Project within Transport and Mobility Solutions – FFI

Enhanced Auditory Reality Scout

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FFI in short

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1. Summary

Enhanced Auditory Reality Scout (EARS) explored how spatial 3D audio can be used to improve accessibility, safety, and user experience in shared and automated mobility services. The project was motivated by the growing demands placed on users in future mobility systems, where individuals will increasingly need to plan and carry out their journeys independently, while human support may become more limited. This development risks worsening the user experience and excluding certain groups, such as people with visual impairments. To address this, the project adopted a design-for-all perspective, aiming to explore and create inclusive solutions that are usable by a broad range of users.

The purpose of the project was to investigate how headphone-based 3D audio with head tracking can function as an intuitive and safe navigation and information support across different phases of a journey, from the starting point to the vehicle, and onward to the final destination. A particular focus was placed on user situations outside the vehicle, where users must navigate to a pickup vehicle (e.g., a robotaxi) in an urban environment, as well as on challenges faced by people with visual impairments.

The project's primary goal was to design and test an app-based demonstrator demonstrating how 3D audio guidance for mobility services can be experienced in various use contexts. An additional goal was to propose the system architecture, including identifying existing technologies, user needs, and the availability of the data required to enable a product based on the project's results. The project's long-term impact goals were to (1) increase acceptance and accessibility of shared mobility services, (2) simplify and improve mobility for all potential users, thereby increasing both perceived and actual efficiency of the transport system, and (3) enhance safety when using these services by supplementing or replacing solutions based purely on visual interfaces.

The project followed a design thinking methodology and was structured into six work packages. WP2 focused on identifying relevant scenarios, user needs, and critical challenges through literature reviews, interviews, workshops, and a master's thesis project. This work resulted in two concept development tracks, one aimed at safely supporting users while navigating to a vehicle, and the other focused on enhancing the in-car experience when traveling to a destination. WP3 built on insights from WP2 by developing and iterating audio design concepts for different user scenarios and user groups with varying abilities, including evaluation in formative studies. This included concepts for pedestrian navigation to a vehicle, as well as concepts designed to create richer user experiences whilst traveling to a destination.

In WP4, a system architecture was developed to illustrate how wearable devices, backend services, connected vehicles, and external stakeholders could interact within a future ecosystem to support the solutions proposed in the project. In WP5, pedestrian navigation audio concepts were implemented in a technical prototype based on the open Soundscape framework. In WP6, the solutions were evaluated through a summative study involving 30 participants, in which three different design approaches were tested in a real urban environment.

The results of the summative study indicated that turn-by-turn guidance was regarded as the safest, most user-friendly, and broadly accepted method for urban navigation. In contrast, the spatial “audio beacon” approach offered a more enjoyable and engaging experience, enhancing feelings of fun and excitement, but it also resulted in a greater cognitive load for users. These findings suggest that different audio-based navigation approaches are suitable for different contexts and navigational purposes. In addition to user studies, the project engaged a reference group of people with visual impairments through discussions and demonstrations of the audio concepts. They confirmed the strong potential of audio-based navigation while also contributing important insights for future design considerations tailored to this user group.

In summary, the EARS project has contributed valuable new insights into the design and application of 3D audio-based guidance to improve accessibility, safety, and user experience in future mobility services. In addition to navigational guidance, the project developed and showcased an innovative approach to spatial sound design, enhancing the user experience when travelling to a destination. Furthermore, the project explored the development and refinement of technical infrastructure necessary to support the proposed solutions before implementation.

2. Sammanfattning

Enhanced Auditory Reality Scout (EARS) undersökte hur rumsligt 3D-ljud kan användas för att förbättra tillgänglighet, säkerhet och användarupplevelse i delade och automatiserade mobilitetstjänster. Projektet motiverades av de ökande krav som ställs på användare i framtidens mobilitetssystem, där individer i allt större utsträckning behöver planera och genomföra sina resor självständigt, samtidigt som mänskligt stöd kan bli mer begränsat. Denna utveckling riskerar att försämra användarupplevelsen och att exkludera vissa grupper, såsom personer med synnedsättning. För att möta detta antog projektet ett design-för-alla-perspektiv med målet att utforska och ta fram inkluderande lösningar som kan användas av en bred grupp av användare.

Syftet med projektet var att undersöka hur hörlursbaserat 3D-ljud med spårning av huvudriktningen kan fungera som ett intuitivt och säkert stöd för navigering och informationsförmedling under olika faser av en resa – från startpunkten till fordonet och vidare till slutdestinationen. Särskilt fokus lades på användarsituationer utanför fordonet, där användare behöver navigera till ett upphämtningsfordon (till exempel en robotaxi) i en urban miljö, samt på de utmaningar som personer med synnedsättning möter.

Projektets huvudsakliga mål var att designa och testa en app-baserad demonstrator som visar hur 3D-ljudbaserad guidning för mobilitetstjänster kan upplevas i olika användningskontexter. Ett ytterligare mål var att föreslå en systemarkitektur, inklusive identifiering av befintliga teknologier, användarbehov och tillgång till den data som krävs för att möjliggöra en produkt baserad på projektets resultat. Projektets långsiktiga effektmål var att (1) öka acceptans och tillgänglighet för delade mobilitetstjänster, (2) förenkla och förbättra mobilitet för alla potentiella användare och därigenom öka både upplevd och faktisk effektivitet i transportsystemet samt (3) öka säkerheten vid användning av dessa tjänster genom att komplettera eller ersätta lösningar som enbart bygger på visuella gränssnitt.

Projektet följde en "design thinking"- metodik och strukturerades i sex arbetspaket (AP). AP2 fokuserade på att identifiera relevanta scenarier, användarbehov och kritiska utmaningar genom litteraturstudier, intervjuer, workshops och ett examensarbete. Detta arbete resulterade i två konceptutvecklingsspår: ett som syftade till att ge säkert stöd till användare vid navigering till ett fordon, och ett som fokuserade på att förbättra upplevelsen inne i fordonet under resan till destinationen. AP3 byggde vidare på insikterna från AP2 genom att utveckla och iterera ljuddesignkoncept för olika användarscenarier och användargrupper med varierande förmågor, inklusive utvärdering i formativa studier. Detta inkluderade både koncept för gångnavigering till ett fordon och koncept som syftade till att skapa rikare användarupplevelser under färd till destinationen.

I AP4 utvecklades en systemarkitektur som illustrerade hur bärbara enheter, backend-tjänster, uppkopplade fordon och externa aktörer kan samverka i ett framtida ekosystem för att stödja de lösningar som föreslås i projektet. I AP5 implementerades ljudkoncept för gångnavigering i en teknisk prototyp baserad på det öppna Soundscape-ramverket. I AP6 utvärderades lösningarna genom en summativ studie med 30 deltagare, där tre olika designansatser testades i en verklig stadsmiljö.

Resultaten från den summativa studien visade att ”turn-by-turn-navigering” med röst uppfattades som den säkraste, mest användarvänliga och bredast accepterade metoden för urban navigering. Däremot erbjöd det spatiala ”ljudfyr”-konceptet en mer njutbar och engagerande upplevelse som ökade känslor av nöje och spänning, men medförde också en högre kognitiv belastning för användarna. Dessa resultat tyder på att olika ljudbaserade navigationsmetoder är lämpliga för olika kontexter och navigationssyften. Utöver användarstudierna engagerade projektet även en referensgrupp bestående av personer med synnedsättning genom diskussioner och demonstrationer av ljudkoncepten. De bekräftade den stora potentialen i ljudbaserad navigering samtidigt som de bidrog med viktiga insikter för framtida designanpassningar för denna användargrupp.

Sammanfattningsvis har EARS-projektet bidragit med värdefulla nya insikter i design och tillämpning av 3D-ljudbaserad guidning för att förbättra tillgänglighet, säkerhet och användarupplevelse i framtida mobilitetstjänster. Utöver navigationsstöd utvecklade och demonstrerade projektet även ett innovativt angreppssätt för spatial ljuddesign som förbättrar upplevelsen vid resa mot destinationen. Projektet utforskade dessutom utveckling och vidareutveckling av den tekniska infrastruktur som krävs för att kunna stödja de föreslagna lösningarna innan implementering.

3. Background

Private cars have for long been the dominating mode of mobility in our cities, and consequently also dominated how we design the cities. The car, once the symbol of freedom, is today in many ways hindering wellbeing in terms of noise, congestion, and various types of pollution. New innovations aim to maintain our access to mobility but at the same time reduce the number of vehicles on the roads, thereby reducing congestion and pollution and allowing people to reclaim urban space.

Autonomous vehicles together with shared and combined mobility services are clear trends but often place a greater responsibility on the traveler to plan their trip but at the same time offer human interaction to a lesser extent. This risk impairs the user experience and thus acceptance, and, even worse, makes it more difficult to use for groups with disabilities. As innovative mobility services develop, innovative ways for all people – not just the majority – to interact with these services are also needed.

The FFI-project Sonic Interaction in Intelligent Cars (SIIC) Dnr 2018-02730 investigated how sound can enhance the user's experience in automated vehicles during actual driving. The project showed that well-designed sounds have great potential to enhance user experience, for example through increased safety and reduced motion sickness. The results also showed high user acceptance of sounds.

In the current project, we have taken the next step and addressed the possibility of using 3D audio throughout the journey in sustainable shared mobility services. Headphone-based 3D audio creates the illusion of being realistically surrounded by the sound, which is also adapted when the user turns their head—effectively allowing the user to locate sound sources just like in real life. Similar technologies are used in Virtual Reality headsets.

By using both proven and new technology to create relevant and realistic sound environments for the user, the goal was to improve usability and appeal of automated, shared, and combined mobility services. Furthermore, we see possible commercial applications for using the technology in, for example, the hospitality industry to create a more appealing overall experience, where the journey to and from facilities can also be made part of the offer.

4. Purpose, research questions and method

The purpose of the project was to investigate and suggest solutions to make shared mobility services more accessible and efficient, as well as safer and more attractive for users. By using new digital solutions and targeted 3D audio to provide users with a simpler and more intuitive guide from the starting point to the end of the journey, we believed that acceptance of the services could increase.

Above all, we saw a potential for increasing acceptance among user groups who may not be able to, or would feel unsafe, using a traditional application with a visual interface; such is the case for people with visual impairment. However, the goal was to embrace a "design for all" perspective and thus create an inclusive platform that promotes participation and independence for all users.

Furthermore, we believed that the project's use cases could potentially include both services based on traditional vehicles of various sizes (e.g. car-pooling, taxi services, micromobility) and those based on autonomous vehicles (e.g. robotaxis). This means that the results can be applied both on today's service offerings as well as future services.

The challenges in making this a practical solution are many and were addressed as following research questions in the project:

(1) What are the typical use cases for mobility services and related apps where guiding 3D audio is the most beneficial?

(2) How should sound interaction be designed to be maximally guiding and safe, and at the same time non-intrusive, intuitive, and pleasant?

(3) What might a system architecture look like that would enable the project's use cases, and what additional requirements are needed to scale up to a production environment?

The project applied a design thinking methodology where the different work packages (WP) (see Figure 1) feed into the different steps of the process. By doing so, we followed a structured but flexible methodology that helped us design solutions that respond to real user needs.

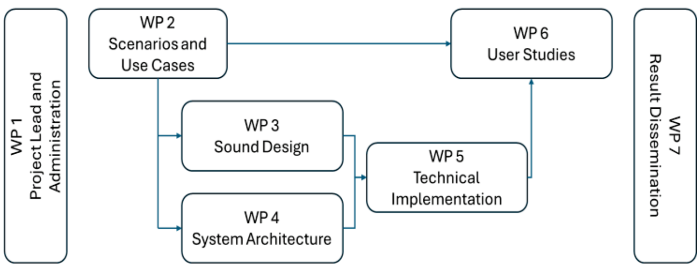


Figure 1: Project Work Packages

WP1 - project management, which includes coordination between the different work packages and project reporting.

WP2 - The purpose was to define several different scenarios for the use of the mobility service, specify use cases, and identify user needs and challenges that in WP3 and 4 were translated into characteristics of the application. Some cases were based on real cases of the project's need owners. User-centric design methods were used to identify needs, challenges, and opportunities, including focus groups and interviews. As part of this work package, a state of the art study was also carried out.

WP3 - The purpose was to develop concepts for audio interfaces based on the results in WP2. The concepts were developed iteratively, combining formative evaluation with concept design. Different types of sound design principles were considered, e.g. abstract/synthetic sounds, earcons, auditory icons, speech, sonification, etc., and mapped to the different parts of the user journey.

The needs of different user groups were considered during the process, e.g. whether visually impaired or hearing-impaired people from different age groups have special needs in different parts of the trip. The purpose of the design was to embrace a "design-for-all" perspective, where the needs of one or more user groups can lead to a design that benefits all user groups. Audio engineering challenges in the implementation, e.g. what type of headphones are best suited, and whether equalization of the sound reproduction is required was also investigated.

WP4 - The purpose was to describe a system architecture in which the technologies developed in the project can be practically feasible. Even if the project combines already mature technologies, it requires an understanding of the requirements and assumptions made of the environment in which the technologies are used. The work package has followed and supported the work in the other work packages to develop architecture to evaluate the assumptions made. The work was conducted as a preparatory development project where system architects participated in and supported the rest of the work packages. Through stakeholder and requirements analysis, the work package developed and documented high-level architecture. Parts of the architecture were implemented and validated as part of WP5.

WP5 - In this work package, the design concepts developed in WP3 were implemented in a technical demonstrator based on the open framework Soundscape (https://github.com/microsoft/soundscape). The goal was to develop prototypes that realize the sound concepts from AP3. Although the intention was for the prototypes to be as realistic as possible, compromises were made, e.g. not all the data required was available, and all use cases were not feasible to implement. Also, due to technical limitations at the time of the main study, tests were carried out with a variant of a technical demonstrator. This is described in chapter 6. These lessons were fed back into WP4 (system architecture).

WP6 - Design solutions developed in WP5 were evaluated with end users in controlled studies. The primary aim was to evaluate the solutions according to the project's first and second research questions, and to better understand how design solutions could be further developed in WP3-5. In addition, a group of visually impaired people were interviewed about the concepts that were developed, and feedback was obtained both from experts on accessibility and from the hospitality industry perspective.

WP7 - Internal seminars and presentations are planned to be held after the project. A final seminar at “SAFER”, Vehicle and Traffic Safety Centre at Chalmers University of Technology, is planned in February 2026 to achieve a broader external dissemination of results. The project will also contribute to research through research publications and network meetings with external parties, at industry seminars, and in popular science contexts, e.g. through project partners' websites and social media.

5. Objectives

The project's goal was to ultimately develop a prototype that demonstrates the experience of 3D audio guidance for mobility services in different types of use cases. The demonstrator was set to be evaluated in a realistic environment with users with different types of functional conditions. However, to limit the ethical challenges about traffic safety, all participants in the test group had normal sight. Therefore, to complement the study, a workshop with visually impaired people was conducted to get important feedback and insights about the developed concepts.

Another goal was to develop the system architecture requirements including identification of existing technologies, needs, and availability of the necessary data required to realize a product based on the project's results.

The technical solution was based on existing technologies and frameworks already commercially available but combined in a new way. The conditions for developing a solution that was demonstrated in real-world situations and that was relatively close to a real product were therefore good. New knowledge was also developed in the form of scenarios for mobility service use, considering different user groups and how the audio interaction should be designed to best meet the users' different needs in these scenarios.

The long-term goal of the project was to contribute to the development of solutions that significantly increase the acceptance and accessibility of shared mobility services. The goal was also to contribute to simplifying and improving the mobility of all possible users, including those in vulnerable user groups, which in turn will increase both the perceived and actual efficiency of the entire transport system. Furthermore, the project goal was to contribute to increased safety in connection with the use of these services by supplementing or completely replacing current solutions that are based on purely visual interfaces.

6. Results and deliverables

6.1 Work Package 2: Scenarios and Use Cases

Various activities were carried out to identify appropriate scenarios and use cases for the subsequent work packages. The overarching purpose with this phase was to steer the direction of concept development. The work package started from a broad viewpoint, investigating the state of the art, including the perspectives of multiple user groups, such as visually impaired as well as presumptive users of shared mobility services. Previous knowledge regarding these topics was fed into the process through the project's domain experts, and additional experts were brought in to expand the scope.

Knowledge gaps and unanswered questions led the project toward its initial research needs. Additional information gathering was therefore conducted on scope-relevant topics such as current and emerging sound-enabled technology, including spatial audio, applications, and accessibility aids. To better understand navigation patterns from the behavioral perspective, guidance and navigation theory was studied; with themes such as pedestrian behavior, wayfinding, choice of route, distant and local navigation, situation awareness, usability, and safety.

Parts of these exploratory studies were carried out in a thesis project, "Guided by Sound - Exploring the use of spatial auditory cues for pedestrian navigation in urban environments" (Chalmers University of Technology), exploring the effectiveness of different sound types and navigation cues for enhancing user navigation by auditory means. The study touched upon themes such as habits, preferences, attitudes, concerns, and familiarity with current navigational solutions and their future potential. After a series of controlled experiments, using sound design concepts produced within the project, the study evaluated path efficiency, error rates, and subjective user feedback.

Interviews and workshops were furthermore conducted within the work package, to deep dive into specific challenges for some potential user groups. As an example, users with different backgrounds and visual impairments participated in activities that led to valuable insights, along with personas and scenarios connected to their specific challenges. These insights filled gaps, unknowns, and uncertainties from the state-of-the-art phase, and added to the greater understanding of the usage context, i.e. the design domain for the presumptive solution.

Prior knowledge about the intricacies of the shared mobility context was used to narrow down the scope and define target groups for potential solutions, based on actual usage patterns and contextual data. To focus the project on the actual needs of the consortium, a series of workshops were held. Additional emphasis was given to scenarios that presumptively work well with 3D-audio, aligning with the project's prerequisites.

Connected to the process of navigating to vehicles, we found significant challenges in the domains of usability, safety, and accessibility. There is currently no well-curated seamless solution that caters for the entire user journey from door to vehicle door. The topic is interesting for many reasons, since it spans a variety of mobility business models: not only does that scope cater for shared mobility scenarios, but also general vehicle finding scenarios and navigation by foot at large – i.e. both current and future business.

For the sake of novelty in the interest of the project's stakeholders, the selected scenarios were connected to hailed mobility, particularly robotaxi services. This scope allows for novel use cases that traditionally have not been addressed by conventional scenarios connected to manual driving and car ownership.

User journeys were described in detail, based on various sources of user-centered research. Attention was given to how users behave in relation to current prerequisites, along with the pains and pleasures, leading up to a magnitude of concept opportunities for the project to explore. Hypotheses and ideas attempting to solve user issues were hence fed forward to the subsequent work packages.

The primary focus was furthermore directed toward the pedestrian phases outside of the vehicle, in accordance with the project's prerequisites, since previous projects such as SIIC took a more vehicle-centric focus. The aim was to leverage 3D audio to improve situational awareness and safety by offloading visual modality and allowing for split attention and multitasking, i.e. supporting both utility and convenience.

To further satisfy and explore the hedonic qualities and opportunities with 3D audio, a second track was moreover selected. This track was based on research connected to Arctic Bath's use cases; centered on the in-vehicle journey as an enabler for enhancing the tourism experience, i.e. potentially using similar audio concepts in a diverse scenario. Challenges were investigated and set the scope for additional concept development further on during the project.

6.2 Work Package 3: Sound Design Iterations

Navigation concept

Benchmark and learnings

An initial test of existing sound navigation applications was performed in Gothenburg with the full project group. The joint analysis within the group after the test walk concluded that there was a potential in exploring new characteristics of the sound design for the existing application Soundscape, with the purpose of facilitating audibility, localization and acceptance. Soundscape is an open source and uses audio beacons which generate a sound in the direction of the destination, for the user to follow. The audio is typically played through headphones and headtracking guides the user toward its destination.

The placement of the destination sound will stay fixed independent of head movements, allowing the user to navigate freely to the destination. The application also allows the user to manually insert several audio beacons to mimic a defined route. A voice support highlighting landmarks and distances is also available in the application.

After the evaluation, initial sound design guidelines were developed.

Beacon sounds should:

- contain broadband, transient components to enable efficient localization
- not be mistaken for, or masked by naturally occurring ambient sounds
- be non-annoying
- be customizable by the user

In terms of voice audio, the user should have the ability to customize voice language, character (incl. gender), as well as speed.

In order to extend the perceptual awareness two new categories were identified as beneficial:

- enhanced auditory actors, which included traceable moving vehicles,
- and enhanced auditory landmarks, i.e. landmarks which play a crucial role in facilitating navigation, such as statues or other distinctive landmarks.

These two categories were not included in the final testing in Soundscape due to lack of reliable data but should be considered interesting for further research.

Soundscape uses four sectors to categorize the 360-degree spatial environment around the user:

- on axis (straight ahead),
- off axis left,
- off axis right,
- and behind (wrong way).

For each sector, a unique sound is allocated, helping the user understand in which direction to move. Proximity sounds further inform the user about helpful events and are categorized by proximity close, proximity far, route start, and route start.

Initial development

A number of sound design concepts were then developed to cater for different preferences:

- A musical track which was spatially rendered in the direction of the destination, paired with a decreased loudness when headed off axis to the destination, while a 180-degree head angle to the destination (wrong way) was represented by silence

- A non-tonal, rhythmical track, with percussive components that gradually disappear as the off-axis angle increases. The track is spatially rendered in the direction of the destination. A sparser rhythm was played when headed off-axis, while wrong way was represented by a short beat with a long pause

- An inverted percussive and rhythmical concept, where the destination of the beacon was represented by silence, while all other directions contained a rhythm, spatially presented in the direction of the destination

- Noise bursts, played in all beacon directions, representing the spatial location of the destination

- Sampled footsteps on gravel, which decreased in tempo with increased off-axis angle. Wrong way was represented by an interrupted rhythm with a longer pause

These new concepts were integrated into Soundscape, evaluated and continuously iterated by walking and judging the aspects of audibility, localization, and acceptance; and then further evaluated as part of a master thesis.

Rhythmical percussive sounds turned out to be the most suitable alternative both for audibility with competing surrounding noises, as well as for spatial localizability. Regarding acceptance, there were a common consensus that the sounds need to be adaptable to loudness changes and preferably also be possible to fade out in the case of eventless walking, e.g. walking straight forward for a long while.

Integration with use cases and scenarios

A workshop was then held in order to take the next step in refining the concepts and connecting them to the project context as described in WP2. Artificial sounds were added on top of a series of pre-recorded videos corresponding to the chosen scenarios and use-cases. Multiple conceptual solutions based on the ideas from previous steps were produced and evaluated by the consortium. Their overall feasibility and adequacy were assessed, leaving the project with two main tracks for the audio concepts.

As a play on recent Volvo slogans, the tracks were dubbed “Freedom to Move” and “Safety First”. The idea was to separate the concepts almost diametrically, to fully explore the range of components and ideas included in the concepts. “Freedom to Move” was designed to allow the user to roam freely, whilst “Safety First” posed as a more stringent and explicit navigational aid. The concepts included a variety of components that allowed the project to test the hypotheses from prior phases.

Formative user evaluations and concept refinement

To further evaluate the ideas from the workshop, a range of small-scale formative studies were performed during the sound design process, with the purpose of exploring and iterating on early design components that would later form parts of the final concepts.

Using a Wizard-of-Oz setup, studies were conducted as a part of an ongoing sound-design iteration, aimed at investigating how different audio characteristics could support movement-related interactions such as walking guidance and turn-by-turn navigation. A secondary objective across the studies was to examine test methodology and potential test environments in preparation for the larger summative user study planned for the later stages of the project. Thus, three short studies were carried out, gradually increasing structure and methodological rigor.

Walking to rhythmic variations

The first evaluation explored "walkability" of different rhythmic concepts. The concepts differed in their base tempo (beats per minute, bpm). In addition, the bpm was gradually decreased and increased during each walk to explore whether the rhythm and tempo variations had a noticeable impact on participants' walking experience.

- Most participants experienced some degree of mental or physical response to rhythmic changes, either falling into the beat intentionally or resisting the urge to match their pace
- Participants expressed that a tempo decrease to an already calm sound made it harder for them to naturally sync their steps with the sound
- A steady groove and melodic variation kept the participants' interest maintained while a more intense sample quickly was perceived as repetitive

In conclusion, one concept provided the most pleasant and immersive walking experience across the three rhythmic concepts. Participants described it as smooth and supportive for natural pacing, with tempo changes that were subtle rather than stressful or intrusive.

This concept was selected for further iteration, due to its subtleness during bpm changes, overall pleasantness and suitable rhythm for walking, which made it the strongest foundation for continued sound-design development.

Walking to different bpm change rates

The next evaluation was conducted with the purpose of further exploring the effect of bpm changes on rhythmic continuous sounds, focusing on the bpm change rate, i.e. how fast the bpm changes.

- Fast bpm changes were generally more noticeable and produced clearer shifts in the walking experience. The rate of change made tempo transitions easier to detect, with reactions ranging from comfort and engagement to a sense of urgency or mild stress, depending on the original rhythm of the concept. These faster transitions were often perceived as influencing movement, with participants describing tendencies or urges toward speeding up during increases in tempo and slowing down during decreases. The immediacy of these changes also highlighted the potential of rapid bpm adjustments to act as intentional cues for movement or situational awareness.
- Slow bpm changes were consistently experienced as subtle and barely noticeable, regardless of concept. The gradual shift created low certainty about whether or when the tempo was changing. Emotional reactions were generally neutral, with only isolated instances of discomfort or confusion, mostly due to the irregularity of the rhythm during

bpm change. The effect on walking was reportedly minimal, and pace typically remained steady. Overall, this slower rate resulted in a smoother tempo drift that blended into the walking experience rather than standing out as a distinct change.

A tentative interpretation was that bpm change rate may influence how effectively tempo can act as an information-bearing cue. One possibility is that a higher bpm change rate may be more suitable when the goal is to provide a clear prompt, since they seem to be easier to detect. At the same time, the slower change rate may offer value when aiming for a more gradual and natural shift in pacing, where the tempo can guide the user over time without demanding focused attention. This insight guided future design choices. Tempo change was included in later iterations specifically as a prompt for slowing down before a crosswalk.

Walking with spatial turn-by-turn navigation cues

Following the previous evaluations, a slightly larger study was conducted in a large hemi-anechoic chamber, with the main purpose of formatively evaluating twelve spatial design variations intended to support turn-by-turn navigation. Participants wore headphones and were instructed to follow auditory instructions that indicated when and where to turn while walking. The twelve concept variations were constructed around a shared foundational element: a continuous rhythmic beat inspired by the favored concept from the previous steps. The beat served as the base navigation signal and moved spatially in the horizontal plane to indicate the direction of the upcoming turn. The participants' task was to walk toward the perceived position of the sound, turning 90 degrees whenever the audio shifted toward a new location.

Building on this base, twelve variations were created by combining three variables:

- type of turn cue; a "pling", a sweeping "swoosh" or no additional cue;
- style of sound shift; the sound shifted positions either dynamically with a sweeping motion, or statically by jumping from one position to another;
- transition time; the duration of the position shift, being either 1 ms or 750 ms.

The results of the study can be summarized by the following insights:

- Concepts with a distinct cue, particularly the pling variations, were consistently perceived as the easiest to understand. Participants described these cues as unambiguous marker of when to turn. In contrast, variations without an additional cue required considerably more concentration and were more often associated with uncertainty about the exact turn moment.
- Static positioning produced the clearest sense of direction, as the fixed left/right separation was stable and easy to localize. Dynamic movements were described as more fluid but also more prone to momentary confusion, especially when participants turned their heads while the turn cue was playing. Several participants expressed that static

swoosh cues, particularly with the longer position shift duration, provided a highly intuitive sense of being “pulled” in the correct direction.

- Concepts without cues were frequently described as requiring the most effort. Participants noted that small changes in the beat could be misinterpreted as signals, resulting in heightened listening effort. These concepts were often ranked as the least preferred despite being described as subtle and pleasant.

- Longer transition time was generally experienced as softer, smoother, and more compatible with natural walking. 1 ms transitions on the other hand, while clear, sometimes felt sudden or urgent. Many participants highlighted that swoosh-based concepts with longer transition times enabled a more fluid turning experience.

- Pling cues were described as highly functional but not always enjoyable, sometimes being resembled to notification sounds. Swoosh cues were generally considered more organic, though the 1 ms versions were occasionally described as stressful or intrusive.

In conclusion, concepts that combined a clear cue with stable spatial positioning provided the highest clarity for execution. Concepts without a cue were perceived as more effortful to interpret, despite being appreciated for being subtle and aesthetically minimal. Based on these insights, the concept with a “swoosh”, static positioning, and 750 ms transition time was selected as the strongest candidate for further iteration due to its intuitive directionality, smoothness and consistently high user preference across both clarity and enjoyment.

Final concept variations

To satisfy the decided concept ideas of “Freedom to Move” and “Safety First”, the sound design was divided into two categories based on two separate rhythmic patterns for further testing.

The design for the “Safety First” approach consisted of a clear direction of travelling indicated by a drum beat which would reduce or add layers to the beat depending on alignment with the correct angle of walking. When approaching a turn, a specific sound would play in the direction of turning. The chosen sound was a “swoosh” sound, similar to a tree branch being swept through the air. The sound was panned, sweeping from centre to the direction of the turn. Another feature of this concept was a tempo reduction when approaching a crosswalk, to mimic the sensation of slowing down the walking pace and paying extra attention to surrounding traffic. The tempo was increased back to default when crossing the road.

The design for the “Freedom to Move” concept consisted of a rhythm designed in three separate layers, a low frequency part, a higher frequency part, and a tonal part. When aligning the head angle to the end destination, all three layers would sound simultaneously but when the head angle was drifting from the end destination, the layers were reduced. If the user was facing 180 degrees opposite to the end destination, an error sound, separated in characteristics from all other sounds would be played instead.

Exploring sound design as part of the visitor journey

As a parallel track, an initial design concept aimed at enhancing the user's experience during travel to a visitor's destination (Arctic Bath in Harads) was developed. The work was conducted in collaboration with an intern studying sound engineering at Luleå University of Technology. The purpose of the project was to explore how sound design can connect the car journey with the destination itself, in order to provide passengers with a richer and more tailored experience during the approximately 1.5-hour trip between Luleå Airport and Arctic Bath.

A concept was developed based on three interacting audio layers meant to contribute to a sense of relaxation, preparation for the destination environment, and an increased understanding of the surroundings along the route and in the area around the destination.

The audio layers consisted of:

- a narrated voice describing the landscape through which the journey takes place,
- a composition of natural sounds recorded in the area and along the route, and
- an interview with an employee at Arctic Bath describing life in the area and in Harads.

The outcome of the work consisted of recorded audio material as well as an approximately 8-minute demo illustrating the complete audio experience. The project and the demo served as an initial source of inspiration for subsequent work within this direction of the project.

Additional sound asset creation work was conducted by Framnäs folkhögskola within their intro course in Game music. The students were given the task to create an auditory soundscape based on information provided regarding both Arctic Bath and Volvo Cars, assuming a trip in an autonomous robotaxi.

The goal was to explore whether sound could be used for elevating the experience of a longer transit trip by sonifying the destination and the surroundings in an enjoyable, pleasant and experience elevating manner. The concepts could be designed to contain information about car status, or points of interest or arrival; but could also be more focused on e.g. well-being or relaxation. An essential part of the concept was interactivity.

The most promising concept ideas were then chosen. Speech prompts were then re-recorded in a studio at Volvo Cars with a female voice, to assure a homogenous voice interface which also had a somewhat Swedish accent. It was deemed to be of importance to connect to Sweden and Scandinavia as well as pronouncing the names of the surrounding villages in their native language.

An automated (GPS triggered) interface was then developed with the intention to trigger audio assets at specific locations along the route.

Design aspects covered various aspects such as:

- An introductory rhythmical musical piece reflecting the unknown journey ahead, meant to be separated from the following musical theme and to serve as a musical bridge between arriving from hectic travelling and the calming experience that lies ahead

- A voice greeting the user and introducing the sound journey. After finishing the voice message, the introductory theme is replaced by a calm version of the main musical theme with varying crescendos

- Separate musical compositions or sounds played when passing landmarks

- Voice messages giving information about landmarks or the surrounding landscape when passing and in eyesight

- Guided relaxation supported by the main musical theme

- Alternative version of the musical theme reflecting a change in the surrounding landscape or highlighting certain local cultures

- A unique musical theme upon arrival

The draft concept was then tuned in car on-location and demonstrated to Arctic Bath.

The final concept was deemed to be calming, inspirational, and very suitable for the destination and the surroundings. The local experience of the Arctic Bath representative also gave some other ideas of information along the route, such as wildlife passages, cultivation zones, and the Northern lights. The concept is to be further developed outside of the project realm in order to potentially find a future implementation.

6.3 Work Package 4: Systems Architecture

The objective of this work package was partly to support the project by evaluating the technical feasibility of proposed concepts and partly to describe how fully developed concepts could be implemented. The results are here documented as a simplified overview of system requirements and how an eco-system with existing technologies can realize the concepts proposed in the project.

As the primary use-case, the EARS project considered how spatial sound can support visually impaired people to find an automated mobility service when there is no human involved that can guide the user.

In this example use-case, a user orders an autonomous mobility service to take them from an agreed pick-up location and to the desired destination. The user receives a preliminary time and location for pick-up and an estimated time of arrival to the destination. The concept defined in the EARS project shall first assist the user to get from their current location to the agreed pick-up location, safely guiding the user with sound. Once at the location, the user shall be guided to the vehicle. Furthermore, as the transport service may be shared, the user may need to be guided to the correct door, and optionally to the trunk in-case luggage needs to be stored.

En route, the vehicle may need to make several stops, e.g., to pick up or drop off other passengers; thus, the user will need to be informed about what the vehicle is currently doing, and when it is estimated that they will arrive at the destination. As there is no human driver, the service will need to provide the user with this information.

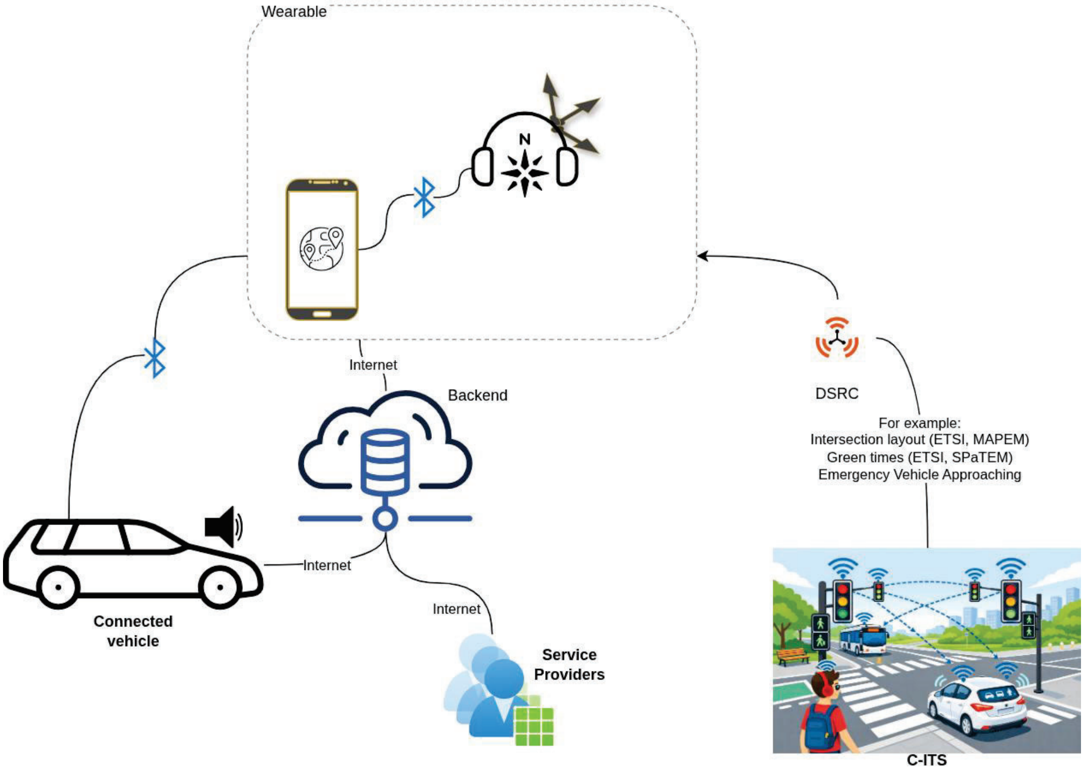
Arriving at the destination, the user may need information on the exact location as well as how to safely exit the vehicle, for instance whether they risk exiting the vehicle on the road or on a bicycle lane as well as get a remainder to fetch their luggage.

Entailed in this are several challenges for a visually impaired person, for instance:

- Guiding the user from their original location to pick-up location must be done in a safe manner, or at least must provide useful information
- The agreed pick-up time may change due to traffic
- The agreed pick-up location may also need to change due to blockage
- Even if the user and the vehicle are at the same location, the vehicle must inform the user exactly where it is as the user may not be able to see it
- The vehicle may already have passengers; thus, the user may need information about what door to enter
- The route from origin to destination may change, affecting arrival time
- The drop-off location may change due to blockage

Architectural Overview

The picture below provides an overview of how a system can be designed to address these challenges.



Wearable

The required wearable equipment comprises a mobile phone and software with spatial sound capabilities, and headphones with head-tracking capabilities. Currently, to the best of our knowledge, only Apple iPhone has built-in support for spatial sound. The software used in the proof-of-concept was Soundscape Community (https://soundscape.services/). The headphones tested in the project were Apple AirPod Max and Bose Frames Rondo.

Backend

A backend application is required for secure integration between the various system components. The backed application will need to be designed with an open API to enable an eco-system of services to connect with users. Such services can include booking a mobility service, as well as allowing the service to keep the user updated with arrival times, and precise pick-up locations.

Connected Vehicle

The automated and connected vehicle used by the mobility service will need to be able to communicate, not only with the backend service, but also directly with the user's device for more granular guidance.

For example, the GPS in the user's device will be able to guide the user to the vicinity of the vehicle but may not be accurate enough to bring the user to within touching distance of it. One approach could be to utilize the external speakers of the vehicle to play the same sound as the software in the user's device (exchanged using the backend software). This would provide a seamless transition from virtual guidance by the software to the physical target. Bluetooth LE proximity sensing and pre-shared security keys (via the backend) would provide secure and safe communication.

Furthermore, onboard sensors can be utilized to determine available seats and RFID-tags to track whether there is luggage left in the vehicle by the user. Sensors that are needed for automated driving, such as cameras, radars and lidars could be used to assess the surroundings before a user exits the vehicle and warns if hazards, such as vehicles or bikes, are detected. Such information can be exchanged using short-range communication (e.g., Bluetooth).

Service Providers

Additional service providers can utilize the platform to offer innovative services to users.
For example, to allow volunteers to help a user in need of assistance. The platform can contain capabilities to stream video and audio along with position and direction from the wearable devices. When connected to a map, this information would allow the volunteers to confidently guide a user.

An open trusted platform can stimulate actors to deliver such innovative services to users.

C-ITS

Already today road furniture, such as traffic lights, are being connected and communicate over DSRC (Dedicated Short-Range Communication, such as G5). Such devices are envisioned to enable more efficient traffic and safer automated vehicles. The information broadcasted can also benefit the visually impaired.

For example, connected traffic lights that implement the ETSI protocols MAPEM and SPaTEM can provide the user with information about the layout of an intersection (MAPEM)—for instance, the number of lanes in a pedestrian crossing or whether there is a pedestrian island—as well as green light timings that will reduce the risk of embarking on a crossing with too short green time.

Another example is emergency vehicle alerts (EVA) that are broadcasted and can be received well before the vehicle is even audible.

Evaluation

In the project, only the wearables, as shown in the figure above, were evaluated. While the general impression is that the technology has potential to be highly useful, it was noted that the maturity of consumer products lack required accuracy and performance; specifically related to the GPS and the head-tracking.

The GPS available in mobile phones at best provide an accuracy of several meters. While this may be precise enough for a fully sighted person that easily can verify their position, it is not enough to confidently guide a visually impaired person in a city environment. This is especially concerning when tasked to guide the user to a pedestrian crossing, or to a vehicle's pick-up location. To create a reliable implementation of the concept, an external, more accurate GPS device is required.

While the head-tracking capabilities in the headphones tested were precise enough to accurately guide a user to a location, it was perceived as too slow to provide a fully immersive experience. This was evident in a "dogfooding" exercise when project members used a mobile phone, head-tracking headphones and the Soundscape application to walk a roughly 5 km route through an unfamiliar city. While all participants eventually arrived at the intended destination, they had to regularly stop and slowly rotate their heads to verifythe correct direction. This was perceived as quite unnatural. Ideally, the head-tracking must respond to normal head movements. This latter issue is assumed to be due to headtracking hardware mainly being a novelty in current consumer grade headphones. To contrast, more expensive contemporary Virtual Reality headsets provide a fully immersive experience regardless of how fast a user turns their head.

6.4 Work Package 5: Technical Implementation

Objectives

This work package implemented design concepts proposed in work packages 2 and 3 as prototypes to enable testing their effect on user experience. The main concepts that WP 5 supported were:

- Evaluation of headphone types
- Evaluation of sound themes

The open-source spatial sound framework Soundscape Community was used. Soundscape was originally developed as a closed-source project by Microsoft. Soundscape was discontinued but subsequently (partly) released as an open-source project, currently maintained by a community of developers. Soundscape Community has a base of visually impaired users that are active in developing the application.

While the main objective of WP5 was to develop proof-of-concept (PoC) implementations of concepts proposed within the EARS project, a secondary objective was to contribute any stable features to the Soundscape community.

Results

The following features were added to the Soundscape Community app:

- **Added new sound themes**
  Improved the sound theming functionality in Soundscape and added approximately 10 themes developed in WP3. The themes were evaluated (qualitatively) with respect to intuitiveness and clarity a user perceived them.

- **Support for Bose Frames headphones**
  The Bose Frames are sunglasses with headphones mounted in the temples. Such headphones are often preferred by visually impaired as they do not cover the ears. Bose Frames have the features needed for Soundscape, but support was not available in the application.

- **Initial support for automatic routing**
  Current implementation of Soundscape support placing individual sound beacons to guide a user's journey. Work package 5 developed an initial PoC implementation for automatic routing, where a user can specify a destination and let the app automatically create the intermediary beacon positions, choosing suitable waypoints such as pedestrian crossings.

Contributions

Primary objectives:

- Evaluation of sound themes (WP3, WP6)
- Evaluation of various headphones (WP3, WP6)

Secondary objectives:

- Contributed with support for the Bose Frames to the Soundscape Community application. The feature has been accepted and merged into the upstream code-base.
- Contributed the routing feature for evaluation to the Soundscape Community. The feature was considered to have promise but not sufficiently mature for merging into the upstream code-base.

6.5 Work Package 6: User evaluation and testing

Summative study

The purpose of the study was to evaluate how three spatial 3D audio-based navigation approaches shape users' perceptions of safety and efficiency, as well as their overall acceptance, when guiding them to a driverless vehicle. The study also compared the approaches to identify which was deemed the most effective by users in a real-world scenario. Two of the concepts were built from the components explored during the sound design iterations, while the third mirrored a traditional navigation solution with higher familiarity to everyday users.

The study was conducted in a residential area in Eriksberg, Gothenburg, during the fall of 2025. The study was approved by the Swedish Ethical Review Authority, reference number 2025-03199-01.

Participants
Thirty participants (16 women and 14 men) took part in the study. Their ages ranged from 23 to 62 years (M = 42.7, SD = 12.6). None of the participants had any significant visual or hearing impairments that would affect their ability to navigate or experience the audio concepts.

Design concepts and stimuli
The design concepts were derived from the sound design process described above and consisted exclusively of audio signals and were experienced through headphones:

- **Audio beacon (Freedom to Move)**
  In this concept, participants were guided by a virtual audio beacon positioned in the direction of the destination. Participants were free to choose their route to the destination, but by turning their heads they could continuously hear the direction of the destination.

- **Turn-by-turn audio signal (Safety First)**
  In this concept, participants received guidance through audio signals indicating when to turn. The signals were presented as spatial vectors—a sweeping sound pointing toward the direction of the turn. Participants also received continuous feedback indicating whether they were walking in the correct direction toward the next turn, conveyed through a musical rhythm that changed if they deviated from the intended direction. The tempo of the music was reduced when approaching pedestrian crossings and walkways.

- **Turn-by-turn verbal**
  In this concept, participants were guided through spoken instructions such as "continue straight," "turn left," and "turn right." During turns, the audio was presented in the left or right ear accordingly. Prior to a turn, participants received a brief advance warning indicating that a turn would occur in 10 meters. This concept most closely resembled existing navigation solutions on the market and was therefore considered the baseline condition in the study.

In all design concepts, participants could hear the surrounding environment by using the transparency (pass-through) mode of the headphones.

Equipment

Participants experienced the audio concepts using headphones (Apple AirPods Max). Audio cues were triggered using a Wizard-of-Oz (WOz) procedure, in which a test leader manually triggered audio signals via a dedicated system and interface. Participants also carried a mobile phone that logged positional data and walking speed.

Procedure

The study employed a within-subjects design in which all participants experienced all three design concepts, with full counterbalancing to prevent order effects. Participants walked three different routes, one for each design concept.

Before the test began, participants were informed about the purpose of the study, the procedure, safety aspects, and their rights as research participants. Written informed consent was then obtained. Participants also completed an initial background questionnaire on a tablet.

During the test, participants experienced the three audio concepts on different routes. Navigation was performed solely through audio delivered via headphones, without any visual support such as maps or screens. Each route took approximately 5–10 minutes. During the trials, participants were accompanied at a short distance by two test leaders: one responsible for test facilitation and safety, and the other responsible for controlling the audio signals (WOz setup). No verbal communication occurred during the navigation tasks.

After completing each route, participants filled out a questionnaire regarding their experience of the specific navigation solution. Once all three solutions had been tested, participants completed a comparative questionnaire and then took part in a short semi-structured interview discussing their overall experiences and comparisons between the concepts. Each test session lasted approximately 60 minutes per participant.

Data Collection

Data were collected through questionnaires, interviews, behavioral logging via the mobile phone, and observations made by the test leader. The following primary methods were used to measure the effects of the design concepts:

Traffic Safety

- Questionnaire ratings of perceived traffic safety, distraction, and attention
- Test leader observations recorded in an observation protocol
- Interview data
- Behavioral data from the mobile application

Navigation Efficiency

- Ratings of perceived ease of navigation
- Behavioral data from the application
- Interview data

User Experience

- Self-Assessment Manikin (SAM): emotional experience
- NASA Task Load Index (NASA-TLX): workload
- User Experience Questionnaire Short (UEQ-S): user experience
- Van der Laan Acceptance Scale: acceptance
- Rating of feeling of freedom

Results

Below, the most central results from the analysis are presented. The analysis was largely based on questionnaire data and interview findings. Questionnaire data were analyzed using statistical methods, while interview data were analyzed using thematic analysis.

General

The Turn-by-turn verbal concept received more positive ratings than the other two concepts across all dependent variables in the study, including perceived traffic safety, acceptance (measured using the Van der Laan Acceptance Scale), workload (NASA-TLX), and emotional response (SAM). The difference was particularly pronounced between Turn-by-turn verbal and the Audio beacon concept. These findings indicate advantages of implementing speech-based interfaces and turn-by-turn solutions for navigation, at least in an urban context where users are navigating toward a waiting vehicle.

Preference

The majority of participants preferred Turn-by-turn verbal, while the Audio beacon was the least preferred. Speech-based guidance also received higher acceptance ratings. Several factors emerged from the interview data:

- Overall, participants emphasized arguments related to the pragmatic quality of the concepts, that is, their ability to support the navigation task effectively. Aspects such as efficiency, clear guidance, and low interface-related cognitive load were central to preference. In other words, reaching the destination easily, efficiently, and without challenges was considered most important

- Experiential aspects (hedonic quality) were also found to influence preferences. The Audio beacon appeared to offer a higher experiential value, whereas Turn-by-turn verbal was described as boring. Many participants experienced the Audio beacon engaging, game-like search experience. However, opinions on its suitability for this type of navigation scenario were mixed. The results further suggest that the Audio beacon may be more suitable for freer navigation in open spaces, rather than in an urban street network with obstacles, as in the present study

- Overall, the findings suggest that pragmatic quality was prioritized when participants evaluated their preferred solution. Participants considered it important to arrive on time and to experience low cognitive load, allowing them to attend to the surrounding environment and traffic. However, some participants valued the experiential qualities of the Audio beacon or Turn-by-turn audio signals highly enough to prefer these over verbal cues. Thus, preference appears to depend on both situational factors and individual differences

- Nudging toward traffic-safe behavior, such as reducing walking speed at pedestrian crossings, was effective for many participants and was generally perceived as a positive and appreciated feature

Traffic Safety

The Turn-by-turn verbal concept received more favorable ratings with respect to perceived traffic safety. The interview data revealed several contributing factors:

- Perceived traffic safety was strongly influenced by how much the interface loaded the user's attention and mental resources, which in turn affected their ability to monitor the surrounding environment. The amount of auditory information also played a role, as excessive sound could both mask environmental cues and become distracting

- Auditory nudging signals may produce both positive and negative effects. For example, a reduction in walking speed can increase safety when crossing streets. At the same time, an Audio beacon guiding users toward the target may encourage more diagonal street crossings for some users. Nudging users to orient their head in a specific direction during navigation may also affect their ability to scan the environment and maintain traffic-safe behavior

- Supporting users' situational awareness and short-term planning by providing brief "heads-up" cues shortly before an action was required was perceived as particularly beneficial in turn-by-turn solutions

- Familiarity with similar navigation solutions appeared to have a positive effect, perhaps because it introduced lower mental load

Sense of Freedom

Participants reported that the Audio beacon concept provided a greater sense of freedom than the other concepts. The interview data highlighted the following aspects:

- A sense of freedom emerged when users were able to make their own navigation choices, which favors solutions such as the Audio beacon. Highly explicit instructions and strong system control were perceived as reducing this aspect of sense of freedom

- At the same time, many participants appreciated clear instructions and feedback, as these increased feelings of safety and confidence in the navigation. Knowing that one is on the right path was often considered desirable. Navigation solutions may therefore benefit from balancing autonomy with sufficient information to ensure users feel confident they will arrive on time

- Familiarity with similar solutions contributed to both a sense of freedom and safety, as users could easily understand the interface and infer how it would behave in case of navigation problems

- High cognitive load, for example due to unclear signals, reduced the sense of freedom by shifting attention toward the interface and the navigation task itself, rather than toward the surrounding environment.

Conclusions

This study compared different audio-based approaches for guiding users to a vehicle in an urban environment. By conducting the study in a real-world setting, high ecological validity was achieved. The results provide several key insights into the use of audio for this type of navigation.

For the majority of users, speech-based guidance with simple and clear instructions offered advantages in terms of acceptance and perceived traffic safety. Efficient guidance, low mental workload, and a reduced risk of making navigation errors were highly prioritized when navigating in urban contexts. In this respect, the verbal turn-by-turn interface performed most favorably.

Turn-by-turn navigation was particularly well suited for this application. Both verbal and spatial 3D audio cues can function effectively within such solutions, although speech-based guidance showed slightly more positive effects in this study.

Audio beacon solutions, which guide users toward a target using spatial 3D sound, appear more suitable for open environments and particularly situations where engagement and experiential value are prioritized, such as playful or exploratory navigation. The findings suggest that navigation interfaces should be adapted to the specific context and task requirements.

Familiarity with speech-based navigation systems seemed to provide a baseline advantage, whereas novel audio interfaces required learning. Navigating using 3D audio cues is new for most users. This highlights the importance of considering onboarding and learnability when introducing new audio navigation concepts.

Interface-related cognitive load was perceived as particularly problematic for both preference and perceived safety. Continuous or non-essential audio was also experienced as distracting and could interfere with users' ability to perceive environmental sounds. On the other hand, supporting short-term planning, such as providing brief cues shortly before an action was required, and nudging through tempo changes at pedestrian crossings were perceived as positive contributions to traffic safety.

Finally, a greater sense of freedom was associated with less restrictive guidance, favoring beacon-based solutions. However, increased mental effort to interpret such interfaces could also reduce the sense of freedom by drawing attention away from the surrounding environment.

Demo and discussion with users with visual impairments

Purpose and objectives

In the last phase of the work package, the project held a reference group with people with visual impairments. The participants were recruited due to their experience of navigating with visual impairments. The purpose of the reference group was to collect feedback on the developed concepts, to understand the needs and areas of improvement to be useful for this user group.

Participants

The reference group consisted of five participants (3 men and 2 women) with severe visual impairment or blindness. All participants had previously used technical solutions for navigation, such as google maps or other applications for navigation.

Design concepts and stimuli

The reference group used the same design concepts and stimuli as in the main user evaluation, see 6.5.

Equipment

The reference group used the same equipment as in the main user evaluation, see 6.5.

Procedure

In the references group sessions, all participants tried the three different design concepts. Due to safety, they didn't navigate a planned route, instead they stood up and rotated to experience the spatial sound experience. After they tried the different design concepts, they got interviewed about the experience and their thoughts connected to use for the user group people with visual impairments.

Results

Below, the most central results from the analysis are presented. The analysis was based on interview findings from the reference group.

Preferences

The reference group clearly expressed a preference for a combination of the different solutions to better address the needs of the user group for people with visual impairment. While audio-based navigation cues were appreciated, certain types of information were considered more suitable to be conveyed through spoken instructions, such as information about upcoming navigation events and surrounding environments. Participants mentioned that even though voice instructions were appreciated, they preferred if they were used sparingly and primary in connection to navigation events, as excessive spoken instruction may be perceived as distracting. Auditory cues were considered suitable for indicating correct route alignment, information about decreasing distance to upcoming events, and the occurrence of those events.

Sound design

Overall, the sound design in the concepts was positively received. Some participants expressed that they preferred less rhythmic sounds and instead favored clicking or beeping sound to indicate correct directions to avoid unnecessary non information audio cues. Others wished to retain a rhythmic character but to increase more low-frequency sounds. The tempo used in the solutions was considered good. The changes in tempo (as in turn-by-turn audio signals) at pedestrian crossings and at destination were appreciated, although participants noted that these changes could be made more pronounced to better suit the user group.

Among the evaluated concepts, turn-by-turn audio signal was the most preferred in terms of sound design. However, the soundscape was described as too intensive for prolonged use and would therefore require adjustments. The reference group emphasized that auditory cues can be more pleasant to navigate with, but that it needs to be designed in a way that it doesn't override ambient environmental sounds. It was also highlighted that having a subtle, background-lever sound would be beneficial, allowing the user to navigate with the solution even during conversations with others.

Precise navigation

It was noted that participants appreciated that the turn-by-turn audio signal and audio beacon concepts provided the user with more precise navigation information the simpler left or right directions that turn-by-turn verbal and common GPS solutions.

Flexibility in sound design

A wish for a soundscape that is being adapted to the characteristics of the route was expressed by several participants. For example, longer uninterrupted stretched without navigation events could be accompanied by a lower-intensity soundscape.

Another aspect to be aware of when designing navigation solutions for people with visual impairments is that they often experience a higher demand in cognitive load while navigating. Therefore, it is important that the sound design is well balanced and that users are given the ability to adjust sound intensity, both in terms of overall volume and individual sound components, on order to accommodate different needs. Which was mentioned by the participants as important.

Need for wider range of information

To better serve the user group it was expressed that the solution needs to provide a wider range of information types. This includes more detailed information about specific events, such as guidance while crossing a street, as well as richer descriptions of the surrounding environment. Examples of such detailed environmental information include curbs, stairs, pedestrian crossings, bicycle racks, and street names. During the reference group discussions, participants expressed a wish for real-time environmental scanning using cameras, where AI-based systems could provide audio descriptions of the surroundings.

Proactive information

A need for more proactive information about upcoming navigation events was expressed by the participants. There was a shared preference for receiving earlier notifications about turns. This was expressed both by participants with and without guide dogs. For users with guide dogs, earlier notifications were considered important in order to support a smoother walking pace and avoid abrupt directional changes. They preferred to get early information about a turn or crossing in spoken language but expressed that after that the guidance about the decreasing distance could be communicated by auditory guidance.

Traffic safety

In relation to traffic safety, the following aspects were identified as particularly important. It was emphasized that the solution must allow users to clearly perceive surrounding environmental sounds. This requirement concerns both technological aspects (such as the user of transparent or open-ear headphones) and sound design considerations (for example, a less intensive sound design). This aspect was considered particularly critical.

Participants also highlighted the risk of developing an overreliance on audio-based navigation solutions, which may guide the user correctly but doesn’t warn the user about obstacles in the environment. Some participants expressed that this could lead to reduced focus on navigation with the white cane for environmental scanning. However, some participants perceived audio-based navigation to lower the risk of false sense of security compared to a solely spoken language-based solution. In connection to false sense of security, the importance of visibility of system status was mentioned as a crucial aspect for safety.
Therefore, constant cadence in audio feedback was considered necessary to ensure that the users remain “in the loop” and can be assured that the guidance is still present.

Possible areas for development

The participants also discussed other areas where these concepts could be useful for the user group.

- **Indoor navigation**
  Participants believed that these concepts could be suitable for indoor navigation as well. For the target group, navigation in indoor environments can be challenging due to the lack of GPS functionality. A potential area for further development could be to explore applications for indoor settings, such as hospitals.

- **Sailing**
  Sailing was mentioned as an area where the solutions could be beneficial. Today auditory beacons are currently difficult to rely on when sailing due to weather conditions and wind. The project concept of headphones connected to auditory beacons could potentially be applied in a sailing context to improve navigational support.

Conclusion

The reference group study highlights the potential of audio-based navigation concepts to support people with visual impairments, while also emphasizing the need for careful design. The results show that a combination of continuous auditory cues and selective spoken instructions is preferred, as different types of information are best conveyed through different modalities. Spoken instructions were considered most useful for proactive and complex navigation events, while non-verbal sounds were preferred for conveying direction, distance, and route confirmation.

Sound design was identified as an important factor. Participants valued subtle, non-intrusive soundscapes that allow awareness of environmental sounds and long-term use without increased cognitive load. The ability to adapt sound intensity and characteristics to both the route and individual user preferences was seen as essential, reflecting the diverse needs within the user group.

The findings also underscore the importance of proactive information and traffic safety. Early notifications about upcoming events were considered necessary to support smooth and safe navigation, while maintaining continuous but unobtrusive feedback helped users remain aware of system status. At the same time, the risk of overreliance on audio-based guidance highlights the need for solutions that complement existing mobility strategies. Overall, the study concludes that effective audio-based navigation for people with visual impairments should prioritize flexibility, balanced information delivery, and safety. The study also identified possible areas for further development of solutions such as indoor navigation and sailing.

7. Dissemination and publications

7.1 Dissemination

During the project, several disseminations were done:

- A master's thesis and presentation titled “Guided by Sound – Exploring the use of spatial auditory cues for pedestrian navigation in urban environments”, conducted at Volvo Cars and Chalmers University of Technology.
- A video film documenting the student project “Design concept for a sound experience for a future self-driving car” conducted at RISE and Luleå University of Technology
- Presentation of a student's project at Framnäs Folkhögskola within their intro course in Game music - “How sound could enhance a longer transit journey by sonifying the destination and surroundings” with a concept reflecting the values and brand identities of Arctic Bath and Volvo Cars
- An article published on the Ictech AB website and on LinkedIn: “Kan hörlursbaserat 3D-ljud göra delad mobilitet säkrare och mer tillgänglig?”1.
- Workpackage 5 engaged a bachelor student from the Software Technology program at Linnaeus University, Växjö, as part of a full semester work experience course. That work resulted in a bachelor thesis (to be published):
- B. B. Mawan, “Geofencing: Investigating the accuracy of elevation-aware geofencing algorithms for smartphones,” Bachelor thesis, Dept. Comput. Sci. Media Technol., Linnaeus Univ., Växjö, Sweden, 2026.

Planned dissemination

- A presentation within the framework of SAFER (Vehicle and Traffic Safety at CTH) is scheduled for February 2026

7.2 Publications

Papers will be written focusing on the results from the summative test.

[1] LinkedIn: https://se.linkedin.com/posts/ictech_fr%C3%A5n-id%C3%A9-till-prototyp-activity-7396896964216344577-vuK
Ictech website: https://ictech.se/2025/09/24/fran-ide-till-prototyp-sa-formar-vi-framtidens-tillgangliga-mobilitet/

8. Conclusions and future research

The user studies in the EARS project led to the following key conclusions:

- Turn-by-turn guidance was perceived as the safest and most user-friendly approach. This type of audio navigation provided clear instructions, reduced uncertainty in urban environments, and was widely accepted across users with different levels of experience and abilities.

- Spatial "audio beacon" guidance created a more engaging and enjoyable user experience but also imposed a higher cognitive load. Users found it intuitive and fun in simpler or more open environments, but more demanding in complex traffic situations.

- No single audio solution is suitable for all situations. The results indicate that different 3D audio navigation approaches are appropriate for different contexts and purposes for example, precise and safe navigation versus exploration and experiential orientation.

- Participants with visual impairment confirmed the strong potential of audio-based navigation, while emphasizing the need for high precision, clear structure, and adaptability to avoid cognitive overload.

In summary, the user studies showed that 3D audio can improve safety and user experience in future mobility services, but that solutions should be context-aware and adaptable to best support diverse users and situations.

The knowledge and concepts developed in the project will be taken further and continued to be developed by the project partners, both within their respective organizations and through ongoing collaboration between partners where relevant. Project partners already have, or will have, continued cooperation based on the concepts created in the project.

The following research areas are considered particularly relevant for future research:

- Future research should explore how AI-based support, including generative AI, can improve usability and user experience in future mobility services by adapting information and interfaces to user needs and contexts. Key questions include how to design effective human–AI interaction and how multimodal communication, such as sound cues and spatial audio, can enhance the experience beyond text and voice.

- EARS explored how spatial audio can enhance the experience of traveling to a visitor destination by linking the car journey with the destination through new sound-based experiences. The project identified promising potential in the developed concepts, but no user evaluations were conducted. Future research should further investigate how this application of sound can improve user experience during car travel.

- Based on the results of EARS, several areas related to sound design and user experience need further investigation. One aspect concern how prior familiarity with a specific type of solution influences user acceptance and preference for that solution. EARS also demonstrated that different forms of nudging through changes in sound signals affected both user experience and safety. Future research should explore this opportunity in greater depth.

9. Participating parties and contact persons

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