). “disabilit*” OR “special education” OR “inclusive education” OR “accessibility” OR “deaf*” OR “blind*” OR “dyslexia” OR “autism” OR “ADHD” OR “neurodiverg*” OR “assistive technolog*” OR “universal design for learning” (among 45 terms).

Block C — Educational-context terms (14 terms). “education” OR “learning” OR “teaching” OR “student*” OR “classroom” (among 14 terms).

The search identified 7,563 records, reduced to 3,777 after deduplication. Title-and-abstract screening excluded 3,252 records. Full-text assessment of 525 reports excluded 410 against the criteria below, yielding 115 records, which correspond to 92 unique studies after removal of 23 duplicate records (Section 3.2). The complete database-specific query strings, the deduplication log and the exclusion log are available from the author on request.

Appendix B. Inclusion and exclusion criteria

Inclusion criteria. A study was included if it (IC1) focused on generative AI rather than traditional machine-learning or rule-based systems; (IC2) addressed an explicit, named disability or accessibility population rather than general usability; (IC3) was set in an educational context, formal or informal; (IC4) reported original empirical data; (IC5) was written in English; (IC6) was published between January 2022 and March 2026; and (IC7) was a peer-reviewed journal article, a conference full paper (≥4,000 words), or a book chapter.

Exclusion criteria. A report was excluded if it involved (EC1) traditional AI without a generative component; (EC2) a general “accessibility” focus without disability specificity; (EC3) a non-educational application; (EC4) non-empirical work (commentary, editorial, protocol); (EC5) a review or meta-analysis; (EC6) an inaccessible full text; or (EC7) insufficient methodological reporting to permit outcome coding.

Appendix C. Construct taxonomy and operational coding definitions

Each study was coded for the presence or absence of 17 outcome constructs organised across three theory-driven axes. The threshold for coding a construct as measured was deliberately inclusive: a construct was recorded as present when a study reported any named outcome measure, instrument, or dependent variable corresponding to it in the Methods or Results

section. Coding was restricted to Methods and Results to avoid false positives from constructs merely discussed in introductions or literature reviews.

C.1. Cognitive axis (Cognitive Load Theory)

- Cognitive load — any measure of mental effort or working-memory burden imposed by the task or tool (e.g., validated subjective load scales, dual-task measures, physiological indices, or explicit load-related self-report items). The code does not distinguish intrinsic, extraneous and accessibility-related load (Section 2.1), because no included study used an instrument that separates them.
- Comprehension — measures of understanding of presented material (e.g., comprehension tests, quiz accuracy, recall of content).
- Learning gains — pre-to-post change in knowledge or skill attributable to the intervention.
- Learning transfer — application of learned material to novel problems or contexts not seen during instruction.
- Working memory — direct measures of working-memory demand or capacity (e.g., span tasks, working-memory load indices).

C.2. Behavioural axis (Technology Acceptance Model)

- Technology adoption / intention to use — measures of uptake, acceptance, or stated intention to continue using the tool.
- Engagement — behavioural or self-reported involvement with the tool or task (e.g., time on task, participation, interaction frequency).
- Disengagement — measures of withdrawal, drop-off, non-adoption, or abandonment of the tool over time.
- Persistence — continuation of use or effort across multiple sessions or over an extended period.
- Self-regulated learning — measures of learners' planning, monitoring, or control of their own learning process.
- Help-seeking — measures of learners' requests for assistance, from the tool or from others, during learning.

C.3. Affective axis (Self-Determination Theory)

- Self-efficacy — learners' beliefs in their own capability to succeed at the task, ideally via domain-specific scales.
- Intrinsic motivation — measures of interest-driven, autonomous engagement, as distinct from externally driven compliance.
- Satisfaction — global evaluative ratings of the experience or tool.
- Attitudes — evaluative dispositions towards the tool or towards AI in learning.
- Anxiety — measures of task-, technology-, or evaluation-related anxiety.

- Frustration — measures of frustration, need-thwarting, or negative affective response during use.

Appendix D. Coding protocol and quality assurance

Coding followed a structured sequence for each of the 115 records: (a) locate all named outcome measures, instruments, and dependent variables in the Methods/Procedure section; (b) examine the Results section for any additional outcomes not listed in Methods; (c) classify each identified outcome into the 17-construct taxonomy; and (d) record study-design features (longitudinal, pre-post, experimental) and, where reported, participant count and instruments.

A two-phase quality-control procedure was applied. In the first phase, a calibration subset of 15 studies (13% of the 115 records) was coded, set aside, and recoded after a 72-hour interval to assess intra-coder consistency. Agreement between the two codings was 91% across all 17 constructs, with the few discrepancies concentrated on the boundary between satisfaction and attitudes, which share conceptual overlap in many instruments; operational definitions were refined to resolve these boundary cases. In the second phase, the full set of records was coded in four sequential batches (n = 30, 30, 30, 25), each followed by a consistency check against cumulative coding decisions to mitigate coder drift.

Inter-coder reliability was then assessed on a random subsample of 23 of the 92 unique studies (25%). The subsample was drawn with a fixed random seed from the 92 unique study identifiers. A second coder with experience in inclusive education, who had not taken part in the original coding, received the codebook (Appendix C), a short written briefing and the full texts (available for 19 of the 23 studies; the other four were coded from their abstracts), and coded the 23 studies independently, without access to the first coder's decisions. For each construct, percentage agreement, Cohen's kappa and Gwet's AC1 were computed. Agreement by construct ranged from 43.5% (engagement) to 100.0% (help-seeking, which neither coder recorded in the subsample, so that kappa could not be computed); kappa ranged from −0.17 to 0.47. Disagreements were not resolved by discussion and the first coder's decisions were not changed; both coders' decisions and the construct-level statistics are deposited in the repository so that readers can examine them.

Appendix E. Coding dataset

The accompanying file 06_Supplementary_Coding_Data.csv contains one row per unique study (N = 92); the 23 duplicate records identified during verification were merged, with a construct coded as present if it was coded in either record. The file has the following fields: a sequence identifier; the study title; the source file reference; reported participant count; the disability population recorded in the parent review; the 17 outcome-construct indicators grouped by axis (cog_*, beh_*, aff_*, coded True/False); the instruments used where specified; and three design indicators (longitudinal, pre_post, experimental). A second file contains the second coder's decisions for the 23-study reliability subsample. These files are the empirical basis for every prevalence figure, asymmetry ratio and agreement statistic reported in the manuscript and permit full reconstruction of the analysis.

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