

# Multimodal Approach to Enhance the Navigation System of the Shared E-scooter

Transforming E-scooter Navigation for Safer and Smoother Rides

Master's thesis in Computer science and engineering

Peiran Wei



MASTER'S THESIS 2025

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UNIVERSITY OF  
GOTHENBURG

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CHALMERS UNIVERSITY OF TECHNOLOGY  
UNIVERSITY OF GOTHENBURG  
Gothenburg, Sweden 2025

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Cover: Schematic diagram of multimodal interaction in riding scenarios.

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## Abstract

Shared electric scooters are an important component of sustainable urban transportation, yet current navigation systems rely heavily on smartphone screens, introducing safety risks and usability limitations. This thesis addresses these issues by designing and evaluating a multimodal navigation interface that integrates ground-projected augmented reality (AR) with auditory instructions and a visual user interface display (UI).

A user-centered design process guided the development of the prototype. Initial qualitative research: interviews and on-site observations to identify user pain points and contextual needs. Then, through quantitative analysis, this study deeply investigates the common issues and riding habits of users. Iterative design phases produced concept sketches and wireframes, leading to a final system featuring AR turn arrows projected onto the ground, synchronized audio prompts, and a mobile screen interface for route overview.

The design prototype was evaluated in a controlled study involving 30 participants, comparing six configurations ranging from single-modality (e.g., user interface display only) to multimodal combinations. The results indicated that the configuration integrating augmented reality (AR), audio interaction, and user interface (UI) display achieved the highest cognitive efficiency ( $E=0.84 \pm 1.20$ ) and the lowest mental workload (NASA-TLX= $33.35 \pm 16.81$ ), demonstrating statistically significant improvement over all other tested setups. The UI-only system produced the lowest efficiency ( $E=1.46 \pm 1.08$ ) and the highest cognitive load. Statistical tests confirmed these differences across performance, effort, and perceived frustration. Participant feedback further validated the design: 18 out of 30 preferred the AR and audio combination, describing it as intuitive, fast, and less distracting. The visual UI was primarily used for route previews at rest points, not during active riding.

These findings highlight the potential of multimodal navigation systems: especially those that integrate projected AR and audio-for improving safety, usability, and rider satisfaction in shared micromobility systems. This work contributes a validated interaction model and design framework for future urban mobility applications.

Keywords: Multimodality in Interaction Design, User Experience, Shared E-scooter, Navigation Systems, Cognitive Efficiency



## Acknowledgements

As I approach graduation, I want to express my heartfelt gratitude to everyone who has been part of my study-abroad journey. I still vividly remember the excitement and joy I felt two years ago when I received the admission email for the Chalmers scholarship. At that time, I was sitting in my university's finance office, designing B2B interaction projects. From the end of the pandemic and the lockdown in Shanghai to my sudden resignation, I spent days watching videos of Nordic natural scenery on YouTube, dreaming of studying there someday. Lucky enough, that dream came true. When I first arrived, everything felt fresh, but academic pressures and environmental adjustments overwhelmed me for the first half year. Still, I learned to find peace in this new environment. I was fortunate to meet Professor Jasmina, whose guidance and support over these two years have been invaluable. I also want to thank Thommy, the academic director, for lending us VR equipment during our experiments, which was crucial to completing our research. To Gergeoisthough I often misspelled his name thank you for patiently reviewing our thesis progress every week. His dedication to our work often made me feel like I was pursuing a doctoral project, but it truly honed my academic rigor. Thank you, my supervisor! To my friends who walked alongside me for these two years: thank you for taking the time to participate in my thesis interviews and tests. To the strangers and classmates I met in the library and invited to join my study: your help was indispensable. Without you, I couldn't have recruited 30 participants for testing or gathered the data that shaped my research. I also want to thank my emotionally stable self, the self who persevered through challenges, and the self who has always loved music. Music has been my anchor: there were countless late nights when I wanted to give up, seething with frustration at seeing others carefree lives, unable to write a word. But after singing at home for two hours, I'd find the calm to push forward with my thesis. Finally, I hope the future holds bright prospects for me.

In this thesis, we utilized large language models (LLMs) such as GPT-4o, DeepSeek, Qwen, and Kimi to assist with language output and expression. Given that none of the authors are native English speakers, these AI tools were occasionally employed to explain concepts. The use of AI has contributed to a more standardized and rigorous writing style, ensuring adherence to academic writing conventions while minimizing linguistic errors to the greatest extent possible.

Peiran Wei, Gothenburg, 2025-11-05





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# 1

## Introduction

With the rapid growth of the sharing economy and urban micromobility services[1], shared electric scooters have become an integral part of sustainable transportation globally (Figure 1.1) to solve <sup>1</sup>"the last 10 yards problem". This service not only promotes environmentally friendly travel, but also helps alleviate urban traffic congestion. However, despite its growing popularity, the interaction design for navigation systems used in e-scooters remains underdeveloped and does not address critical safety concerns [1] and User Experience concerns [2].



Figure 1.1: E-scooters are ubiquitous in Stockholm and Gothenburg (the figure shows the e-scooters of the VOI brand.) <https://www.itsinternational.com/its17/its8/news/vianova-boost-micromobility-stockholm>

### 1.1 Related Work

In light of the recent prevalence of the sharing economy and the surge in the use of e-scooters, the exploration of multimodal interaction in navigation systems has emerged as an area of active research over the past seven years (since 2017), with diverse applications and approaches being investigated.

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<sup>1</sup>The last 10 yards problem in micromobility refers to the final moments of a user's journey, where the rider must transition from riding to reaching their exact destination often on foot or through confusing or constrained environments.

In 2017, during the conference "Defining Multimodal Interactions: One Size Does Not Fit All", Google addressed the application of multimodal interaction in its design. Starting from the perspectives of input and output, as well as users' capacity channels, Google put forward the following three guidelines:

- If one mode goes away, the other should take over
- Optimize for the strongest mode, but allow both
- Leverage the strength of each mode and avoid redundancy across modalities

In 2017, Lock and colleagues proposed a multimodal interaction approach for aiding blind individuals in navigation[3]. This method involved attaching sensors to the arms, hands, and body of the visually impaired and providing navigation assistance through auditory and haptic feedback. This multimodal interface was implemented on Google's Project Tango device developed using Android and Tango SDKs. While this approach offers significant convenience and inclusivity, it may prove cumbersome for everyday cycling scenarios. Additionally, there is the Assistive Sensor Solutions for Independent and Safe Travel (ASSIST) indoor navigation system in 2018[4].

The EyeBeacons system (2019) is a framework for multimodal wayfinding communication that makes use of wearable devices. This framework employs three distinct modalities: aural, tactile, and visual to convey navigation instructions[5]. It consists of three main components: a bone-conduction headset, a smartphone, and a smartwatch. The smartwatch is utilized to detect wayfinding messages presented as vibrations. However, the participants who tested the system reported that differentiating between vibrations and audio tunes was challenging.

HapAR(2020) is a mobile augmented reality application designed to guide users within a university campus. Users can initiate the application by issuing a voice command to Siri[6]. Once the system receives the request, it processes it and attempts to locate the user's point of interest. When the user nears the destination or any area of interest, both aural and haptic feedback mechanisms are activated. However, user feedback indicated that the sound feedback was often drowned out by outdoor environmental noises, such as wind and the chatter of people.

The Vibro-Audio map(2020) put forward by facilitating environmental learning, the development of cognitive maps, and wayfinding behavior. Vibro-Audio map made use of a low-cost, touchscreen-based multimodal interface on a commercial tablet. It served as an instance of a digital interactive map created using vibro-tactile and auditory information. The tablet device's built-in vibration motor was utilized to generate haptic (vibro-tactile) output. However, the results of this study were restricted solely to indoor building environments[7].

Andrii Matviienko et al. (2022) conducted a comparison. Using situations with no warnings as a baseline at intersections with approaching vehicles, they compared three unimodal warnings for e-scooter riders[8]. The augmented reality warning presents a text "Warning! Detected Car getting close." (left), the auditory warning gives out beeping signals (middle), and the vibrotactile feedback is activated on

the grips of the handlebar (right)(Figure 1.2). Their results indicate that AR and auditory warnings lead to shorter reaction times, have better perception, and create a better feeling of safety than vibro-tactile warnings. Moreover, auditory signals have a higher acceptance by the riders compared to the other two types of warnings.



Figure 1.2: Unimodal Warnings for E-Scooter Riders in Augmented Reality

Miao, Ning and colleagues (2022) conducted research focusing on the use of haptic interaction to enhance bike traffic safety. Their study aimed to increase cyclists' awareness of traffic information and improve their overall safety. To achieve this, they implemented user interaction methods involving head-mounted displays and wearable haptic displays for bicycle riders.[9].

Tabatabaie and colleagues (2024) proposed a Cross-modality E-scooter Naturalistic Riding Understanding System, namely CENRUS, from a human-centered AI perspective(Figure 1.3).

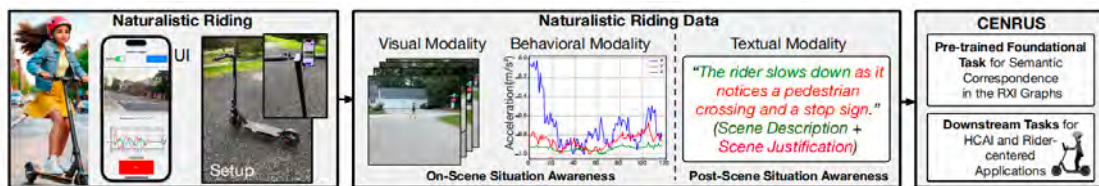


Figure 1.3: Naturalistic riding setup including user interface (UI) and e-scooters, data, and the pre-trained foundation task[10]

Yucheng and colleagues (2024) presented an embodied navigation with multi-modal information with three main components: *Perception and Memorization*, *Multi-modal Information Understanding*, and *Action Decision-making*(Figure 1.4).

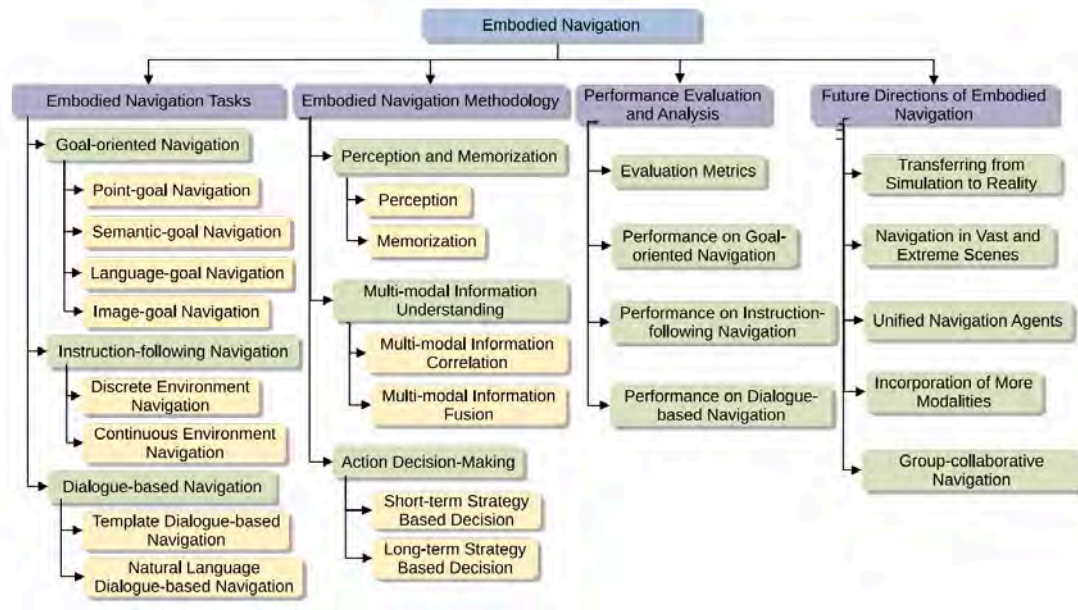


Figure 1.4: Framework of embodied navigation research[11]

In 2025, Kazemzadeh, K. conducted an online video experiment and polled 920 e-scooter users in Sweden [12] and investigated the perception of safety which focus more on the riding habits and road situations, ignoring the scooter itself and human interaction. What's more, shared e-scooter brands in Sweden such as Voi, Ryde, and Lime primarily focus on addressing the placement of smartphones. However, during the riding process, users often rely on third-party applications like Google Maps for navigation.

It is evident that the safety issues of shared e-scooters have consistently drawn significant attention from researchers, with numerous strategies proposed to address them. However, when it comes to interaction methods and the overall riding experience, neither companies nor researchers have made substantial breakthroughs or proposed effective solutions. Therefore, this study holds promising theoretical and practical value from the multimodality aspect.

## 1.2 Purpose

Multimodal interfaces are generally intended to deliver natural and efficient interaction[13]. This thesis aims to use a multimodal interaction approach to design and evaluate the navigation system tailored to the unique challenges of shared E-scooters. By integrating different modality such as visual, auditory, and haptic feedback, we aim to develop a more intuitive, safer, and efficient interaction design. The results of this research can contribute to the fields of human-computer interaction and urban transportation by offering a novel approach to improving micromobility navigation systems.

- Designing a multimodal interface that combines visual, auditory, and haptic feedback for seamless navigation.

- Ensuring the system is compatible with existing e-scooter hardware, providing reliable data for the e-scooter providers.
- Conducting user-centered evaluations to assess system performance and usability.

### 1.3 Problem Statement

Currently, riders often rely on their smartphones as primary navigation tools, mounting them on handlebars, or holding them while riding, which creates significant distractions and unsafety on the road (Figure1.5). As for usability concerns, most users use navigation provided by Google Maps or other third-party software. Usually, voice navigation or interface-based navigation is used as the interaction method. For voice navigation, when used on noisy or complex roads, users may not be able to hear the navigation clearly due to background noise. As for interface-based navigation, when used in open outdoor environments, users are prone to being distracted, and the interface may be over-exposed, making it difficult to identify the information. In summary, the interaction methods provided by a single channel have usability deficiencies.



Figure 1.5: Rider holds the smartphone to navigate when riding which may trigger accidents

Through literature research and on-site observation( Figure1.6), the existing interaction problems during the riding can be classified into two major categories: safety issues and experience issues.



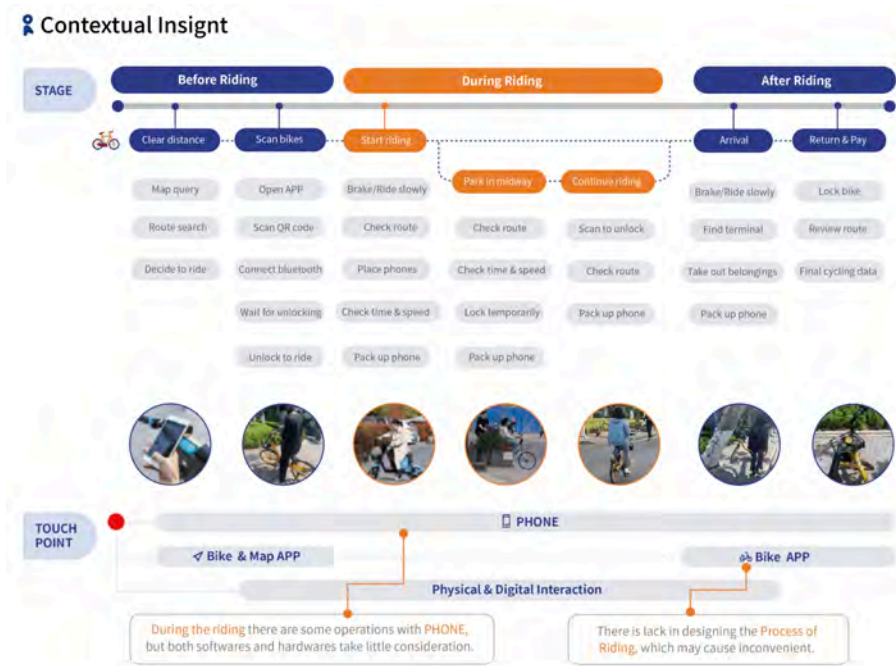


Figure 1.6: Riding User Journey Analysis

## 1.3.1 Safety Concerns

- **Distraction:** According to Badeau et al. [14], the majority type of injuries (44 %) occurred on sidewalks, lacking of concentration on their way. One major reason from our observation is that riders must visually interact with their smartphones for navigation, diverting their focus from the road.
- **Single Modality Limitations:** Although audio navigation is an option, it can isolate the user from ambient traffic sounds, compromising safety.

## 1.3.2 User Experience Concerns

- **Lack of Interaction from User Input:** Existing navigation systems primarily rely on one-way communication, delivering information to the user without considering their real-time input or context. For example, changes in the riders speed, environment, or road conditions are not accounted for, making the system static and less adaptive to dynamic situations.
- **Overload of Information:** Multimodal integration also referred to as the fusion engine, which is the key technical challenge for multimodal interaction systems[13]. Visual and auditory instructions often overwhelm users by providing too much information at once, leading to cognitive overload. Riders may struggle to process excessive or irrelevant details during their trips, detracting from the overall usability of the navigation system.

## 1.4 Research Objectives and Questions

Through preliminary research, we define several research questions to discuss.

**RQ1: In what ways does multimodal interaction enhance both user safety and user experience in navigation systems for shared mobility?**

Underlying position: Multimodal interaction in shared mobility navigation systems enhances user safety and user experience through multiple pathways. However, the realization of these enhancements is constrained by the inherent limitations of multimodal systems in recognizing the number and type of input modes[15]. Despite users generally showing a preference for multimodal over unimodal interaction, the specific design of a multimodal interface may not enable them to issue every command multimodally.

**RQ2: Which modality is dominant when riding and in what contexts? What modality synergies can we construct from observation studies, and what prototypes can we develop to facilitate multimodal interactions?**

Underlying position: In the cycling scenario, users' visual attention is mainly drawn to the road environment. Therefore, their attention to navigation mainly focuses on auditory interaction. However, in unfamiliar and unpredictable scenarios, users may rely on visual and interface interaction to determine their location. When users are interacting with roads that are stable, they may tend to use tactile interaction, as it is often more convenient and natural.

**RQ3: Would the number of navigation output modalities during cycling affect users' safety and user experience?**

Underlying position: There may be a certain learning curve for more than one input modality at the beginning, and it may also impose a certain cognitive load on users in complex scenarios. However, once users have learned it, the interaction will be more convenient and faster. After riding a certain number of times, users may gradually adapt and start to feel the increased efficiency.

## 1.5 Ethical Considerations

The proposed multimodal navigation system aims to be fair, inclusive, sustainable, and ethical by prioritizing the safety and usability of shared e-scooter navigation. By integrating visual, auditory, and haptic feedback, the design ensures accessibility for a diverse range of users, including those with varying abilities or sensory preferences. The project adopts a user-centered approach, ensuring that feedback from real-world users informs the system's development, which promotes inclusivity and relevance.

From a sustainability perspective, the system utilizes existing hardware, minimizing resource waste and supporting eco-friendly urban mobility trends. However, as societal values around safety and convenience evolve, the design must continuously

## 1. Introduction

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adapt to new mobility practices. For instance, balancing privacy with personalized navigation could pose challenges. Overall, the system strengthens urban micro-mobility by enhancing safety and user experience, fostering trust and engagement in sustainable transportation options.



# 2

## Background

### 2.1 Micromobility and E-scooter

In recent years, micromobility has emerged as a significant trend in urban transportation worldwide (Figure 2.1), revolutionizing the way people move within cities[16]. This shift is driven by a combination of factors, with e-scooters and shared-bikes being a prominent and rapidly evolving component of the micromobility landscape. According to the International Transport Forum (2020)[17], micromobility can be defined as "Personal transportation that makes use of devices and vehicles with a weight of up to 350 kg. In the case of powered ones, their power supply is gradually decreased and completely cut off once a certain speed limit, which does not exceed 45 km/h, is reached."



Figure 2.1: Overview of the free-floating e-scooter offer in the world during 2019(6T-Research office, 2019)

Traditional modes of transportation, such as cars and buses, often contribute to traffic jams, air pollution, and longer commute times. Micromobility solutions offer

## 2. Background

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solutions for first and last-mile connectivity, as well as assisting in the reduction of traffic [18]. For example, in cities like Shanghai and Beijing, where traffic congestion has become a major concern, e-scooters and shared-bikes provide a convenient way for commuters to cover short-to-medium-distance trips, avoiding the gridlock on major roads.

With growing awareness of environmental issues, there is a global push towards sustainable transportation. E-scooters and bikes are an eco-friendly alternative to gasoline-powered vehicles. They produce zero tailpipe emissions during operation, helping to improve air quality in urban centers. This aligns with the broader goals of many cities to reduce their carbon footprint and combat climate change.

Today's consumers, especially the younger generation, value convenience, flexibility, and shared experiences. Micromobility services, often provided through mobile apps, offer seamless access to e-scooters. Users can locate, unlock, and ride an e-scooter with just a few taps on their smartphones. This on-demand nature of the service fits well with the modern lifestyle. Moreover, the sharing economy model behind e-scooter services appeals to consumers who prefer not to own a vehicle but still want the freedom to move around easily.

In response to the growth of micromobility, many cities and regions are adjusting their transportation policies and regulations. In most European countries (such as the Czech Republic, all Scandinavian countries, Poland, and Italy), e-scooters are legal and are categorized as bikes. According to the Swedish Transportation Agency[19], in Sweden, an e-scooter can be regarded as a bike provided that it does not surpass a speed of 25 km/h and has a maximum engine power of 250 Watts. However, in Germany, Austria, Spain, Belgium and France, e-scooters are classified in a separate category. For instance, in Germany, e-scooters are a new category of vehicles that is similar to light mopeds and bicycles [20]. Some areas have introduced dedicated bike and scooter lanes to ensure the safety of micromobility users. Others are implementing rules regarding helmet use, parking, and speed limits for e-scooters. These regulatory changes are aimed at balancing the benefits of e-scooter use with the need to maintain traffic safety and order.

Despite the rapid growth and potential benefits, e-scooters also face challenges. During the period from April to August 2019, 14% of the people who were examined in hospitals in Stockholm had been injured in traffic accidents involving e-scooters[21]. Among these accidents, Andreas et al found that most of the e-scooters is not associated with an increase in pedestrian or bicycle accidents but are predominantly involved in accidents with cars[16]. Issues such as sidewalk clutter due to haphazard parking, safety concerns related to rider behavior and vehicle-pedestrian collisions, and the need for proper maintenance of the scooters are areas that require further attention. However, as the micromobility industry continues to evolve, these challenges are likely to be addressed through technological innovation, better user education, and more refined regulations.

## 2.2 Multimodal Interaction

### 2.2.1 Human Behavior and User Experience

Human interaction with the world is inherently multimodal[22].For instance, when we are in a conversation, we do not just rely on the spoken words (auditory modality). We also pay attention to the facial expressions (visual modality) and body language(a visual-kinesthetic modality) of the speaker, which can convey emotions such as happiness, sadness, or surprise.

The advent of multimodal interfaces based on recognition of human speech, gazes, gestures, and other natural behaviors represents only the beginning of a progression toward computational interfaces capable of relatively human-like sensory perception(Figure 2.2) [15].

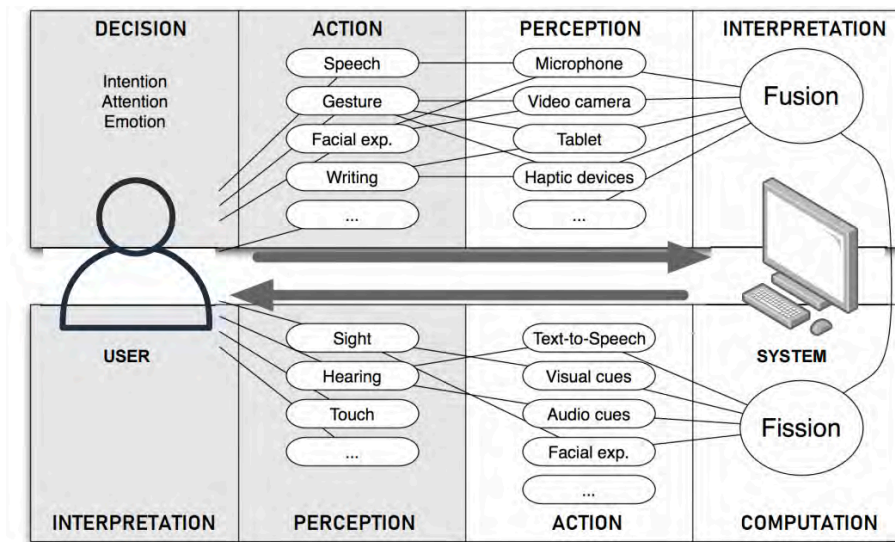


Figure 2.2: Human decision and relation with modality interaction(adapted from[23])

In the past, human-computer interaction mainly focused on unimodal interactions, like pure voice-dialogue systems, graphical user interface (GUI) interactions with mouse or keyboard operations, and touch-based interactions on touch-screen devices. The advantage is that with technological maturation, norms were set for these interactions, and users developed consistent mental models. For example, people now instinctively know that double-clicking an icon opens a program or swiping on a touch-screen performs certain actions, which eases the learning and adoption of new technologies.

Although unimodal interaction is simple and specialized, with the increasing complexity of life scenarios and the widespread popularity of ubiquitous mobile computing, a single interaction modality can no longer meet people's needs. Multimodal interfaces, which coordinate the processing of combined natural input modes such as speech, touch, hand gestures, eye gaze, and head and body movements, represent a

research-level paradigm shift away from conventional windows-icons-menus-pointers (WIMP) interfaces toward providing users with greater expressive power, naturalness, flexibility, and portability[24].

In 2000, Oviatt et al.[25] pointed out eleven advantages of multimodal interaction:

- They permit the flexible use of input modes, including alternation and integrated use.
- They support improved efficiency, especially when manipulating graphical information.
- They can support shorter and simpler speech utterances than a speech-only interface, which results in fewer disfluencies and more robust speech recognition.
- They can support greater precision of spatial information than a speech-only interface since pen input can be quite precise.
- They give users alternatives in their interaction techniques.
- They lead to enhanced error avoidance and ease of error resolution.
- They accommodate a wider range of users, tasks, and environmental situations.
- They are adaptable during continuously changing environmental conditions.
- They accommodate individual differences, such as permanent or temporary handicaps.
- They can help prevent the overuse of any individual mode during extended computer usage.

Multimodal interaction ought to be personalized, enhancing the user experience by making it more unique. For instance, Siri(Figure 2.3) has the ability to recognize the distinct voice of the phone's owner and then engage in interaction with the user.

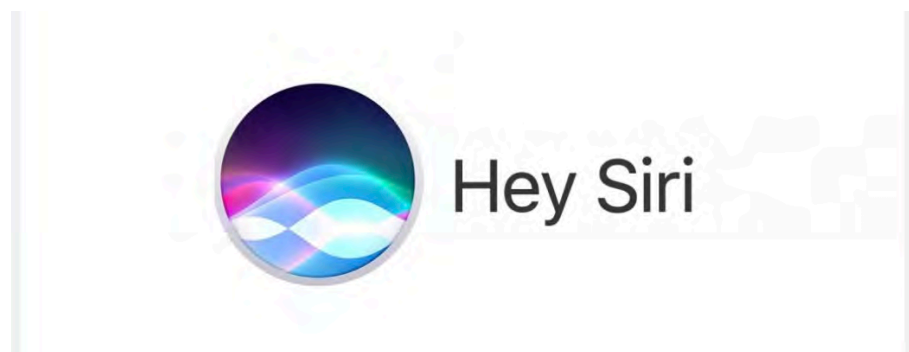


Figure 2.3: Voice mode of Apple's Agent: Siri experience

## 2.2.2 Factors in Multimodality

In 2017, during the conference "Defining Multimodal Interactions: One Size Does Not Fit All", Google addressed four main factors that influence multimodality:

- **Motion:** Specifically, when compared to bicycle riding, e-scooter riding was associated with more severe vibration events, irrespective of the types of pavement[26].
- **Environment:** In noisy settings, voice commands, and hand gestures work together to clarify user intent as sound can be hard to hear. In hands-free or immersive AR, VR, and MR environments, gaze-based input combines with touch or speech. Different environments determine the best input modality combinations, showing that the environment significantly influences how users interact with systems and how systems are designed to fit various scenarios.
- **Proximity:** In multimodal interactions, the physical distance between the user and the interface plays a crucial role. When using an e-scooter, the user's proximity to the display, handlebars, and other interaction points determines which input methods are most effective. For instance, while touchscreens might be viable when stationary, voice commands or haptic feedback become more practical during motion. Similarly, proximity influences the responsiveness of location-based features, such as navigation prompts that adjust based on the user's real-time position and movement.
- **Human Capacity:** Factors such as cognitive load, attention span, and motor skills affect how users process and respond to multiple interaction modes simultaneously. For e-scooter riders, balancing navigation assistance with situational awareness is essential: overloading them with complex auditory or visual cues can lead to distractions and potential safety risks. An effective multimodal design optimizes interactions to align with human capabilities, ensuring that users can seamlessly interpret and act upon the provided information while maintaining focus on the riding experience.

What's more, modality fusion is also a crucial topic in designing a better and more seamless interaction. Precisely coordinating the integration of diverse input modalities is essential to guarantee that they enhance one another instead of creating conflicts. This process encompasses intricate input synchronization, modality fusion, and context awareness. All these aspects necessitate sophisticated algorithms and machine-learning techniques[27].

Fusion can take place at various levels, as depicted in Figure 2.4, contingent upon the system's requirements. Early-stage or sensor-level fusion entails merging the raw data originating from different modalities during the initial processing phase[28]. One key element of modality fusion is dealing with conflicts that arise between different inputs. In situations where modalities offer conflicting information, for example, when a gesture indicates one object but speech refers to a different one, the system has to figure out which input should be given precedence[29].

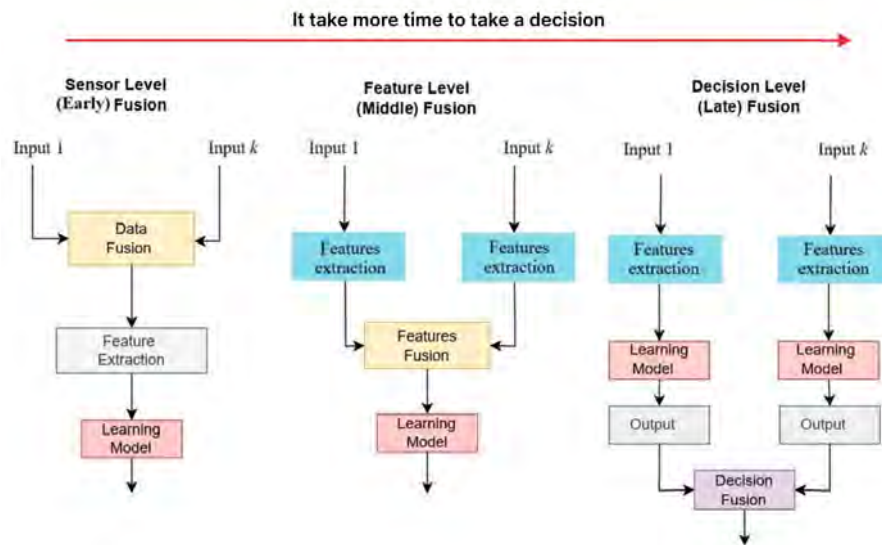


Figure 2.4: An overview of different levels of modalities fusion (adapted from [28])

### 2.2.3 Technology Development

Advancements in sensor technology and computing technologies have been instrumental in the growth of multimodality interaction in various applications, including virtual assistants, intelligent environments, healthcare, and accessibility technologies[27]. High-resolution cameras, microphones, and touch-sensitive surfaces are now commonly integrated into devices, enabling accurate detection of user input across different modalities. For example, modern smartphones are equipped with front-facing cameras that can recognize facial expressions and gestures, adding a new dimension to user interaction.

As vision-based technologies mature, one important direction is the development of blended multimodal interfaces that combine both passive and active modes[15]. Moreover, AI makes contributions to multimodal systems through its capacity to adapt dynamically to both user behavior and environmental contexts[30].

The Internet of Things (IoT) and augmented reality (AR) are widely popular technologies. They enable interaction systems to integrate the real-world context of the user (agent) with immersive AR content[31]. AR functions by visualizing graphical objects within the view of the real world. Usually, the view is presented through a real-time camera feed on a device or a head-mounted display (HMD)[32].

As multimodal interfaces gradually evolve toward supporting more advanced recognition of users' natural activities in context, they will expand beyond rudimentary bimodal systems to ones that incorporate three or more input modes, qualitatively different modes, and more sophisticated models of multimodal interaction[15]. This trend already has been initiated within biometrics research, which has combined recognition of multiple behavioral input modes[33].

Furthermore, more scientists are exploring emerging sensory technologies like brain-computer interfaces (BCIs)[34].

In summary, multimodality interaction has now become a fundamental aspect of modern technology design, with the potential to create more inclusive, intuitive, and user-friendly experiences for everyone. As technology continues to evolve, the field of multimodality interaction is likely to expand further, incorporating new modalities and applications.

## 2.3 Navigation Systems

The cognitive process of "navigation" is composed of two main elements: locomotion and wayfinding. Locomotion pertains to the physical movement of a person within their immediate environment. Wayfinding, on the other hand, is the process of devising a plan to reach a specific destination[35].

### 2.3.1 Unimodal Navigation Systems

Typical unimodal navigation systems can be classified into four distinct types by interaction, as noted in [11]:

- **Point-goal navigation:** This type of navigation task was initially put forward by Anderson et al. in [36]. In point-goal navigation, the user simply drags and clicks on a point within a map to navigate to a specific location.
- **Semantic-goal navigation:** Here, the navigation goal is described in semantic terms. For example, a user might be given the task 'find a restaurant'. This requires the system to understand the semantic concept of a restaurant and guide the user to a relevant location.
- **Language-goal navigation:** In language-goal navigation, the destination is defined by a short sentence. A common example is "GO TO X", where "X" usually refers to an object or a room. The system must interpret the natural language instruction to determine the correct navigation path.
- **Image-goal navigation:** Zhu et al.(2017) designed the first image-goal navigation task and proposed a framework for it. In this type of navigation, an environment with high-quality 3D scenes and a physics engine is presented for embodied AI agents. The task is to find a target object that is represented by a previously shown image. The agent must analyze the visual features of the image and search for the corresponding object in the 3D environment[37].

### 2.3.2 Multimodal Navigation Systems

Vainio stated that multimodal navigation systems offer users the flexibility to provide inputs or receive outputs in their preferred modality [38]. For instance, in a noisy setting, when receiving directions, vibratory feedback can prove more effective than aural feedback. On the other hand, if the user desires to obtain more details about the navigation environment, like landmarks and traffic signs, audio might be a more appropriate option.



Visual maps offer several benefits as a navigation tool. They can provide an overall view of an environment and have a high information density. In recent decades, many promising technologies have come to the fore, aiming to replace visual maps. These include point and sweep gestures, spatial sound, tactile information, and other multimodal alternatives.

Tactile maps enable users to access geographical representations. While these maps are valuable for acquiring spatial knowledge, they also have certain drawbacks. For example, they often require the user to be able to read braille, which limits their accessibility to those who are proficient in this reading system[39].

Baus et al. [40] presented a hybrid navigation system that relies on visual and haptic modalities to determine the users location and that adapts the presentation of route directions to the limited technical resources of the output device and the limited cognitive resources of the user(Figure 2.5).

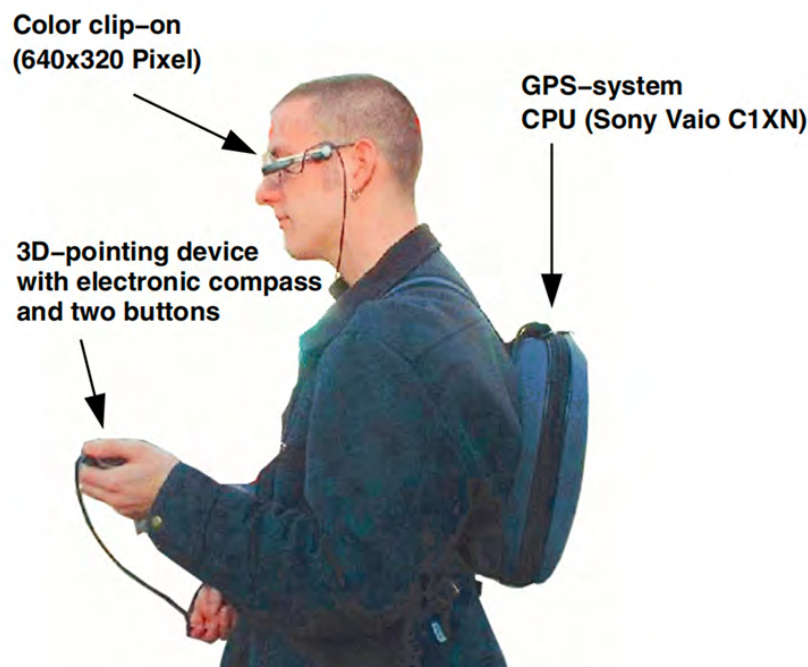


Figure 2.5: The system architecture of the hybrid navigation aid

## 2.4 Stakeholders

### 2.4.1 E-scooter Riders

They are the primary end-users of the e-scooter navigation system. Their safety, convenience, and overall riding experience are directly affected by the navigation system. They expect a navigation system that is easy to use, provides accurate directions, and does not cause distractions while riding. For example, a commuting rider in a busy urban area needs a navigation system that can quickly adapt to traffic changes and guide them to their destination safely.



### 2.4.2 Pedestrians

According to Matús Sucha et al., approximately 20-30% of e-scooter riders ride on sidewalks, regardless of whether it is permitted. Those who do not ride e-scooters are inclined to claim that riding an e-scooter is quite dangerous. With the exception of Australians, pedestrians view e-scooter riders and the operation of e-scooters as irritating[41].

### 2.4.3 E-scooter Providers

Companies like Lime, Bird, and Voi are major stakeholders. They are interested in providing a high-quality service to their customers. A well-designed navigation system can enhance customer satisfaction, leading to increased ridership and loyalty. Moreover, they need a system that is compatible with their existing e-scooter hardware and can provide data on user behavior, such as popular routes and riding patterns. This data can help them optimize their fleet deployment and service offerings.

### 2.4.4 Urban Planners

They are concerned with the integration of e-scooters into the existing urban transportation infrastructure. A good navigation system can influence the way e-scooters are used in the city, potentially reducing traffic congestion and improving the overall flow of urban mobility. For instance, if the navigation system can direct e-scooter riders to less congested routes, it can help in better traffic management. Urban planners also need to ensure that e-scooter usage aligns with the development of bike lanes, sidewalks, and other transportation-related urban features.

### 2.4.5 Other stakeholders

Policymakers, who set regulations governing e-scooter operations; safety advocacy groups, which push for safety-enhancing features in the navigation system; and technology developers, who are responsible for innovating and improving the multimodal navigation technology, all play crucial roles as other significant stakeholders in the e-scooter navigation ecosystem.

## 2.5 Existing Solution

### 2.5.1 Google Maps

- **Route Planning:** Google Maps offers comprehensive route planning for e-scooter riders. It takes into account factors such as distance, estimated travel time, and traffic conditions. For example, it can calculate the fastest route to a destination, considering both major roads and smaller, less-congested streets that are suitable for e-scooter travel. It also provides options for different types of routes, such as the shortest route or the route with the least amount

## 2. Background

of elevation change, which can be beneficial for e-scooter riders conserving battery power.

- **Visual Interface:** Google Maps has a highly visual interface. Riders can view their current location, the route to their destination, and nearby points of interest on a detailed map. The map is designed to be easy to read, with clear markers for turns, intersections, and destinations. However, in the context of e-scooter riding, the visual interface can be a distraction when riders need to look at their smartphones while on the move.
- **Voice Navigation:** It offers voice-based navigation, where turn-by-turn instructions are provided through synthesized speech. This allows riders to keep their eyes on the road while getting directions. However, as mentioned earlier, in noisy urban environments, voice instructions can be difficult to hear, especially when riding at higher speeds or in areas with a lot of background noise.

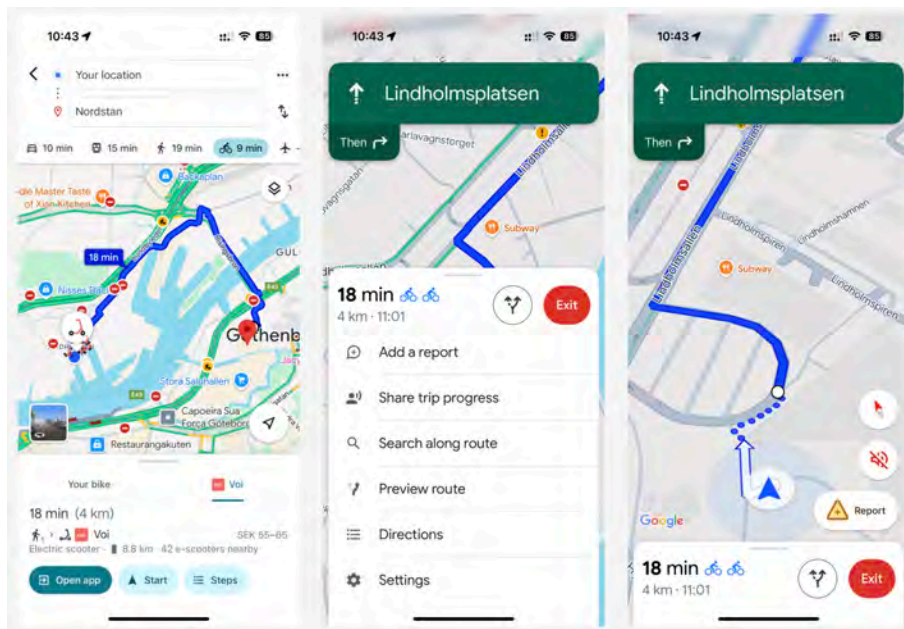


Figure 2.6: Google Maps: IOS version 18.0

### 2.5.2 Ryde

- **Navigation Experience:** The navigation feature in the Ryde app is essential for helping users find their way while riding, but it presents some usability challenges. Currently, users rely on a map-based interface that requires them to glance at their phones for directions, which can be inconvenient and distracting while riding. Unlike standalone navigation apps like Google Maps, Ryde does not provide clear, continuous voice guidance, making it harder for users to follow directions without stopping. Additionally, the interface does not seem optimized for quick decision-making, as turn indications can sometimes be unclear, especially in complex urban areas with multiple intersecting

roads. A more intuitive design with larger, more visible directions or a simplified navigation view could improve usability, making it easier for riders to follow their route safely without frequent screen interactions.

- Platform Differences: IOS vs. Android:** The user experience of the Ryde app differs depending on whether it is used on iOS or Android devices, affecting how easily users can find and use the navigation feature. On iOS, the app follows Apples interface guidelines, making navigation tools more visually consistent and accessible. Users may find it easier to locate the map view and start a ride, as the layout appears more refined with smooth animations and predictable interactions. Additionally, Apple Pay integration simplifies the unlocking process, allowing for a quicker start to the ride. On Android, however, there are noticeable variations in performance and design consistency. Some users report that map rendering takes longer to load, and the navigation feature may be slightly harder to find due to different menu placements. The app may also behave inconsistently across different Android devices due to varying screen sizes and system optimizations. These differences can create an uneven experience, making it less convenient for some users to quickly access navigation and start their ride without delays. Improving consistency across both platforms, particularly in how navigation is presented and accessed, would enhance overall usability and ensure a more seamless experience for all users.

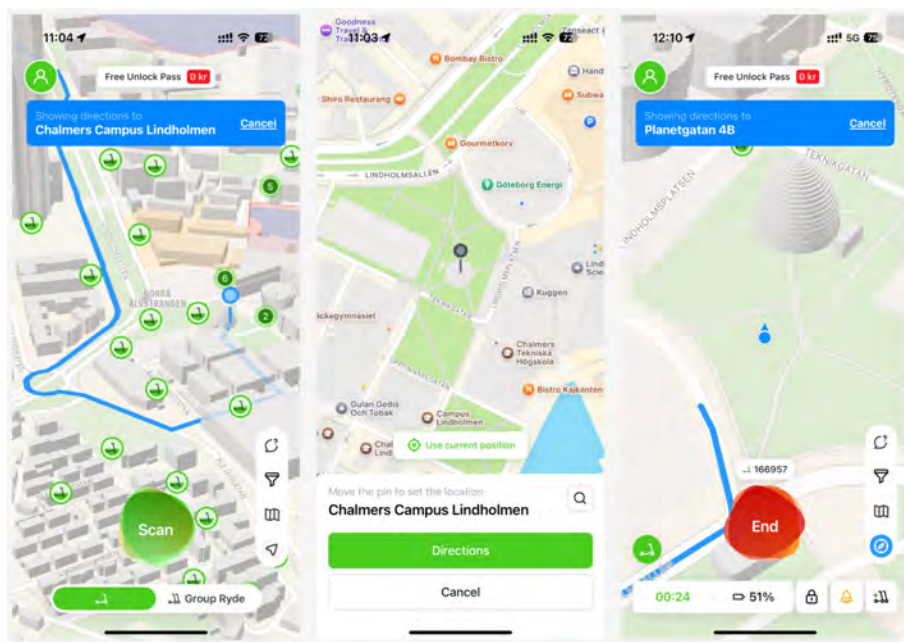


Figure 2.7: Ryde Application: IOS version 18.0

### 2.5.3 VOI

Major developments have occurred in the hardware and software needed to support key component technologies incorporated within multimodal systems, as well as in techniques for integrating parallel input streams[15].

## 2. Background

The latest Voi ride has added a new interface, but the current interaction mode is still a single-channel solution at the visual level (Figure 2.8).



Figure 2.8: Hardware of VOI 7

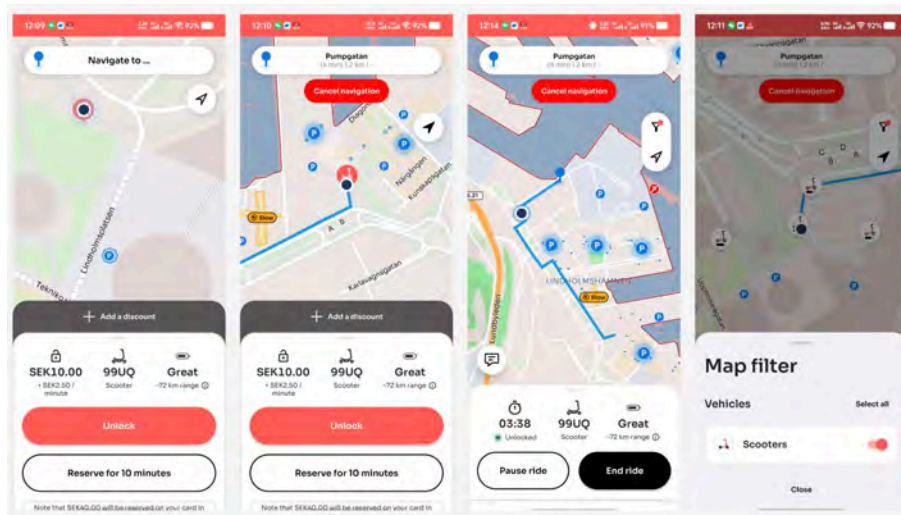


Figure 2.9: Hardware of VOI 7

# 3

## Theory

### 3.1 User-Centered Design Theory

User-centered design (UCD) is a design approach that places users at the core of the development process, ensuring that products meet their needs, preferences, and limitations[42]. The UCD framework emphasizes iterative design, usability testing, and feedback loops to refine and optimize interactive systems. In the context of shared e-scooter navigation, UCD ensures that multimodal interfaces are designed based on user requirements, considering factors such as cognitive load, safety, and ease of use[43].

### 3.2 Cognitive Load Theory

The cognitive science-related theories on intersensory perception and intermodal coordination provide a foundation of information for user modeling, as well as information on what systems must recognize and how multimodal architectures should be organized [15].

Cognitive Load Theory (CLT) centers on creating instructional strategies. These strategies aim to effectively utilize the restricted cognitive processing capabilities of people, allowing them to transfer the knowledge and skills they've learned to new and unfamiliar circumstances[44][45].

CLT is founded on a cognitive architecture. This architecture comprises a working memory that has a limited capacity and partially independent processing units for visual and auditory information. Moreover, this working memory interacts with a long-term memory that has an essentially unlimited capacity[46].

### 3.3 Design Guidelines of Multimodal Interaction

Creating multimodal systems is challenging, as the typical design choices and intuitions from standard computing environments do not necessarily translate well to multimodal environments.

Oviatts "Ten Myths of Multimodal Interaction" [24] offers useful insights for those researching and building multimodal systems, with a few especially apropos:

*Myth1: If you build a multimodal system, users will interact multimodally.*

Rather, users tend to intermix unimodal and multimodal interactions. Fortunately, multimodal interactions are often predictable based on the type of action being performed.

*Myth2: Multimodal input involves simultaneous signals.*

Multimodal signals often do not co-occur temporally, and much of multimodal interaction involves the sequential (rather than simultaneous) use of modalities.

*Myth3: Multimodal integration involves redundancy of content between modes.*

Complementarity of content may be more significant in multimodal systems than redundancy.

*Myth4: Enhanced efficiency is the main advantage of multimodal systems.*

Multimodal systems may increase efficiency, but not always. Their main advantages may be found in other aspects, such as decreased errors, increased flexibility, or increased user satisfaction.

*Myth5: Individual error-prone recognition technologies combine multimodally to produce even greater unreliability.*

In an appropriately flexible multimodal interface, people determine how to use the available input modes most effectively; mutual disambiguation of signals may contribute to a higher level of robustness.

Reeves et al. [47] defined the following guidelines for multimodal user interface design:

*Multimodal systems should be designed for the broadest range of users and contexts of use.*

Designers should support the best modality or combination of modalities anticipated in changing environments (for example, private office vs. driving a car).

*Designers should take care to address privacy and security issues in multimodal systems.*

For example, non-speech alternatives should be available in a public context to prevent others from overhearing information or conversations.

*Maximize human cognitive and physical abilities, based on an understanding of users' human information processing abilities and limitations.*

For example, match the output to an acceptable user input style, such as constrained grammar or unconstrained natural language.

*Multimodal interfaces should adapt to the needs and abilities of different users, as well as different contexts of use.*



Individual differences (for example, age, preferences, skill, sensory or motor impairment) can be captured in a user profile and used to determine interface settings.

*Be consistent in system output, presentation and prompts, enabling shortcuts, state switching, etc.*

## 3.4 Related Concepts

### 3.4.1 Input and Output modalities

Humans primarily interact with the world through their five major senses sight, hearing, touch, smell, and taste. In perception, a mode or modality refers to receiving stimuli from a particular sense[13].

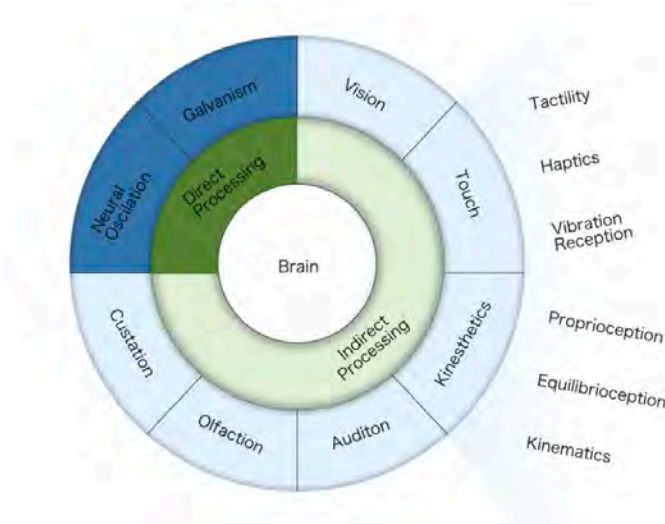


Figure 3.1: Taxonomy of interaction modalities proposed by Augstein and Neumayr[48]

### 3.4.2 Cognitive Efficiency

According to Pass et al., there are three main aspects to measure the cognitive load[49]:

- *Mental load* is the aspect of cognitive load that originates from the interaction between task and subject characteristics.
- *Mental effort* is an element of cognitive load. It pertains to the cognitive capacity that is actually assigned to meet the demands set by a task. As a result, it can be regarded as a reflection of the real-time cognitive load.
- *Performance*, which is another aspect of cognitive load, can be defined by a learner's accomplishments. These include metrics like the number of correct test items, the number of errors made, and the time spent on the task. Per-

formance can be evaluated either while individuals are engaged in a task or after they have completed it.

$$E = \frac{z_{\text{Performance}} - z_{\text{Mental Effort}}}{\sqrt{2}} \quad (3.1)$$

An instructional condition efficiency score (E) is calculated. This score is determined as the perpendicular distance between a dot-represented by the z-score for mental effort and the z-score for performance-and the diagonal line where E =0 (Figure 3.2). The formula used for this calculation is based on the general formula for finding the distance from a point p(x, y) to a line ax+by+c=0. In this case, the square root of 2 in the formula is derived from that general distance-calculation formula.

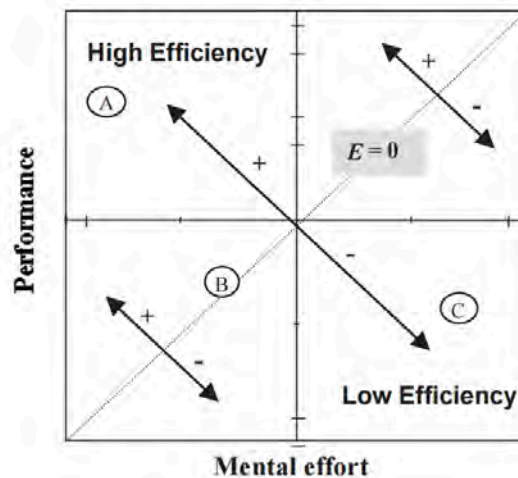


Figure 3.2: Graphic presentation used to visualize instructional efficiency[50]

**3.4.2.0.1 NASA-task load index** NASA-task load index(NASA-TLX)[51] consists of six subscales that represent somewhat independent clusters of variables: Mental, Physical, and Temporal Demands, Frustration, Effort, and Performance(Figure 3.3).



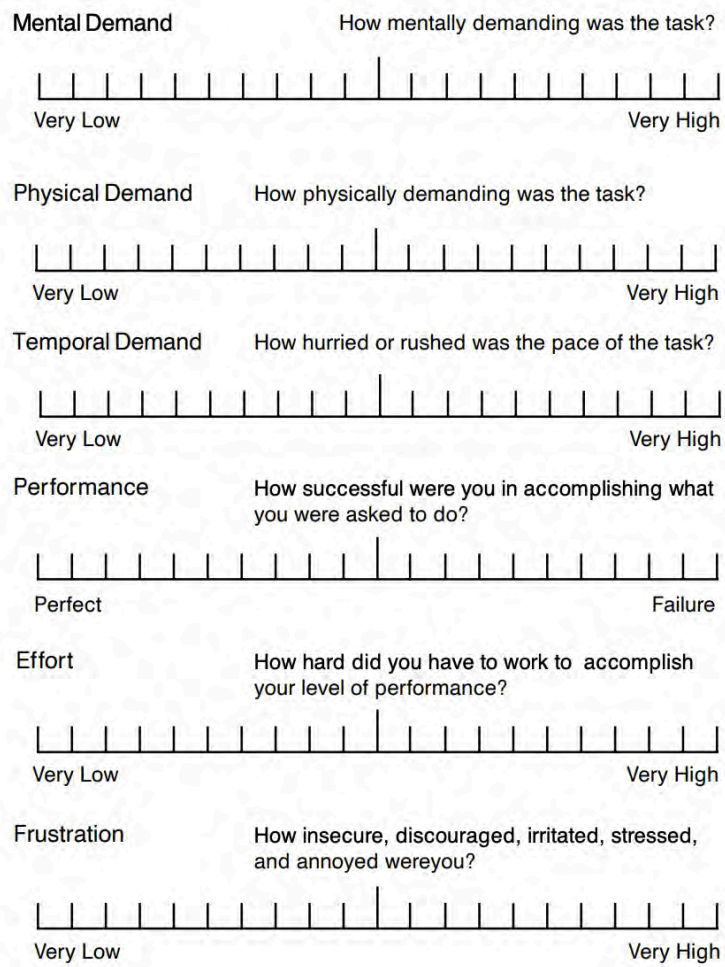


Figure 3.3: NASA-task load index[48]



# 4

## Methodology

To investigate how a multimodal approach can enhance the interactive navigation system of shared e-scooters, this study employs a mixed-methods research design combining qualitative and quantitative techniques. The methodology is structured as follows:

### 4.1 Research Approach

A Research through Design (RtD) approach will be employed. As Gaver (2012) discussed in "What Should We Expect From Research Through Design?", research through design acquires insights into specific issues via design practice. The theories it generates tend to be provisional, context-specific, and inspiring [52]. This approach enables us to continuously explore and discover new possibilities during the iterative design of the multimodal navigation system, rather than merely relying on pre-established theoretical frameworks. Moreover, Gaver pointed out that research through design is generative and is more concerned with creating what might be. This aligns with our goal of enhancing the shared e-scooter navigation system through design innovation, helping us break free from traditional thinking and create a better navigation experience for users.

### 4.2 Design Approach

This study adopts a user-centered design (UCD) methodology, ensuring that the navigation system improvements align with user needs and behaviors. By applying UCD principles, this study aims to design a multimodal navigation system that enhances user experience while minimizing distractions. Through iterative prototyping and user evaluations, the system will be refined to align with real-world navigation challenges faced by e-scooter users.

### 4.3 Design Process

The design process follows the Double Diamond framework (Figure 4.1), a structured approach to problem-solving that consists of four phases: Discover, Define, Develop, and Deliver. This methodology ensures a balance between user research, ideation,

prototyping, and refinement, leading to a user-centered navigation system for e-scooter riders[53].

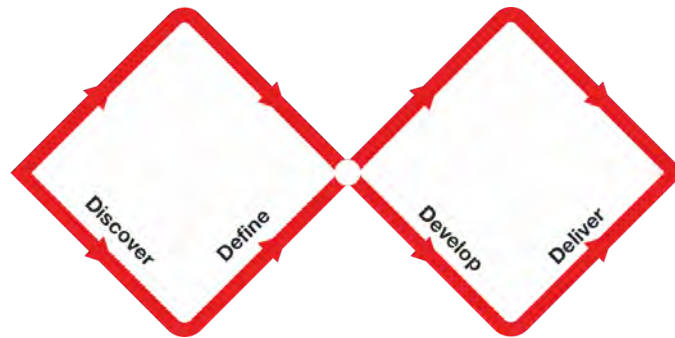


Figure 4.1: Double Diamond Model from Design Council[54]

### 4.3.1 User Research

To develop a user-centered navigation system that effectively addresses the needs of e-scooter riders, various research methods will be employed. These methods will provide both quantitative and qualitative insights into user preferences, navigation challenges, and real-world behaviors. The combination of surveys, interviews, and observational studies will ensure a well-rounded understanding of user needs, guiding the design and refinement of the system.

#### 4.3.1.1 Questionnaires

Questionnaires will be distributed to e-scooter users to gather quantitative data on their current navigation experiences, preferences, and expectations. These structured forms will include multiple-choice questions, Likert scale ratings, and open-ended responses to assess key aspects such as the frequency of navigation use, common pain points, and desired improvements. By reaching a broad audience, surveys will help identify patterns in user behavior and highlight recurring challenges, such as difficulties in following turn-by-turn directions or distractions caused by smartphone-based navigation. The results will inform design decisions by prioritizing the most common user concerns.

#### 4.3.1.2 Interviews

To gain deeper qualitative insights, semi-structured interviews and focus groups will be conducted with e-scooter users. These discussions will explore context-specific challenges that may not be fully captured in surveys. Interviews will provide in-depth perspectives on user frustrations, safety concerns, and feature preferences, while focus groups will facilitate interactive discussions, allowing participants to compare their experiences and suggest potential improvements. These conversations will help ensure that the system is designed to align with actual user needs and expectations.

### 4.3.1.3 Observational Studies

Field observations will be conducted to analyze real-world navigation behaviors and identify pain points in actual usage conditions. Researchers will observe e-scooter users navigating different environments, such as busy city streets, bike lanes, and pedestrian areas, to assess how they interact with existing navigation tools. Key factors such as how often users check their screens, whether they rely on audio cues, and how they respond to environmental distractions will be documented. These observations will provide unfiltered behavioral data that may not be fully captured through self-reported surveys or interviews.

### 4.3.1.4 First-person perspective

First-person perspective studies will involve equipping participants with wearable cameras or head-mounted devices to record their real-time interactions with navigation tools during rides. This method captures unfiltered, context-rich footage of how users visually scan their environment, engage with UI elements, and divide attention between navigation cues and traffic conditions. By analyzing these recordings, researchers can identify subtle behavioral patterns (e.g., glance frequency, hand movements) that reflect usability issues or cognitive load in naturalistic settings.

## 4.3.2 Problem Definition and Design Goal

Defining the problem accurately is crucial to ensuring the design addresses real user challenges effectively. The research findings from interviews, focus groups, and observational studies will be synthesized using an Affinity Diagram[55] to categorize insights into key themes. This method helps in identifying patterns in user behaviors, pain points, and expectations, allowing for a structured approach to problem-solving.

### 4.3.2.1 Thematic Analysis

Thematic analysis (TA) is a method for identifying, analyzing, and interpreting patterns of meaning (themes) within qualitative data[56]. This method will be applied to qualitative data (e.g., interview transcripts, focus group discussions) to identify, organize, and interpret recurring themes related to navigation experiences. Researchers will systematically code data to uncover patterns in user needs, frustrations, and preferences (e.g., "difficulty interpreting complex visual cues," "reliance on audio instructions in high-risk scenarios"). This iterative process ensures themes are grounded in participant insights, providing a foundation for design requirements that address core user challenges.

### 4.3.2.2 Text Quantitative Analysis

Text quantitative analysis allows the identification of themes and the text relations with semantic analysis[57]. This method will involve using computational tools to quantify and statistically analyze linguistic patterns in open-ended survey responses, first-person perspective and interview data (e.g., word frequency, sentiment scores).

For example, researchers may measure the prevalence of keywords related to "distraction," "clarity," or "safety" to identify dominant user concerns. This approach complements qualitative thematic analysis by offering numerical insights into the salience of specific issues, helping prioritize design improvements based on data-driven trends.

### 4.3.2.3 MoSCoW

The MoSCoW method will be used to prioritize design requirements by categorizing them into four tiers: Must-have (critical for basic functionality, e.g., clear turn directions in high-risk zones), Should-have (important but non-essential, e.g., personalized audio tone options), Could-have (nice-to-have enhancements, e.g., AR-based landmark highlighting), and Wont-have (out-of-scope for this iteration, e.g., social sharing features). This framework ensures resources are allocated to high-impact solutions first, aligning the design process with user priorities and technical feasibility.

### 4.3.3 Design & Ideation

The design and ideation phase is essential in transforming user research insights into actionable design concepts. This phase ensures that the navigation system is developed with user needs at the forefront, allowing for iterative improvements based on real feedback.

Concept development begins with generating initial design ideas informed by user research findings. These ideas are translated into low-fidelity sketches and wireframes, focusing on key navigation features, interface layout, and interaction flows. The goal is to explore multiple possible solutions before refining the most promising ones. By visualizing different approaches early, potential usability issues can be identified and addressed before investing time in high-fidelity prototypes.

### 4.3.4 Prototyping

Prototyping is a critical step in the design process as it allows designers to test, evaluate, and refine ideas before committing to a final solution. According to Lim, Stolterman, and Tenenberg (2008), prototypes serve as both *filters* and *manifestations* of design ideas, helping designers explore specific interactions while narrowing down effective solutions [58].

Prototypes can vary across several dimensions as a manifestation, including [58]:

- **Material:** The substance or medium used to create the prototype, such as paper, digital interfaces, or physical models.
- **Resolution:** The level of detail and refinement, ranges from rough sketches (low resolution) to polished, detailed representations (high resolution).
- **Scope:** The extent of the design aspects covered, whether focusing on a specific component or encompassing the entire system.

Prototypes can also vary across different dimensions as filters, influencing what aspects of a design are tested and refined. These filtering dimensions include:

- **Appearance:** Visual elements and aesthetics of the design.
- **Data:** Information handling and processing within the design.
- **Functionality:** Operational features and behaviors of the design.
- **Interactivity:** The nature and quality of user interactions are facilitated by the design.
- **Spatial Structure:** The arrangement and organization of elements within the prototype, influence how users perceive and interact with the system.

In the context of a multimodal navigation system for e-scooters, prototyping enables iterative improvements, ensuring that design decisions are driven by real user needs and usability testing rather than assumptions. By developing prototypes early, potential usability issues can be identified and resolved before the final implementation, reducing development risks and enhancing the overall user experience.

#### 4.3.4.1 Visual Feedback

The goal is to create clear and easily readable on-screen and even more out-of-screen navigation instructions (such as AR or head-up display) that riders can quickly glance at without distraction. This includes optimizing font size, contrast, iconography, and layout to ensure high visibility, even in outdoor conditions where lighting may vary.

#### 4.3.4.2 Auditory Cues

Since riders cannot always look at a screen, the aim is to design adaptive voice prompts that provide navigation instructions while ensuring ambient traffic sounds remain audible for safety. Factors such as volume control, speech clarity, and frequency adjustments will be tested to create a non-intrusive yet effective audio experience.

#### 4.3.4.3 Haptic Feedback

The advantage of haptic feedback is that users can use it anywhere, anytime, without interrupting others [59]. To further minimize distractions, we are designing vibration-based cues embedded in the handlebars to signal turns, directional changes, or nearby hazards. This ensures that riders can receive navigation guidance without needing to rely on vision or hearing, making the system more accessible and intuitive.

### 4.3.5 Evaluation & Testing

To ensure the effectiveness, safety, and usability of the proposed navigation system, a series of structured evaluation methods will be employed. These assessments will

provide both qualitative and quantitative insights into user experience, cognitive demands, and overall performance compared to existing solutions.

### 4.3.5.1 A/B Testing

A/B testing is a method used to compare two versions of a design to determine which performs better in meeting user needs[60]. In this thesis, A/B testing was employed to compare the original Google Maps navigation interface with the improved navigation interface design. The goal was to evaluate whether the redesigned interface could reduce user cognitive load and improve usability. The study used the NASA-TLX scale to measure mental workload across six dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. Wilcoxon tests were then conducted to assess significant differences between the two interfaces. The results provided empirical evidence for the effectiveness of the redesigned interface in enhancing navigation experience, highlighting whether modifications led to statistically significant improvements in user interaction and cognitive efficiency.

### 4.3.5.2 Cognitive Load Analysis

To measure the mental effort required during navigation, cognitive load analysis will be performed using the NASA-TLX (Task Load Index) tool [51]and the Efficiency equation[49]. Participants will rate different aspects of their cognitive burden, such as mental demand, frustration, and perceived effort, after completing navigation tasks. This analysis will help determine if multimodal guidance reduces cognitive strain, making navigation more efficient and less overwhelming for users.

In this study, the NASA-TLX used default/standard weight assignment, meaning that in the cognitive scale for the user driving task, each parameter was equally assigned a weight of 1/6. The details are as follows:

$$\text{Weighted Score} = \frac{\text{Mental} + \text{Physical} + \text{Temporal} + \text{Performance} + \text{Effort} + \text{Frustration}}{6}$$

### 4.3.5.3 Wilcoxon test

The Wilcoxon test (a non-parametric statistical method)[61] will be employed to analyze ordinal or non-normally distributed data (e.g., NASA-TLX ratings, user preference rankings) collected from paired samples (e.g., comparing mental effort scores between the old and new UI designs). This test helps determine whether there are statistically significant differences in user performance or subjective perceptions across conditions (e.g., low vs. high-risk cycling scenarios) when parametric assumptions (e.g., normal distribution) are not met. By ranking data points and assessing shifts in distribution, the Wilcoxon test provides robust insights into the effectiveness of design modifications while accommodating the studys mixed-methods data structure. When conducting repeated validations across multiple groups to prevent data bias, Bonferonni correction[62] is performed.



$$\alpha_{\text{corrected}} = \frac{\alpha}{\text{number of comparisons}} \quad (4.1)$$

### 4.3.6 Iterative Design

The usability optimization phase is a critical step in refining the multimodal navigation system to ensure a seamless and intuitive user experience. Building on insights gathered from usability testing, we will address key usability issues by identifying pain points, such as confusing feedback cues or inefficient interaction flows, and implementing targeted improvements. A primary focus will be on enhancing feedback mechanisms- visual, auditory, and haptic- by ensuring they are clear, timely, and contextually appropriate to guide users effectively without causing distractions. Additionally, we will streamline interaction flows to reduce cognitive load, making it easier for riders to process navigation instructions quickly and intuitively, even in fast-paced or complex environments. The system interface will be simplified by eliminating unnecessary steps and aligning interaction patterns with users' natural behaviors and expectations. Through iterative design rides, we will continuously test and refine these improvements, ensuring that the final prototype is not only efficient but also user-centered, promoting safety and ease of use in real-world riding conditions.



# 5

## Planning

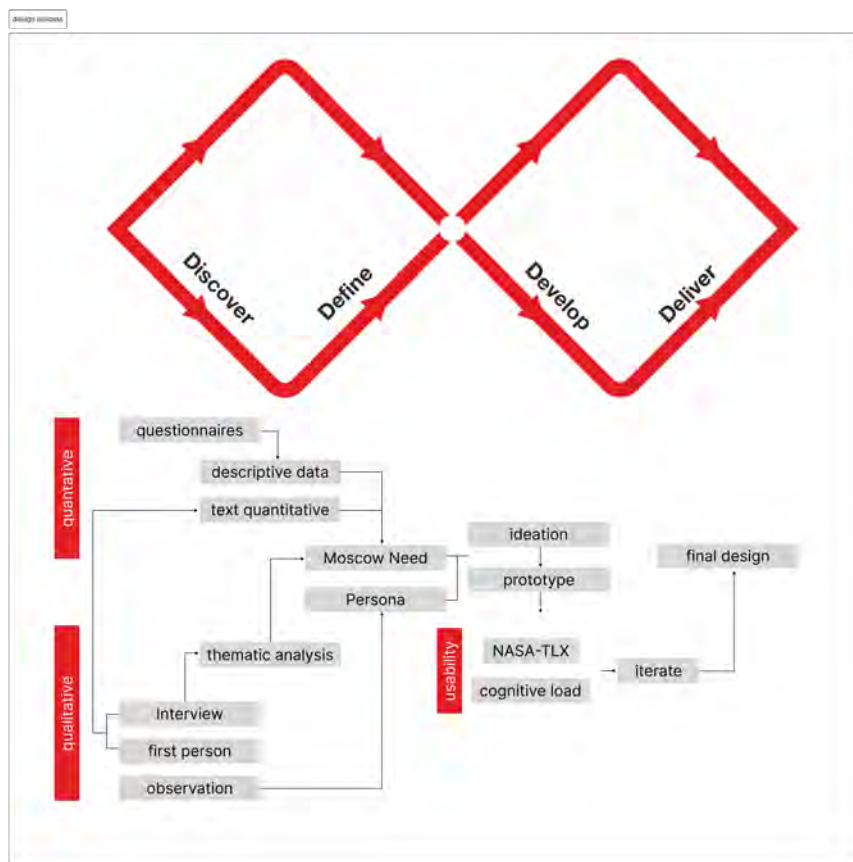


Figure 5.1: Design process and user studies of the thesis

The thesis project follows a structured user-centered design (UCD) methodology, integrating iterative feedback loops to ensure continuous improvement within a compressed three-month timeline(Figure5.1). We chose UCD because it prioritizes user needs, making it particularly effective for designing an intuitive and safe navigation system for shared e-scooters. By continuously involving users in the design process, we can identify usability challenges early, refine solutions based on real feedback, and create a system that aligns with actual rider behavior and preferences. This iterative approach ensures that our final product is not only functional but also enhances user experience and safety in real-world scenarios.

## 5. Planning

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The planning is divided into key phases, some of which overlap to maximize efficiency. The literature review phase lasts for 1 to 2 weeks, focusing on reviewing relevant research on navigation, micromobility, and user-centered design theories. It runs in parallel with the user research phase, which spans 1.5 weeks and involves surveys, interviews, and observational studies to gather insights into user needs and behaviors.

Following this, the design and ideation phase takes place over 1 to 2 weeks, translating research findings into initial design concepts through brainstorming, storyboarding, and wireframing. This phase is crucial because it transforms user insights into tangible design solutions. It is important to explore multiple ideas, test different interaction models, and validate design assumptions before committing to a final approach. A well-executed ideation phase ensures that the navigation system is intuitive, accessible, and aligned with user expectations. Additionally, this phase runs parallel to prototyping, which lasts for two weeks and involves the development of a high-fidelity interactive prototype incorporating visual, auditory, and haptic feedback elements.

Evaluation and testing begin midway through prototyping and last for 1 week. It includes usability testing, cognitive load assessments, and performance benchmarking. The insights gained from testing feed into the data analysis phase, which lasts for half a week and involves qualitative and quantitative analysis of user feedback and performance metrics.

The iteration and refinement phase, lasting 1 week, focuses on making necessary improvements based on evaluation results, ensuring optimal usability. The final phase, documentation and final submission, takes one week, involves the compilation of findings, preparation of the final report, and submission of the thesis.

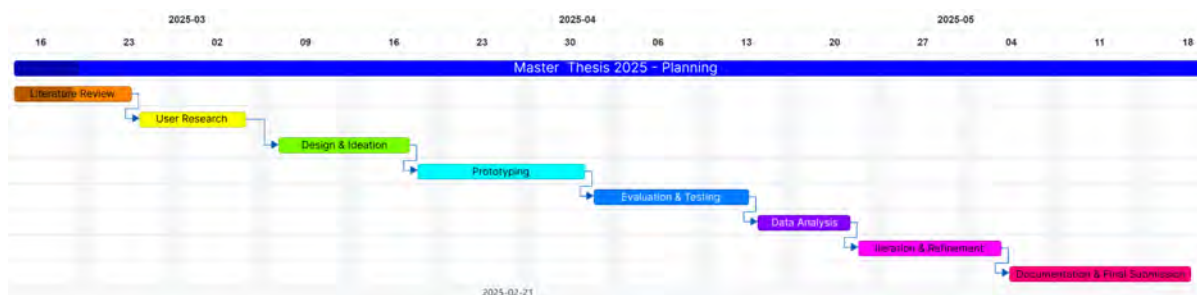


Figure 5.2: Gantt Chart of Planning

# 6

## Execution

### 6.1 User Research

From the "what-how-why" user research framework [63], at this stage, we mainly study the behaviors of users at these three levels to help us define the goals of the navigation systems in e-scooters.

As Christian Rohrer mentioned [64], the research on user experience is mainly divided into a 3-dimensional framework with the following axes:

- Attitudinal vs. Behavioral: This distinction can be summed up by contrasting "what people say" versus "what people do".
- Qualitative vs. Quantitative
- Context of Use

In order to explore the characteristics of user behaviors, this research mainly adopted qualitative analysis methods such as interviews and field investigations to think about the user behaviors at the "why" and "how" levels. Quantitative analysis is mainly used to explore "how many" and "how much", helping us to consider the duality of problems: for example, whether the pain point exists and whether users care about this behavior(Figure 6.1).



Figure 6.1: The user research methods which the thesis conducted

### 6.1.1 Quantitative Research

#### 6.1.1.1 Questionnaires

In this user research, questionnaires were mainly used in the initial stage. The main research objectives are as follows:

- To understand users' usage habits, which helps us define users' main applicable needs for navigation.
- To obtain users' riding behavior patterns and scenarios.
- To explore the riding capabilities and habits of the main user group.
- To understand users' expectations regarding riding safety and experience-side requirements.

In the questionnaire, we mainly divided it into five parts, namely personal information, riding experience, safety perception, navigation and interaction, and future improvements (Appendix B). Among all the questionnaire questions, there are 13 columns of categorical variables and 10 columns of numerical variables. For numerical variables, we used the 5-points Likert scale[65] to conduct a satisfaction analysis of the factors that influence the riding experience(Table 6.1).

In this study, questionnaires were distributed online in European cities where scooters are available, such as Stockholm, Gothenburg, Milan, Copenhagen, etc. The distribution channels included WeChat groups and social media platforms like LinkedIn. The collection period lasted for one week.

#### 6.1.1.2 Text Quantitative Analysis

The text sources of this study mainly come from the interviews in the qualitative analysis stage, some open questions from questionnaires and the log texts written from a first-person perspective. First, all text data(around 4,900 words) was cleaned and encoded. For instance, other languages were translated into English.

Then, this study conducted data sorting and key information extraction: Carefully read the text data and extract key information relevant to the 5 research questions, such as usage frequency, usage scenarios, opinions on safety, requirements for navigation functions, and evaluations of vehicle design.

Finally, through semantic and thematic analysis, it is possible to gain an in-depth understanding of users' opinions, needs, and concerns regarding electric scooters. Regarding semantic analysis, this study utilizes the Rawgraph(<https://app.rawgraphs.io/>), which is mainly used to display the proportions of positive, neutral, and negative elements in the text.

Table 6.1: Factors that influence the riding experience

No.	Category	Question
F1	Safety Perception (overall)	How safe do you feel while riding an e-scooter on a scale
F2	Safety Perception (attachments)	How important do you think it is for e-scooters to have safety features like lights, brakes, and helmets
F3	Safety Perception (handlebars)	How comfortable do you find the handlebars of the e-scooter on a scale?
F4	Safety Perception (foot-rest)	How comfortable do you find the foot-rest area of the e-scooter on a scale?
F5	Navigation and Interaction (phone holder)	To what extent do you want to put your phones inside the phone holder on a scale?
F6	Navigation and Interaction (audio)	Auditory (beeping, voice prompts)
F7	Navigation and Interaction (visual)	Visual (lights, text messages)
F8	Navigation and Interaction (vibratactile)	Vibrotactile (vibrations on the handlebars)
F9	Future Improvement (software)	If an e-scooter had a more advanced interaction system, like touch-screen controls or voice commands, would you use it?
F10	Future Improvement (hardware)	If in the future there is a helmet/handlebar that combines vibration and voice interaction, would you be willing to use it?

## 6.1.2 Qualitative Research

### 6.1.2.1 On-site observation

In this study, through a week of continuous tracking and observation, the behaviors of people using scooters were observed on specific road sections, such as areas around schools, near bus stops, and in bustling downtown regions. Finally, the empathy map tool was used to record these observations(Figure 6.2).

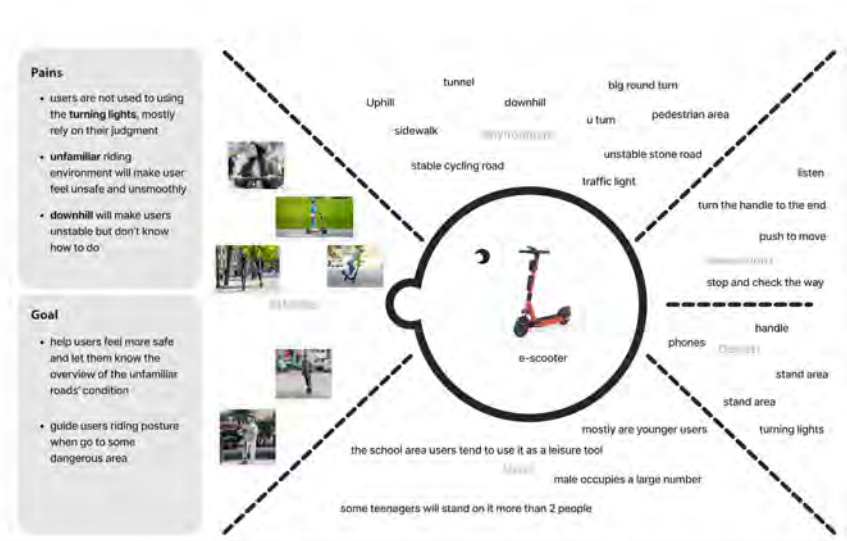


Figure 6.2: Empathy map from the observation study

### 6.1.2.2 First-person perspective

This study invited three senior e-scooter users to write down their riding record and some details thoughts (Figure 6.3). The records were mainly in text form. Eventually, we obtained the initial data. Then, through data cleaning and encoding, we used these data as the text source for quantitative analysis.

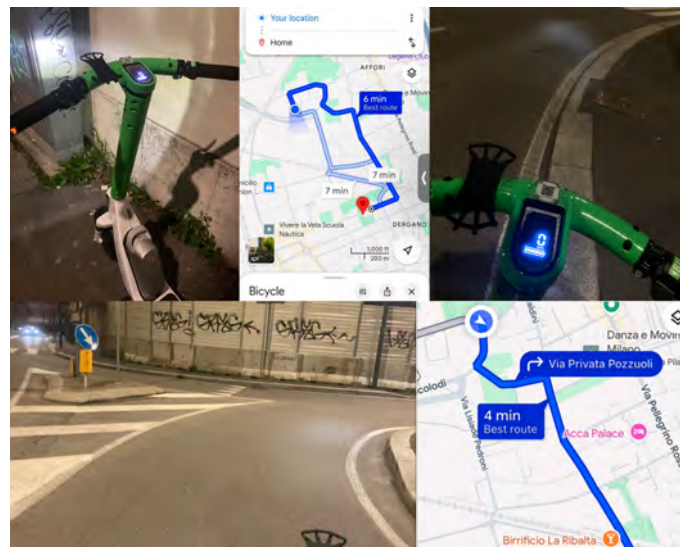


Figure 6.3: First-person perspective riding log in Milan

### 6.1.2.3 Semi-structured interview

This research mainly adopts the semi-structured interview method for interviews (Appendix A). The main implementation means include face-to-face interviews, on-



line interviews, and telephone conferences. The duration of a single interview is controlled at around 30 minutes. The main purposes of this interview are as follows:

- To understand users' attitudes towards the current riding situation and their expectations.
- Gain an in-depth understanding of users' riding habits and navigation interaction habits.
- To explore users' acceptance level of multimodal interaction methods.

To this end, this research first adopted the method of stratified sampling interviews[66], inviting 12 interviewees(Table 6.2). First, based on the frequency and experience of users' riding, this research divided users into three categories: occasional users (who have a small amount of riding experience and occasionally choose to travel by scooter), extreme users (who have no riding experience and will not consider riding as a means of transportation), and typical users (who often ride). From different categories of users, this research can obtain the expectations and needs of different users regarding riding behavior, thus achieving more accurate and diverse results.

Table 6.2: 12 participants in the interview phase

No.	Gender	Age	User Category	Riding Experience
P1	Female	27	Occasional User	2 times
P2	Female	28	Occasional User	2 times
P3	Female	27	Extreme User	Never
P4	Male	22	Typical User	3-4 times a week
P5	Female	24	Occasional User	More than 10 times
P6	Male	23	Typical User	2 times a week
P7	Male	24	Typical User	4-5 times a week
P8	Male	28	Typical User	3-4 times a week
P9	Male	26	Occasional User	More than 10 times
P10	Male	41	Extreme User	Never
P11	Male	31	Occasional User	More than 10 times
P12	Male	23	Typical User	3-4 times a week

In this study, all interviews were recorded and then directly transcribed into text. For non-native speakers in the interviews, the text was translated into English using the GPT-4o model. Subsequently, information was extracted from the text for thematic analysis.

### 6.1.3 Context of Use

One strand of research has zeroed in on objective driving risk analysis. This area can be partitioned into two key aspects: macroscopic traffic data and microscopic operating parameters of the driving process. These two approaches are employed to identify and analyze risk factors[67].

In the scenario of riding a scooter, macroscopic traffic can be regarded as the ordinate indicator-predictable, and microscopic operating parameters can be regarded as the abscissa indicator-familiar(Figure 6.4).



Figure 6.4: Risk analysis based on riding context

In terms of classifying users' riding scenarios, according to users' familiarity with the riding scenarios and the predictability of the riding conditions, it can be divided into three types of risky riding: low-risk, moderate-risk, and high-risk. Zheng et al. proposed in 2021 that there are two main factors influencing users' decisions during driving, namely safety and efficiency [68]. For different riding risk modes, users' main decision-making factors also vary.

- **Low-risk:**

When the riding time in a single direction exceeds 1.5 seconds, users will feel extremely safe [68]. This situation mostly occurs in familiar and predictable environments. At this time, the main goal of users' riding is dominated by efficiency(Figure 6.5).

- **Moderate-risk:**

For roads that are familiar but unpredictable, users are mainly dominated by the pursuit of efficiency.

For roads that are unfamiliar but predictable, users are mainly guided by safety. At this time, the riding characteristics of users are generally as follows: The navigation only occupies a single channel for interaction with the users, and the users' main attention remains on the road environment rather than the route.

- **High-risk:**

When safety is the dominant factor, users need to make dynamic decisions in a dynamic environment.

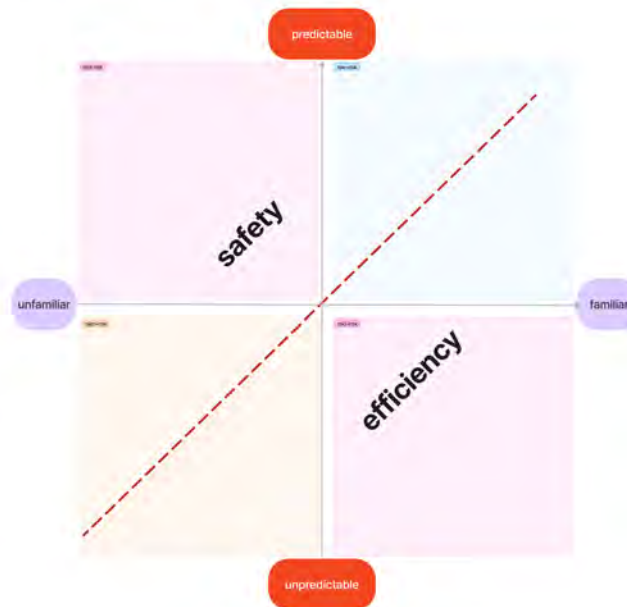


Figure 6.5: User goal when meeting different riding contexts

## 6.2 Problem Definition

### 6.2.1 Persona

To design an effective multimodal navigation system for shared e-scooters, it is essential to understand user behaviors, pain points, and needs. Based on user research, this persona analysis defines key rider profiles, highlighting their unique challenges and expectations.

#### 6.2.1.1 Persona 1

**Character:** Anna (22 years old, Short-Distance Commuter)

- A student at the University of Gothenburg, residing near the Lindholmen campus.
- Relies on electric scooters for commuting to school, grocery shopping, and visiting friends, with a daily average riding distance of 1.5-3 km.

**Goals:**

- Quickly complete short-distance commutes (e.g., attending classes, shopping).
- Reduce walking time and avoid inconvenience caused by cold weather.

**Pain Points and Needs**

- Fixed angle of the phone mount forces (lowering the head to view maps), affecting visibility, and also making it hard to control the phone.
- Urban roads are often under maintenance, and road layouts change and update frequently.
- Outdated navigation routes fail to reflect construction updates, leading to getting lost multiple times (e.g., near Chalmers University).

### **Behavior Patterns:**

- High-frequency usage scenarios: Sunny days during daylight hours (avoids slippery conditions in rainy weather).
- Relies on memorized routes and uses navigation only in unfamiliar areas.

### **6.2.1.2 Persona 2**

**Character:** Ling (25 years old, Tourist/New User (First-Time Rider))

- Visiting Stockholm for the first time, trying out scooters to explore the city.
- Unfamiliar with riding operations and has safety concerns.

### **Goals:**

- Conveniently visit attractions.
- Experience the convenience of urban short-distance transportation.

### **Pain Points and Needs**

- Unfamiliar with brake controls ("Sudden acceleration causes nervousness").
- Silent operation of e-scooters increases risk as pedestrians may not notice them.
- Navigation voice is in English while the roads' names are in Swedish; relies on map text instead ("Trusts written instructions more than voice prompts").
- 

### **Behavior Patterns:**

- Avoids riding at night or in bad weather.
- Relies on social media to share experiences (e.g., taking photos at cemetery landmarks).

## **6.2.2 MoSCoW Analysis**

### **6.2.2.1 Must Have**

- Optimization of brake system
- Improvement of mobile phone holder reliability

- Design of anti-slip tires and vehicle body stability
- Integration of basic navigation functions

#### 6.2.2.2 Should Have

- Real-time traffic update and route optimization
- Adjustment of economic model
- Windproof and rainproof design

#### 6.2.2.3 Could Have

- Vibration feedback and multilingual voice prompts
- Nighttime lighting and reflective design
- User Feedback and emergency support system

#### 6.2.2.4 Won't Have

- Shared helmet rental system
- Long-range battery

## 6.3 Design Concept

During the preliminary questionnaire analysis and interviews, many users expressed anticipation for vibration-based interaction. Therefore, in the earliest concept development phase, this study primarily explored three modalities—visual, auditory, and vibration—as navigation input modalities to assist user interaction (Figure 6.6).



Figure 6.6: Design concept of the multi-modal navigation systems

For the visual component of the conceptual design: 1. Optimize the interface interaction design to better align with users' mental models during riding. 2. Introduce an AR projector interaction to assist users with directional recognition, reducing frequent head-down movements and stops during driving.

For auditory interaction: 1. Shorten the duration of voice interaction. 2. Refine the content prompts of voice interaction (e.g., reduce street names that may cause confusion due to language differences and focus on directional cues).

For vibration interaction: Activate handlebar vibration prompts before users make turns.

What's more, combined with the context of use, three riding concept hypotheses under different driving risk modes are proposed as follows(Figure 6.7):

- **Low-risk scenario:** This scenario is where users can perform single-operation within 1.5 seconds [68]): The main interaction methods are single-modality interactions, such as auditory or AR.
- **Medium-risk scenario:** Dynamic interaction design based on users' driving behaviors (mainly reflected in users' control of handlebar speed):
  - 1) When users press the brake, the UI dynamically adjusts information, and audio and AR interactions are displayed simultaneously.
  - 2) When users only coast, audio and AR interactions serve as the main input modalities, with the UI assisting in displaying directional information.
- **High-risk scenario:** Maintain the effectiveness of the UI at all times, with AR and audio as auxiliary reminders.

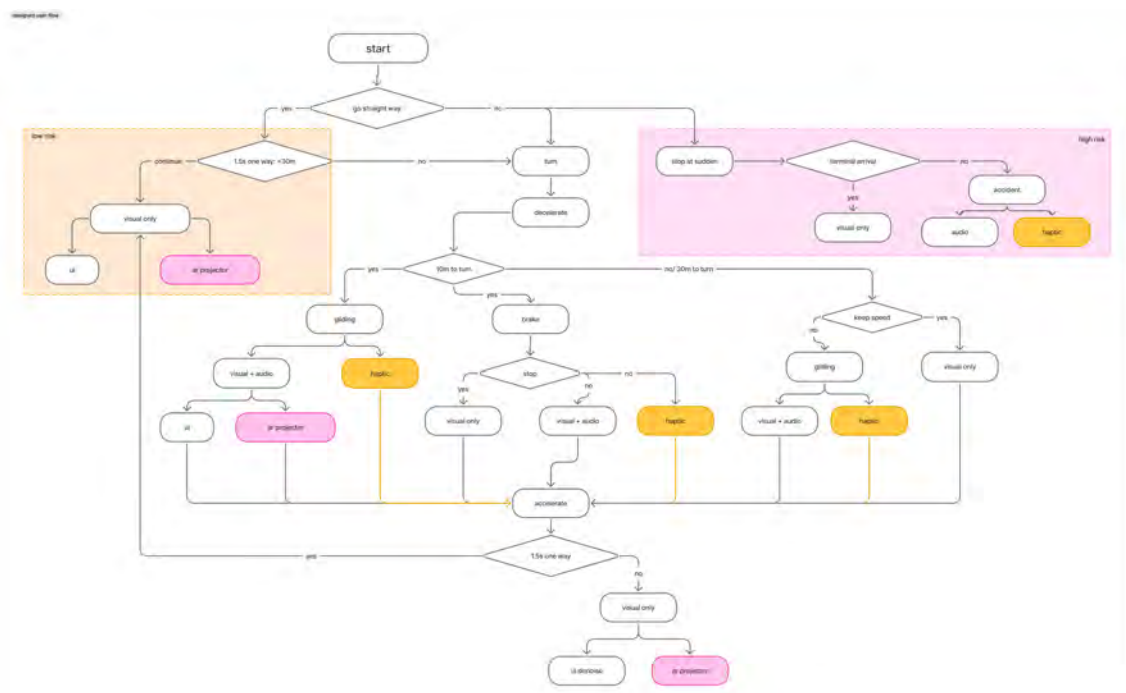


Figure 6.7: User flow and interaction design based on different scenarios

## 6.4 Prototype

At this stage, low-fidelity prototypes were primarily used to conduct early pivot studies on the design. Through continuous feedback from users and iterative design, a more refined design solution was developed, which also helped reduce the pressure during the usability testing phase. This section of the thesis only presents the low-fidelity prototypes, while the high-fidelity prototypes are shown in the results section.

### 6.4.1 Software design

To address the issues of excessive information display on the original UI interface, overly granular navigation interaction (e.g., navigation instructions changing every 10 meters with frequent directional reminders), and difficult touch interaction due to the phone being placed on a stand, the interface design introduces three key innovations:

- Remove street information display and enlarge directional indicators to reduce cognitive load(Figure 6.8).
- Dynamically adjust interface information based on the users riding speed and distance to the next turn. Set 30 meters as the first turn reminder (the headway distance THW[69] calculated using the formula:  $1.5s$  (critical point for low/medium-risk scenarios) \*  $25km/h$  + braking distance  $\ominus$  friction coefficient  $30m$ ). At 10 meters before the turn, highlight the prompt and enlarge junction details(Figure 6.9).
- Minimize accidental navigation exit by placing the exit button in the left-hand operation area and the thumbnail toggle function in the right-hand area for easy access.

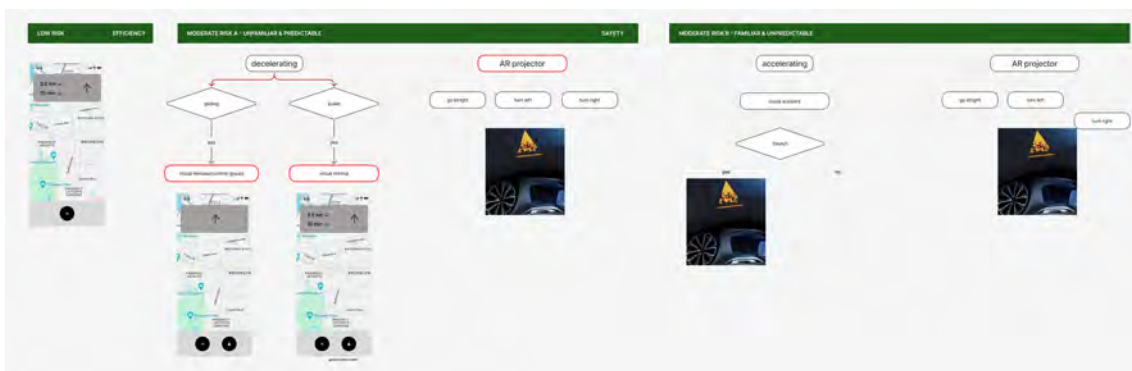


Figure 6.8: Low fidelity of the app: low risk and medium scenario

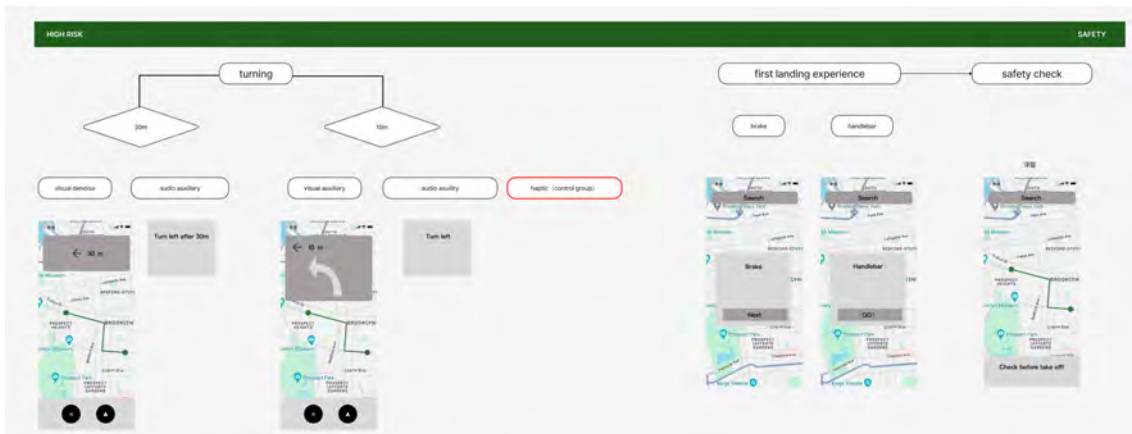


Figure 6.9: Low fidelity of the app: High risk scenario

### 6.4.2 AR Projector design

The preliminary design details for the projection light hardware are as follows:

- **Position and Projection Distance:** The projection light is placed on the front of the e-scooter. The specific height and angle require testing across different brands and are not discussed further here(Figure 6.10).
- **Projection Frequency:** Existing research provides limited theoretical guidance on blinking patterns. Given the challenges of defining optimal frequencies and durations at the low-fidelity prototype stage, the initial interaction involves projecting indicators for 2 seconds exclusively at turns.
- **Color Coding:** Green for straight paths and red for turns.
- **Signal Indicators:** The initial interaction includes only straight, left, and right directions. More complex scenarios requiring higher data precision are not addressed at this stage.
- **Interaction and Connectivity:** The projection light synchronizes with map data via Bluetooth from the users smartphone.



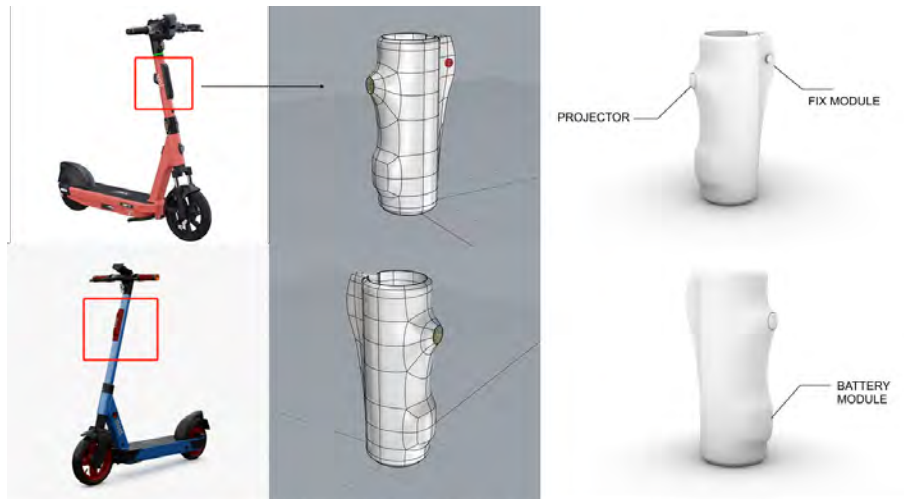


Figure 6.10: Low fidelity of Model in the Rhinoceros

## 6.5 Iterative Design

During the preliminary design phase, five users who had previously participated in interviews were invited to conduct a pilot study based on low-fidelity prototypes. The study aimed to observe whether the design met their initial expectations and effectively addressed their pain points. Following this, a second round of optimization was carried out before proceeding to high-fidelity prototype development and the setup of a usability testing environment.

To enhance participants' task experience and obtain more objective psychological cognition ratings among different modalities, this study constructed a simulated riding environment within a VR setting. Users could control the riding movement by standing or sitting and operating a directional keyboard, and the UI display was toggled through head-up and head-down movements, mirroring the real-world behavior of looking at a mobile navigation device. The VR environment meticulously replicated the complexity of road conditions, integrating various risk scenarios (Figure 6.11). In low-risk situations, users were required to ride straight for 1.5 seconds, while high-risk scenarios featured moving riders and roadblocks that demanded users to make evasive maneuvers.

## 6. Execution

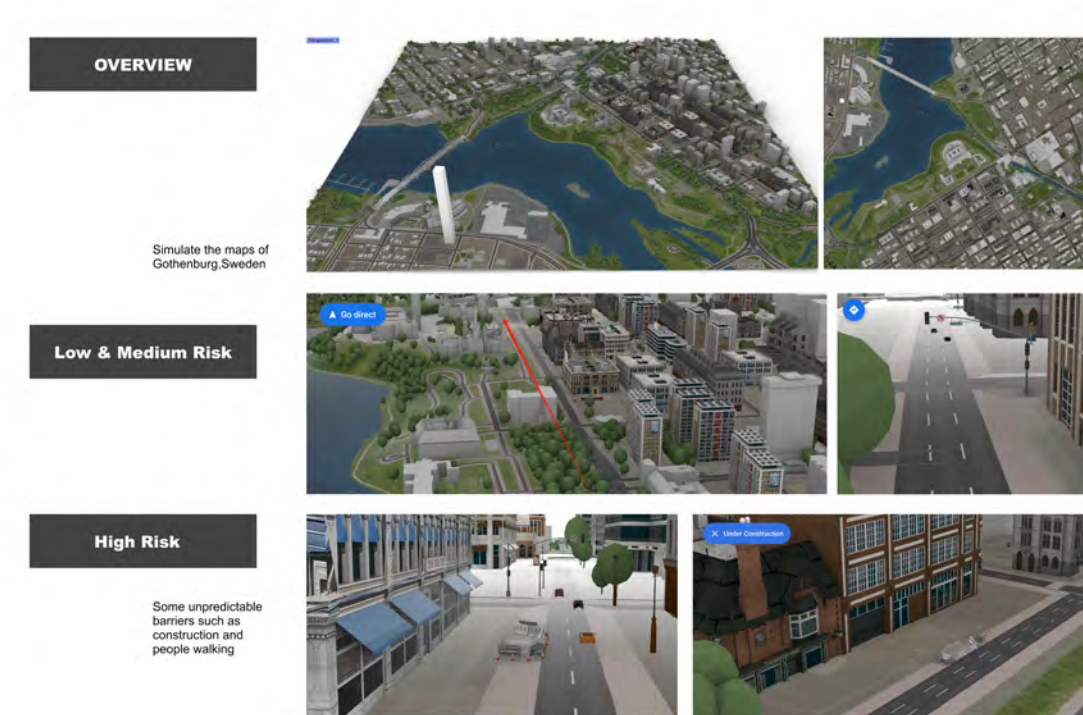


Figure 6.11: Environment build-up for testing the user's driving attitudes on the design concept in Unity, the video of usability test [https://drive.google.com/file/d/1SeaHAHI4Y9\\_ORG5nwu7Xwym0sCfB-zxM/view?usp=sharing](https://drive.google.com/file/d/1SeaHAHI4Y9_ORG5nwu7Xwym0sCfB-zxM/view?usp=sharing)

During testing, while participants manipulated controls, researchers observed their movements via a screen and provided limited assistance, recording driving behaviors and errors (Figure 6.12). After each ride, participants were asked simple questions, such as: "Which modality (or combination) did you prefer most, and why?" and "How do you think this would differ or what additional concerns might arise in a real riding environment?" This mixed approach of observation and post-task interviews aimed to capture both quantitative usability data and qualitative insights into user preferences and real-world applicability.

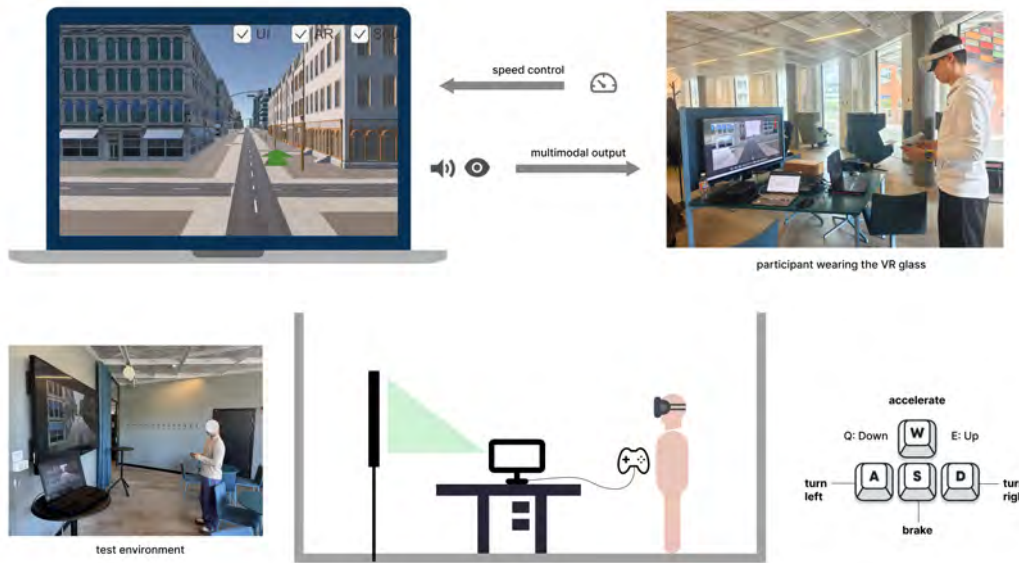


Figure 6.12: Experiment for participants to do usability test

When establishing the testing environment, the research used Unity to simulate scenarios in a VR environment for user testing. However, during this process, it was found that virtual simulation of vibration modality was highly challenging. Forcing vibration feedback (e.g., sudden 1-second vibrations from VR controllers during simulated riding) risked introducing errors into the research results, rendering them unreliable. As a result, discussions of this modality were omitted from the final outcomes.

After analyzing the results, the design solutions were optimized by integrating Google Guidelines and multimodal design principles, with the final outcomes presented in the \*Final Result\* section of the thesis.



# 7

## Results

This chapter presents the findings from both the research and design evaluation phases. It summarizes the key outcomes from user studies and usability testing, moving from the results of preliminary data collection to the validation of the final high-fidelity prototype.

### 7.1 Research Results

#### 7.1.1 Results of Qualitative Research

##### 7.1.1.1 Interview

Data from the semi-structured interviews were categorized into two main themes: user needs (pain points such as unstable braking or poor navigation) and user wants (desired improvements such as adaptive navigation). Four overarching themes emerged from the analysis: external environmental conditions, braking and warning systems, scooter design, and commercial strategy (Figure 7.1):

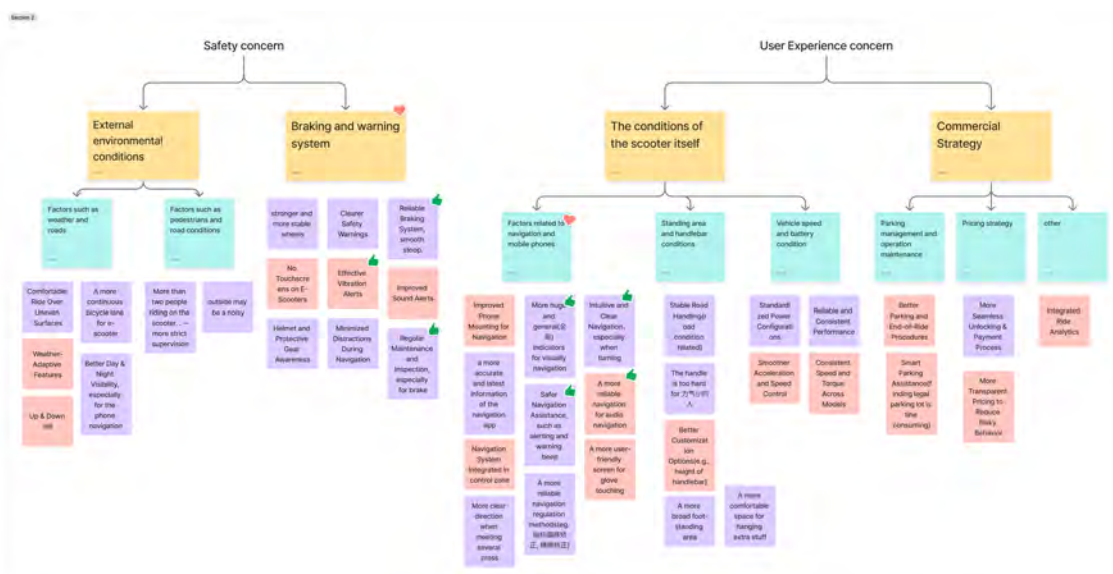


Figure 7.1: Affinity diagram from the semi-structured interview

In terms of user experience, several participants mentioned that commercial-side factors such as pricing and QR-code scanning affected convenience, but the most consistent concerns were related to safety and navigation. Users commonly described current navigation systems as unintuitive, unreliable, and sometimes hazardous due to their visual or manual operation:

"Yes, I use Google Maps on my phone if I'm going somewhere new. Since I cant hold my phone while riding, I usually start the navigation in audio mode and listen through my earphones. Sometimes, I also glance at my phone while stopped, but thats not ideal." [P8]

"I think it's better to combine different types of warnings. Sometimes, the visual navigation position on apps like Google Maps can be inaccurate." [P6]

Hardware design issues were also frequently mentioned, particularly the height and angle of phone holders:

"So, I think they do it on purpose. They don't make the phone holder properly, so that you have to use these fragmented moments of time to check the navigation, and in this way, they can make more money." [P2]

"The current placement for securing the phone isn't very convenient, especially for larger phones." [P7]

#### 7.1.1.2 Thematic Analysis

Semantic analysis revealed that positive evaluations of scooter riding were relatively rare (9.6%), while most comments were negative (60.5%), focusing on safety, navigation, and cost. Neutral statements (29.8%) tended to describe environmental conditions such as weather or road quality. Table 7.1 summarizes the thematic categories.

Table 7.1: Semantic and thematic Analysis

Theme	Negative	Neutral	Positive	Typical words
Safety and design	45%	10%	-	brake failure, unstable, accident, vibration
Navigation and Interaction	30%	5%	-	inaccuracy, difficulty using, distraction
Cost	25%	15%	-	unfair pricing, public transport comparison, extra fees
Convenience	-	20%	60%	time-saving, instant access, no waiting, short distance

In particular, braking and warning systems were identified as critical to perceived safety. Many riders recalled near-miss incidents due to braking instability:

"Its mainly the brakes-especially when accelerating and braking, the scooter is very abrupt. When you brake, the scooter wobbles from side

to side, making it unstable. It doesn't feel very secure." [P1]

"Sometimes, when going downhill and needing to brake urgently, the brakes of the Ryde e-scooter slow down gradually instead of immediately. So, sometimes the braking might be too late. You need to predict the stopping distance in advance, and it can be difficult to stop in time, which makes people feel a bit dangerous." [P12]



Figure 7.2: Visualization of semantic and thematic analysis

Overall, the qualitative findings suggest two key insights:

- **High dependence on external navigation tools:** most users relied on Google Maps (mentioned 14 times) rather than the navigation built into scooter apps. About 30% expressed dissatisfaction with current solutions, citing distraction, inaccuracy, and limited interactivity.
- **Speed strongly influences perceived safety and comfort:** factors such as braking response and stability directly affected riders' sense of control and satisfaction.

## 7.1.2 Results of Quantitative Research

### 7.1.2.1 Questionnaire

A total of 100 responses were collected, producing a data matrix of 100 X 23 variables. After cleaning and normalization, mean and mode values were calculated for key indicators (Table 7.2).

Table 7.2: Result of the 10 numerical variables

No.	Category	Average	Mode	Data Features
F1	Safety Perception (overall)	3.4	4	The data is left-skewed, with some extremely low scores. For example, scores of 1 point account for 5%.
F2	Safety Perception (attachments)	3.8	4	High scores are concentrated, and users generally attach great importance to safety functions.
F3	Safety Perception (handlebars)	3.5	3	The distribution is relatively uniform.
F4	Safety Perception (footrest)	3.3	3	There are quite a lot of low scores, which reflect problems regarding space or materials.
F5	Navigation and Interaction (phone holder)	3.1	3	The distribution is relatively uniform.
F6	Navigation and Interaction (audio)	3.4	3	There is a large difference in the preference scores. Some users consider it to be a source of interference.
F7	Navigation and Interaction (visual)	3.2	3	There are quite a lot of low scores, indicating concerns about distraction.
F8	Navigation and Interaction (vibratile)	3.0	3	Users have feedback that the sensitivity is insufficient.
F9	Future Improvement (software)	4.1	5	85% of the users are willing to try out new features.
F10	Future Improvement (hardware)	3.9	5	The acceptance level is high, but some users are concerned about hygiene issues.

The data normalization process was carried out for each of the above 10 indicators respectively. Correlation matrix analysis (Figure 7.3) revealed several relationships between safety perceptions and interaction preferences.



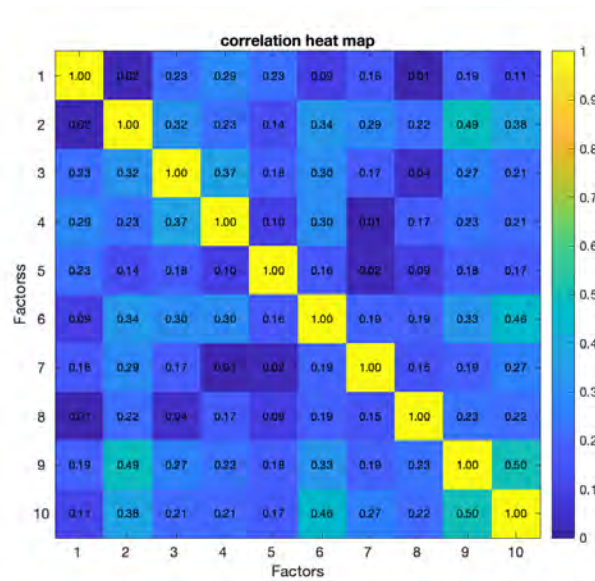


Figure 7.3: Correlation matrix of 10 factors that influence riding experience

Key insights include:

- **Acceptance of audio feedback correlates with openness to advanced navigation** variables F6 (audio interaction) and F10 (hardware improvements) showed a moderate positive correlation ( $r=0.49$ ). Users who valued audio cues were also more interested in richer, multimodal navigation.
- **Safety-conscious users are more receptive to new technology** F2 (safety perception) correlated positively with F9 and F10 ( $r=0.50$ ). Those emphasizing safety were more willing to try advanced systems.
- **General satisfaction with current safety remains low** average safety ratings were 3.4/5, with 5% of respondents giving the lowest score.

### 7.1.2.2 Text Quantitative Analysis

This study first conducted a word frequency analysis on approximately 4,900 pieces of text, and finally presented the word frequencies. Words without main meanings, such as subjects and prepositions, were removed. At the same time, the two topic keywords "scooter" and "e-scooter" were also removed. The 10 words with the highest occurrence frequencies were selected to find the correlations among them, as follows (Table 7.3):

Table 7.3: Result of word frequency analysis

No.	Words	Counts	Related Theme
W1	ride	34	Riding experience, distance, time
W2	safety	28	Safety, braking problems, accident risks
W3	navigation	22	Navigation system, map usage, direction guidance

W4	brake(s)	18	Defects in the braking system, emergency braking issues
W5	speed	15	Speed control, speed limit issues
W6	Google Maps	14	Dependence on navigation tools and functional defects
W7	cost	12	Rental fees, economic efficiency
W8	route	12	Route planning, navigation accuracy
W9	handlebar(s)	10	Handle design, grip comfort level
W10	phone holder	10	Practicality and design flaws of mobile phone holders

### 7.1.3 Usability Testing

Usability evaluation comprised two complementary studies: (1) an A/B comparison between the redesigned and original Google Maps UIs, and (2) a multimodal efficiency test measuring cognitive workload and performance across six interface configurations.

#### 7.1.3.1 User Interface test

Thirty participants compared the original Google Maps UI with the redesigned version (Figure 7.4) and completed the NASA-TLX questionnaire (0100 scale). Although Wilcoxon tests showed no statistically significant differences across dimensions (Table 7.4), participants generally perceived the new UI as clearer and less visually demanding.

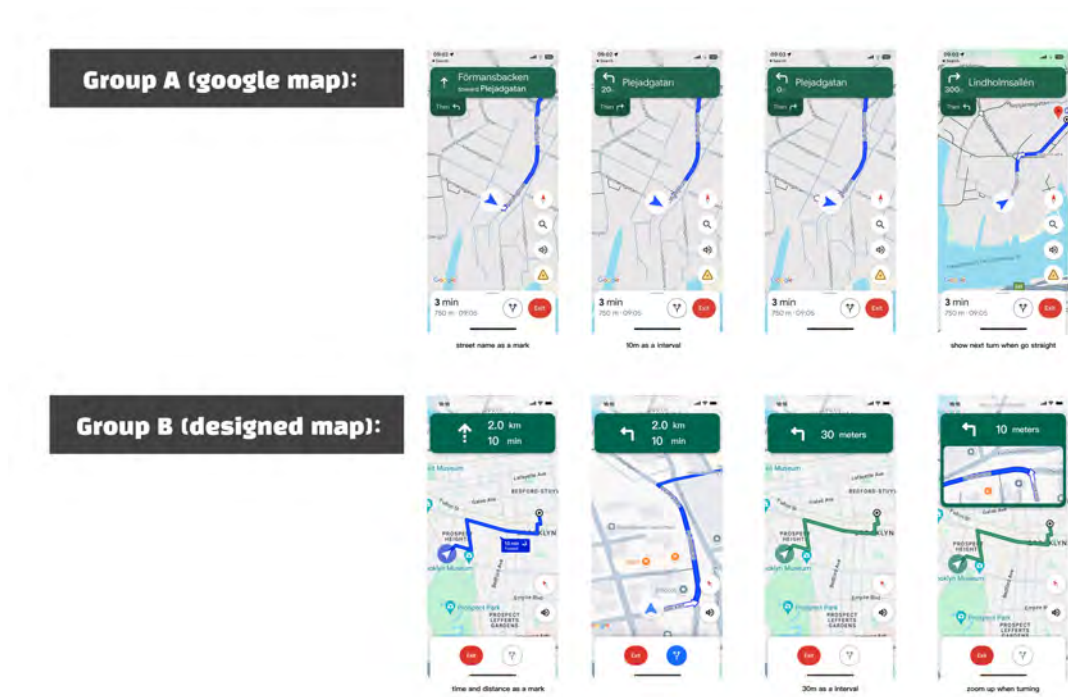


Figure 7.4: A/B test of designed interface and Google map UI

Common observations included:

- **Overall new UI shows positive, though not significantly (Table ):** Users generally accepted some optimized elements, but certain design flaws persisted. For example, some users noted: "Distance and time information are redundant-distance should be deprioritized as non-critical and further optimized."
- **Usability issues in niche interactions (4/30 users):** For example, the left-hand placement of the exit button contradicted original ergonomic intentions, with users reporting discomfort. And for turning indications, the dynamic zoom feature during turns required a learning curve, confusing some riders during navigation.

Table 7.4: New UI vs Google Map UI: Statistics of 6 different aspects in NASA-TLX

Variables	New-UI		Old-UI		Significance
	Mean	Std	Mean	Std	
Mental Demand	38.50	16.67	43.83	18.55	$p = .212$ , Non-Significant
Physical Demand	39.67	14.26	41.17	18.65	$p = .560$ , Non-Significant
Temporal Demand	39.83	19.76	44.33	19.20	$p = .298$ , Non-Significant
Performance	30.33	19.43	36.67	21.63	$p = .235$ , Non-Significant
Effort	38.83	20.46	43.33	19.80	$p = .410$ , Non-Significant
Frustration	37.83	19.99	41.17	22.00	$p = .593$ , Non-Significant
<b>Score</b>	<b>37.50</b>	<b>14.28</b>	<b>41.75</b>	<b>15.59</b>	$p = .174$ , Non-Significant

Nevertheless, 25 of 30 participants preferred the new interface, reporting reduced visual fatigue. Scores improved by  $> 10$  points in mental demand, performance, and effort dimensions (Figure 7.5).

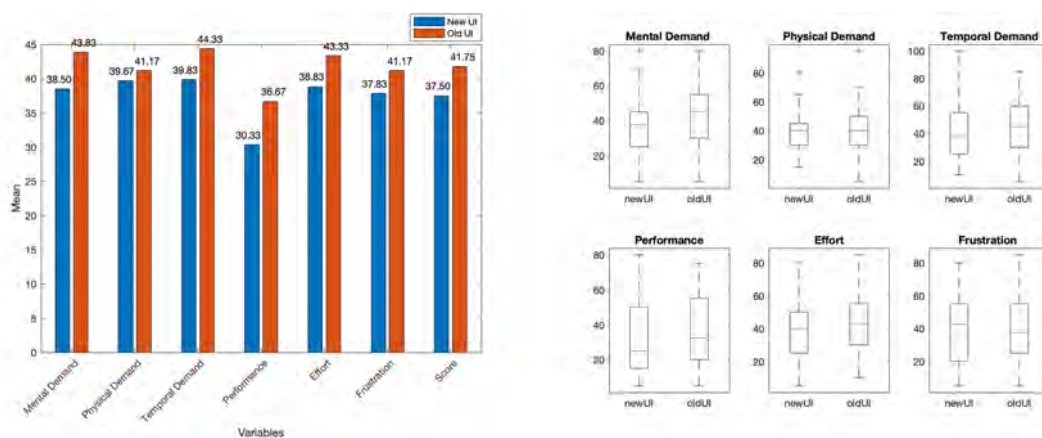


Figure 7.5: Difference of the NASA-TLX between the new UI and old Google UI in detail

### 7.1.3.2 Cognitive Load Test of interaction design

This study employed a cognitive load efficiency analysis formula to conduct usability analyses of task performance across different modalities. Users' cognitive efficiency in riding tasks consisted primarily of two components: *user performance* and *mental effort*.

In the end, this study invited a total of 30 participants to take part in the test, recording users' performance and mental effort:

- **Performance:** was measured by the time users took to complete the same distance.
- **Mental effort:** was quantified using the NASA-TLX subjective cognitive scale for riding tasks, with standard weighting applied consistently.

According to the calculations, users in the UI-only group spent significantly more time and had higher NASA TLX scores compared to other groups (Table 7.5). Additionally, the mean cognitive efficiency of this modality was the only one shown as negative across all groups, indicating that users generally perceived this interaction as inefficient. During interviews about their experiences with the UI-only modality, users commonly reported feedback such as, "*It's too troublesome to keep looking down and up,*" and "*I sometimes have to stop other tasks and focus on the UI, which is very inefficient.*"

Table 7.5: Descriptive Statistics of Various Indicators

Variables	Mental(Nasa-tlx)		Performance(seconds)		Efficiency	
	Mean	Std	Mean	Std	Mean	Std
UI	59.98	10.32	219.83	143.90	-1.46	1.08
AR	36.00	17.16	110.00	103.06	0.72	1.11
Audio	36.00	17.16	130.13	110.73	0.22	1.02
UI+Audio	39.3	15.97	139.50	129.52	0.28	1.16
UI+AR	40.93	14.22	128.83	97.20	0.16	0.85
UI+AR+Audio	33.35	16.81	120.70	106.24	0.84	1.20

*Note:* Mental measures users' cognitive effort (assessed via the NASA-TLX scale); Performance refers to the total time (in seconds) users took to complete a fixed distance in a lab (VR) environment; Efficiency denotes the cognitive efficiency calculated from Mental and Performance, where positive/negative values indicate high/low efficiency, and the magnitude represents the degree of efficiency.

In addition, a higher E-value (efficiency) indicates more effective modality interaction: AR ( $E=0.72 \pm 1.11$ ) and UI+AR+audio ( $E=0.84 \pm 1.20$ ) significantly outperformed other groups, suggesting AR intervention can improve riding efficiency to some extent.

Regarding why the UI+AR groups efficiency value lagged far behind UI+AR+audio: testing and post-interviews revealed that most users only utilized AR+audio in the

full-modality group, treating the UI as a psychological safety net for occasional route checks. When asked about preferred interaction modalities:

- 18/30 users favored the AR+audio combination, citing it as the most efficient. They noted that AR and audio complemented each other without interference. While most users(10/18) still saw value in UI during real-world riding, particularly for quick route overviews at the start or during stops.
- 8/30 users preferred UI+AR: some users(3/8) express that they like listening to music while riding and wanted audio as an optional feature. Others emphasized that ambient noise in real environments could hinder road condition awareness.
- 4/30 users preferred the full UI+AR+audio combination.

**7.1.3.2.1 Performance** First, the user’s task performance was analyzed. According to the QQ plot(Figure 7.6), the data did not exhibit a significant normal distribution, so the Kruskal-Wallis H test (nonparametric test) was used. The results showed significant differences between the parameters. Subsequently, Wilcoxon rank-sum tests were conducted for pairwise comparisons of data between different groups. Finally, Bonferonni correction was applied for multiple comparisons.

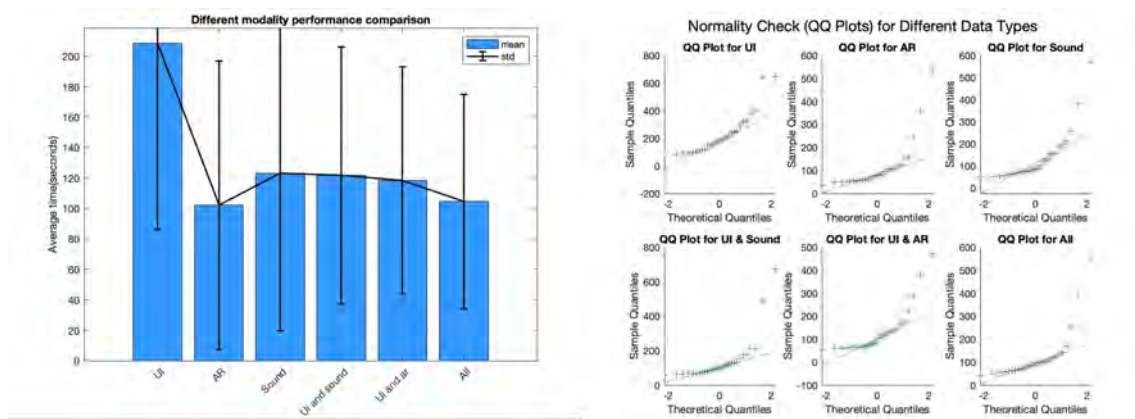


Figure 7.6: User Performance time(seconds) in different modalities and qq plot normality analysis

The final significance results show that the UI modality performed worst in terms of time (average duration: 219.83s), while other modalities averaged around 120s. The AR modality demonstrated the best time performance (average duration: 110s). Wilcoxon tests for each group revealed the following patterns(Table 7.6):

- The UI modality showed significant differences compared to all other modalities ( $p < .001 < \alpha = .003$ ).
- The single AR modality significantly outperformed the audio modality ( $Z = 2.921$ ,  $p = .003$ ,  $r = .533$ ), the UI+AR combination ( $Z = 2.927$ ,  $p = .004$ ,  $r = .553$ ), and the UI+Audio combination ( $Z = 2.778$ ,  $p = .006$ ,  $r = .507$ ). Insights from interviews and usability testing indicate that AR provides nearly instant

visual feedback, whereas audio often requires waiting for the voice prompt to complete, introducing a delay in user guidance.

- The UI+Audio+AR combination relatively outperformed the UI+Audio combination ( $Z = 2.397$ ,  $p = .017$ ,  $r = .438$ ), suggesting that AR as an additional modality enhances efficiency in time.

Table 7.6: Performance in Significance Analysis Between Different Modalities with Wilcoxon’s test

P-value	UI	AR	Audio	UI+AR	UI+Audio	ALL
UI	-	-	-	-	-	-
AR	$p < .001$	-	-	-	-	-
Audio	$p < .001$	$p = .004$	-	-	-	-
UI+AR	$p < .001$	<b><math>p = .003</math></b>	$p = .510$	-	-	-
UI+Audio	$p < .001$	$p = .006$	$p = .153$	$p = .552$	-	-
ALL	$p < .001$	$p = .245$	$p = .334$	$p = .371$	$p = .017$	-

*Note:* After Bonferroni correction, a total of 15 repeated comparisons were conducted, so the corrected significance level was set  $\alpha = .003$ .

**7.1.3.2.2 Mental Effort** Regarding the measurement of mental effort, this study used the NASA-TLX scale (0-100, with users reporting values in steps of 5). Visual comparisons of the six dimensions across six groups were made via radar charts (Figure 7.7), yielding the following findings:

- The UI group showed the most mediocre performance in both mean scores and dimensional ratings, with an average user score of 60 (a score above 50 signifies a high mental workload [70]).
- The comprehensive mental effort scores of other groups ranged between 30 and 41, with relatively consistent performance. The all (UI+AR+Audio) group performed best (weighted score: 33.35), indicating that the input of three modalities did not impose cognitive burdens on users. Instead, the ability to choose modalities enhanced convenience.

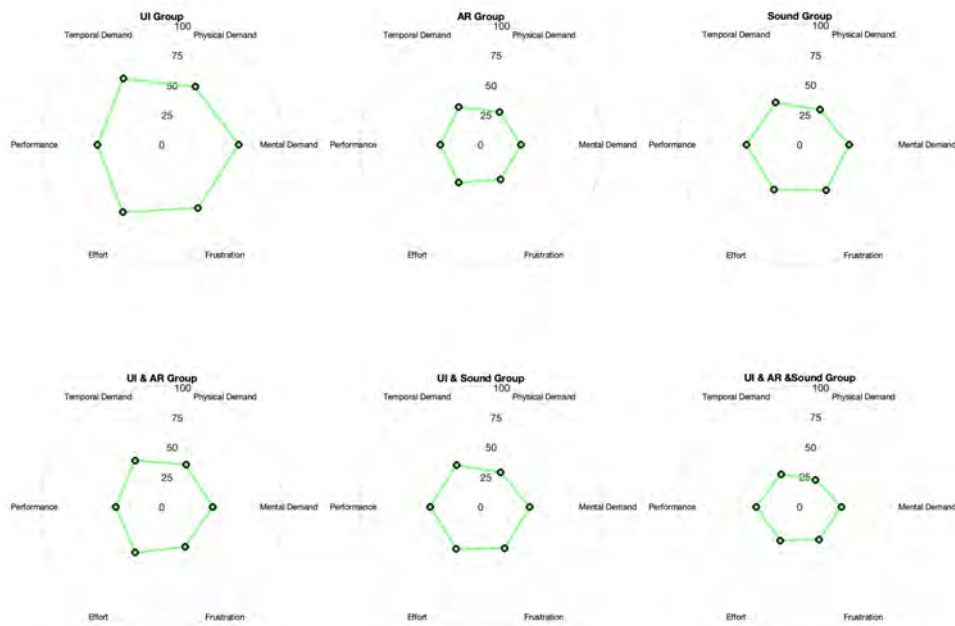


Figure 7.7: Radar Map visualization of Mental effort Analysis in different modalities

For the measurement of mental effort, this study directly employed Wilcoxon tests to conduct pairwise comparisons across different modalities to verify their significance (Table 7.7). The final results are as follows:

- The UI group's psychological cognitive performance remained significantly lower than that of other groups ( $p < .001$ ). Through usability testing, when asked about the reasons, users universally reported that constantly looking down and up was troublesome, significantly creating "seams" in interaction behavior.
- Notably, the UI+AR group performed worse (weighted score: 40.93) than the AR group ( $Z = 2.386$ ,  $p = .017$ ,  $r = -.451$ ), suggesting that the two visual input modalities (UI and AR) created some degree of conflict.
- The UI+audio+AR group significantly outperformed the audio group ( $Z = 3.498$ ,  $p = .001$ ,  $r = .661$ ), the UI+AR group ( $Z = 2.964$ ,  $p = .003$ ,  $r = .550$ ), and the UI+audio group ( $Z = 3.386$ ,  $p = .001$ ,  $r = .640$ ).

**7.1.3.2.3 Efficiency** For the calculation of efficiency, this study first performed z-score normalization on performance and mental effort values to facilitate operations between different types of data. Finally, Wilcoxon tests were conducted on the calculated "E values" for significance analysis.

To more clearly display the cognitive efficiency across different modalities, the data were normalized to an interval of  $[-3, 3]$ , making it easier to observe data concentra-



## 7. Results

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Table 7.7: Significance Analysis Between Different Modalities (NASA Weight) with Wilcoxon's test

P-value	UI	AR	Audio	UI+AR	UI+Audio	ALL
UI	-	-	-	-	-	-
AR	$p < .001$	-	-	-	-	-
Audio	$p < .001$	$p = .050$	-	-	-	-
UI+AR	$p < .001$	$p = .017$	$p = .869$	-	-	-
UI+Audio	$p < .001$	$p = .327$	$p = .069$	$p = .308$	-	-
ALL	$p < .001$	$p = .144$	<b><math>p = .001</math></b>	<b><math>p = .003</math></b>	<b><math>p = .001</math></b>	-

*Note:* After Bonferroni correction, a total of 15 repeated comparisons were conducted, so the corrected significance level was set  $\alpha = .003$ .

tion(Figure 7.8). The results are as follows:

- The vast majority of users perceived the UI-only group as inefficient ( $E < 0$ ), and the data points were far from the diagonal, indicating a high degree of inefficiency.
- The AR, UI+Audio, and allUI+AR+audio groups showed the best performance with generally concentrated data, suggesting these three modality combinations offer the highest cognitive efficiency and are suitable for scenarios requiring urgent responses.
- The UI+AR and audio-only groups exhibited more average distributions. Key influencing factors included the poor situational applicability of audio (users easily missed information) and visual input conflicts in the UI+AR group, which caused certain visual stress for users.



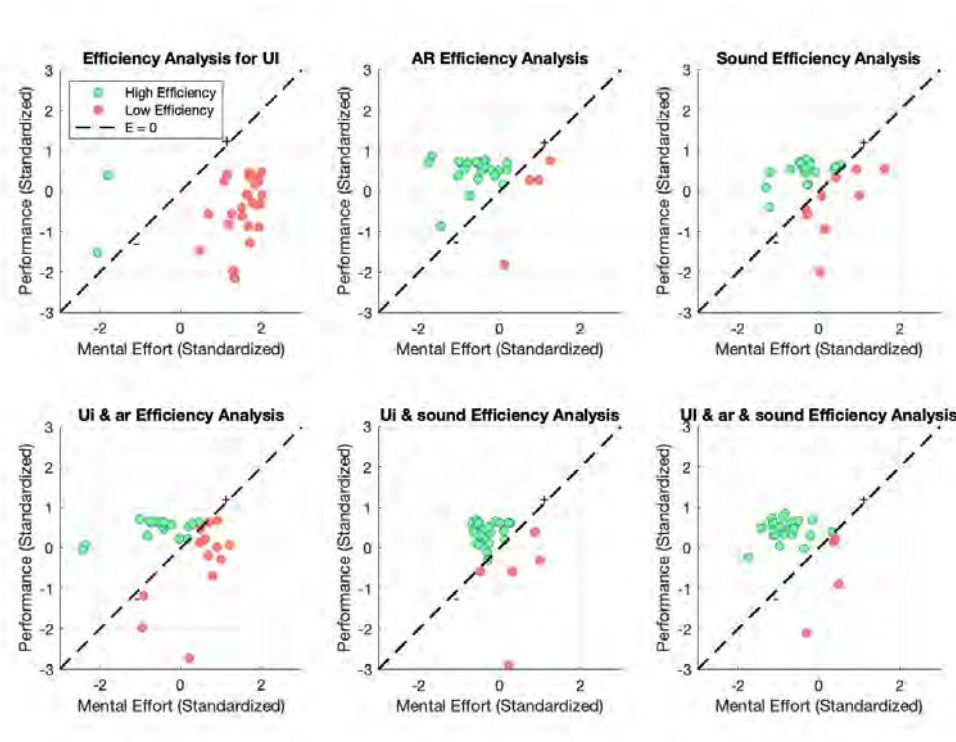


Figure 7.8: Scatter plot of Efficiency Analysis in different modalities

Finally, through comparative verification among different modalities, the following results were found (Table 7.8):

- The cognitive efficiency of the UI group was significantly lower than that of other modalities ( $p < .001$ ).
- The cognitive efficiency of the AR group was significantly better than the UI + AR group ( $Z = 3.445$ ,  $p = .001$ ,  $r = .629$ ). The main reasons were the timeliness of feedback in the visual channel and the redundancy of a single channel.
- The cognitive efficiency of the All group (audio + AR + UI) was significantly better than that of the audio group ( $Z = 2.952$ ,  $p = .003$ ,  $r = .539$ ), the UI + AR group ( $Z = 3.260$ ,  $p = .001$ ,  $r = .595$ ), and the UI + Audio group ( $Z = 3.137$ ,  $p = .002$ ,  $r = .573$ ).

In summary, the study revealed that users of e-scooter navigation systems face significant challenges in safety perception (average score 3.4/5), navigation intuitiveness, and hardware design flaws (e.g., phone holder ergonomics). Qualitative interviews highlighted heavy reliance on external tools like Google Maps and dissatisfaction with current UIs due to distraction, inaccuracy, and monotonous interaction. Quantitative data showed strong correlations between safety prioritization and acceptance of advanced features. While A/B testing of a new UI showed no statistically significant reductions in NASA-TLX workload metrics compared to the old design, 25/30 users reported reduced visual strain. Multimodal interaction testing found that AR + audio achieved the highest cognitive efficiency ( $E = 0.84 \pm 1.20$ ) and lowest mental workload (NASA-TLX =  $33.35 \pm 16.81$ ), outperforming UI-only systems

Table 7.8: Cognitive Efficiency Significance Analysis between different modalities with Wilcoxon's test

P-value	UI	AR	Audio	UI+AR	UI+Audio	ALL
UI	-	-	-	-	-	-
AR	$p < .001$	-	-	-	-	-
Audio	$p < .001$	$p = .013$	-	-	-	-
UI+AR	$p < .001$	$p = .001$	$p = .572$	-	-	-
UI+Audio	$p < .001$	$p = .026$	$p = .629$	$p = .478$	-	-
ALL	$p < .001$	$p = .349$	$p = .003$	$p = .001$	$p = .002$	-

*Note* After Bonferroni correction, a total of 15 repeated comparisons were conducted, so the corrected significance level was set  $\alpha = .003$ .

( $E = -1.46 \pm 1.08$ ), which caused frequent gaze-shifting frustrations. The full multimodal system (UI+AR+audio) balanced redundancy and efficiency, preferred by 18/30 of users for complementary feedback. Key recommendations include prioritizing AR and audio as core interaction modes, refining UI redundancies (e.g., distance displays), and integrating real-time safety alerts to address user concerns.

## 7.2 Final Design

The final design integrates insights from the empirical studies into a multimodal navigation framework emphasizing user safety, efficiency, and accessibility. It is organized across five design dimensions: Strategic, Scope, Interaction, Information, and Sensory, corresponding to key usability test findings.

### 7.2.1 Strategic Design

Through qualitative and quantitative research, the final product goals are positioned to design a user-friendly, usable, and accessible product, focusing on user safety and user experience through multimodal interaction navigation. The specific design strategies are as follows:

- **User Safety:** Optimize the cognitive efficiency of the UI interface, using UI as a safety guarantee for riding. Dynamically display prioritized information based on the users primary objectives in different scenarios.
- **User Experience:** Adopt AR as the primary interaction medium to enhance users cognitive efficiency (Figure 7.9).



Figure 7.9: AR projector position and functionality

### 7.2.2 Scope Design

The final research targets two main user groups:

- First-time commuters/tourists unfamiliar with urban roads
- Frequent commuters facing route changes due to ongoing urban construction

Additionally, adhering to inclusive design principles, the multimodal options provide navigation feedback for users with single-modality impairments (e.g., hearing loss, myopia). Specific dynamic input modalities include(Figure 7.10):

- **Speed control:** Real-time recognition of cycling speed changes to adapt the riding interface and provide intuitive feedback.
- **Screen interaction:** Adjusted button placement to prevent physical barriers to touch inputs (e.g., inaccessible click areas).
- **Brake detection:** Identification of speed fluctuations to trigger brake signals, enhancing the comprehensiveness and reliability of the riding interface.

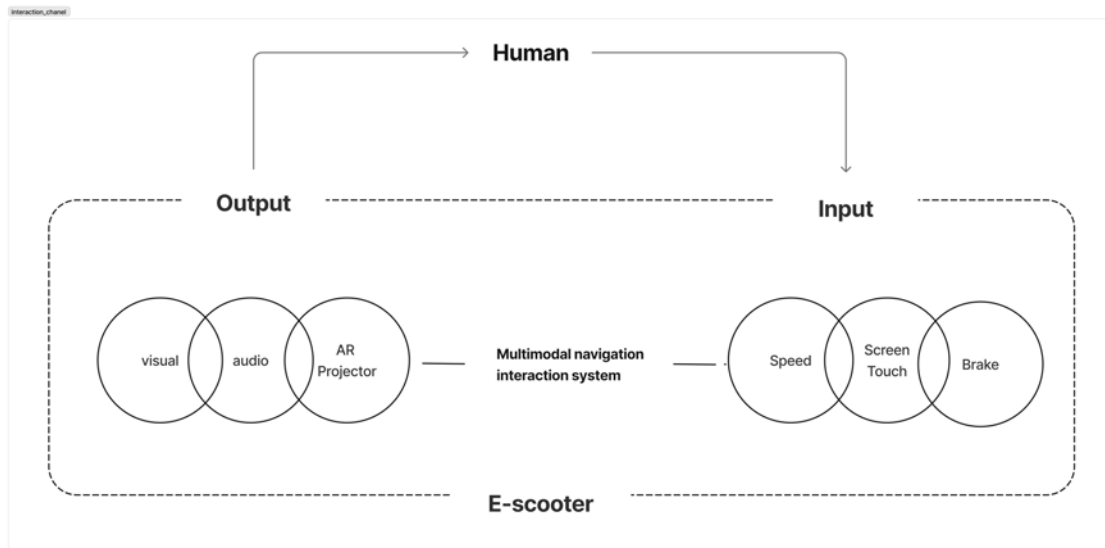


Figure 7.10: Input and output of the interaction design

The corresponding relationships between specific user interaction scenarios and different cycling scenarios are as follows:

Table 7.9: Multimodal Navigation Strategies Under Varying Risk Contexts

Scenario Type	Environmental Features	User Needs	Multimodal Application
Low-Risk	Familiar routes, straight roads, minimal traffic	Maintain speed, occasional direction checks	- AR projection for turns - Optional audio feedback for straight paths
Moderate-Risk	Urban main roads, intersections	Timely response to traffic changes, collision avoidance	- Dynamic AR arrows + audio countdown for turns - UI overview when braking
High-Risk	Rainy/night-time, unfamiliar routes, construction zones	High safety needs (e.g. high pedestrian flow), multiple confirmations	- AR + audio + UI alerts (red arrows + screen highlights)

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Scenario Type	Environmental Features	User Needs	Multimodal Application
Special Contexts	Noisy environments (e.g., near subway stations), hands occupied	Navigation without visual/auditory input	- AR projection for turns - Optional audio feedback

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### 7.2.3 Interaction Design

The details of Dynamic Modality Switching and corresponding interactions are as follows (also refer to Figure 7.11):

- **Accelerating:** Automatically reduce visual feedback to minimize distraction and rely primarily on AR guidance.
- **Braking:** Simultaneously highlight AR arrows and the UI interface, with repeated audio instructions to prevent missed cues during sudden stops. The UI should display detailed route information, including total remaining distance and distance to the next turn.
- **Decelerating:** Use AR and audio interaction as the primary channels. When approaching a turn, the UI should amplify route details to allow users to reconfirm the path visually.

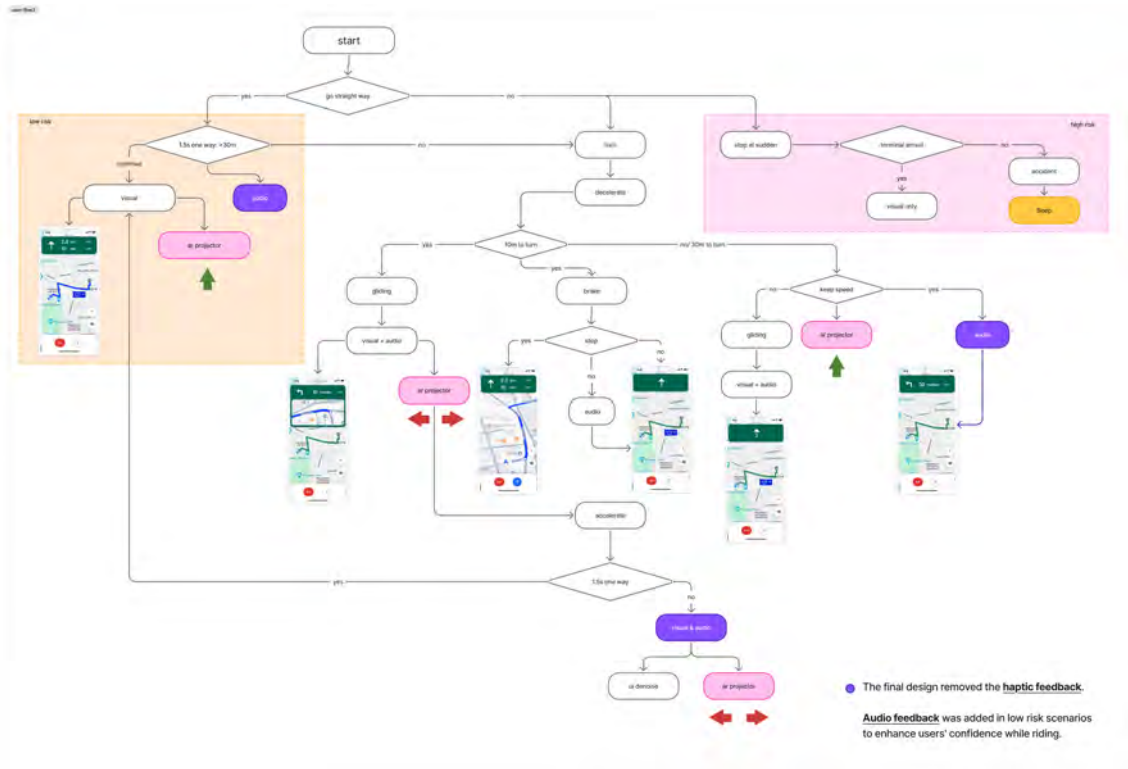


Figure 7.11: User flow and interaction design based on different scenarios

### 7.2.4 Information Design

For low-risk mode cycling scenarios, the final UI optimization removes street name details (addressing the contradiction of users unfamiliar with road names while needing navigation) and enlarges arrow indicators (Figure 7.12). Meanwhile, both distance (km) and time information are displayed. As an efficiency-focused scenario, the design prioritizes users primary needs by streamlining non-essential data.



Figure 7.12: High fidelity of the app: Low risk scenario

For medium-risk scenarios, the UI incorporates dynamic information prompts and behavioral distinctions (Figure 7.13). This layered design ensures the UI dynamically aligns with users' mental workload and physical actions, balancing situational awareness and navigational efficiency.

- Deceleration Intent Analysis
  - Active Braking: Indicates high cognitive load; prompts users to pause and view holistic navigation details.
  - Gliding Deceleration: Signals ongoing mobility; the interface only enlarges directional cues for the forward path.
- Distance-Based Adaptation:
  - 10m Deceleration: Triggers enlarged road details (e.g., junction layouts) to support turn execution and improve task completion (Figure 7.14).
  - 30m Deceleration: Marks the threshold of low-risk driving; pre-alerts users of an upcoming turn to facilitate proactive adjustment.
- Behavior-Information Mapping:
  - Heavy braking correlates with overwhelming information load, necessitating simplified, high-priority UI (e.g., route summaries).

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- Gradual coasting allows for focused but non-intrusive guidance (e.g., enlarged arrows without full-map expansion).

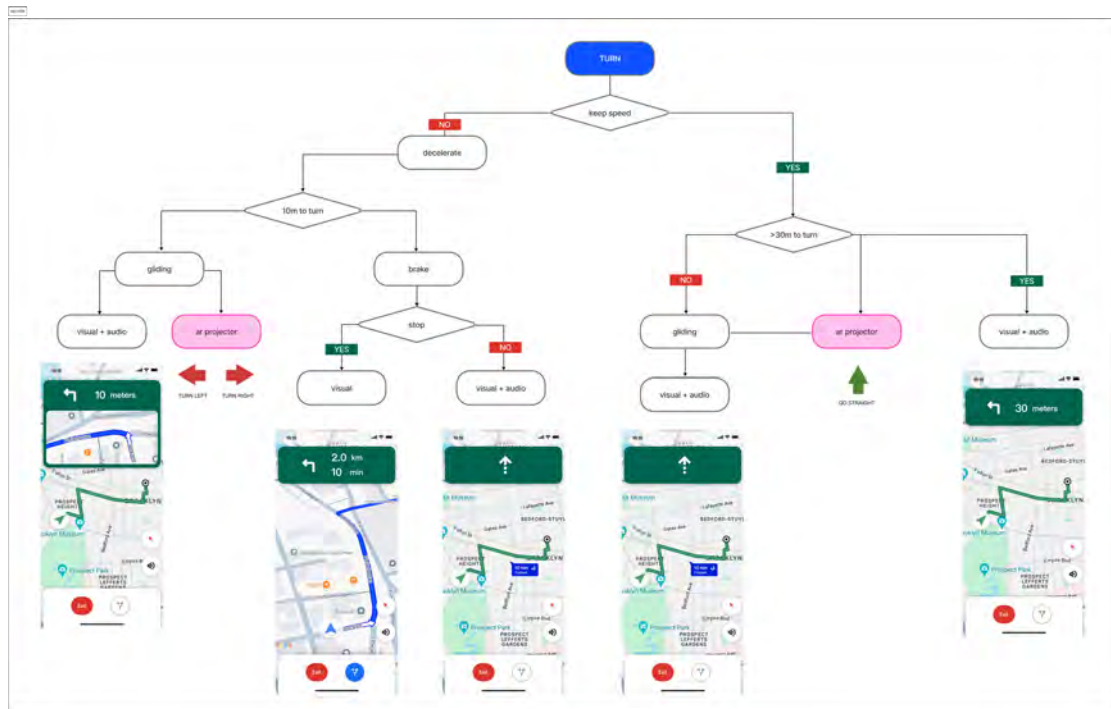


Figure 7.13: High fidelity of the app: Moderate risk scenario



Figure 7.14: High fidelity of the components: amplified route details

### 7.2.5 Sensory Design

The final iterative design deliverables include *pattern design* and *hardware design*. The hardware portion remains in the conceptual design phase, with key specifications as follows:

- Primary Materials: Foamed TPE/TPU for shock absorption and lightweight construction.
- Structure: Bolt-and-tubular nesting connections for modular assembly and adjustability(Figure 7.15).
- Projection Geometry: The projector is angled to optimize road coverage, with a raised lower section housing the battery and chip module.





Figure 7.15: Different views of the rendering of AR projector Model

Since this AR projector design does not actually involve hardware development, the conceptual design was carried out in a VR environment. The specific AR projection parameters are as follows:

- AR indicators will only be projected 3 meters before a turn, with no interaction displayed on other road sections, minimizing interference with the user's driving behavior.
- Each AR prompt will flash for 2 seconds and then stop.
- A green arrow will indicate a straight path, while a red arrow will indicate a turn(Figure 7.16).



Figure 7.16: The pattern design of the AR projector



# 8

## Discussion

This chapter reflects on the research findings, interpreting how the multimodal navigation design addressed the study's research questions and objectives. It also critically examines methodological decisions, discusses the process and design outcomes, and outlines implications for future work.

### 8.1 Result Discussion

#### 8.1.1 Design Result

The final prototype integrated three sensory channels—visual, auditory, and augmented-reality feedback—into a cohesive navigation experience. The combination of AR visual cues, audio guidance, and a map-based UI allowed riders to maintain focus on the road while still accessing spatial information when necessary. Key features included:

- **Augmented Reality (AR) visual cues:** Directional arrows were overlaid onto the rider's view (via a smartphone-based AR display), providing clear, eyes-on-road guidance for upcoming turns.
- **Auditory prompts:** General audio cues (voice) signaled turn timing in sync with the AR arrows.
- **Map-based UI:** A smartphone app displayed an overview map and route; this screen-based UI was intended for occasional strategic checks rather than constant use.

Quantitative testing demonstrated that this multimodal approach substantially improved both task performance and cognitive efficiency compared with unimodal systems. The full AR + audio + UI condition achieved an efficiency score of  $E = 0.84$ , the highest among all configurations. Although NASA-TLX results suggested a marginal increase in overall workload relative to simpler dual-modality setups, the differences were small and acceptable within the riding context. Riders consistently completed navigation tasks more quickly and with fewer perceived interruptions.

From a user-experience perspective, the AR and audio modalities provided clear temporal synchrony—the projected arrow visually indicated the turn direction while the corresponding auditory cue confirmed timing. Participants described this as smooth, natural, and easy to trust. In contrast, the UI-only condition forced fre-

quent head movements and manual confirmations, which disrupted concentration and induced visual fatigue.

These findings reinforce a central insight: multimodal feedback does not simply add information; it redistributes cognitive effort across channels. When designed coherently, it enhances attention and situational awareness rather than overloading the rider. This synergy explains why riders reported both greater comfort and stronger confidence in traffic, even though the number of cues increased.

### 8.1.2 Research Questions Result

#### 8.1.2.1 Research Question 1

*In what ways does multimodal interaction enhance both user safety and user experience in navigation systems for shared mobility?*

The results clearly demonstrate that multimodal interaction enhances safety by reducing visual dependency and allowing riders to maintain continuous environmental awareness. Compared with single-modality conditions, the inclusion of AR and auditory guidance significantly improved task accuracy and reduced response times. Statistical tests confirmed the superiority of multimodal setups ( $p < .001$  for all comparisons with UI-only).

Subjectively, participants described the AR projection and audio combination as a form of eyes-up navigation. Instead of glancing down at a phone screen, riders could interpret directional information through peripheral vision and spatial hearing. Eighteen out of thirty users highlighted that this dual channel helped them trust the system without looking. Consequently, both objective measures (e.g., lower NASA-TLX scores) and self-reported feedback aligned to indicate enhanced perceived safety and smoother experience.

In sum, multimodal interaction enhanced performance and minimized mental load by distributing information across channels that match riders natural perceptual strengths: vision for direction, hearing for timing, and touch for occasional control.

#### 8.1.2.2 Research Question 2

*Which modality is dominant when riding and in what contexts? What modality synergies can we construct from observation studies and what prototypes can we develop to facilitate multimodal interactions?*

The findings indicate that AR and audio cues play dominant roles during actual riding, while the UI serves mainly as a supportive reference. Participants relied on AR for directional guidance and used audio to confirm timing and proximity to turns. The visual UI was most often consulted before or after the ride to review routes or when the rider stopped temporarily.

Different contexts affected which modality was prioritized. In low-risk or familiar

environments, riders mainly used AR, as it provided enough information for smooth navigation. In moderate-risk situations, such as intersections or unclear routes, the auditory channel became more important for alerting and timing. In high-risk or unfamiliar environments, users occasionally checked the UI for reassurance but still depended primarily on AR and audio while in motion.

Interview responses further showed that riders viewed the visual interface as a backup tool rather than a constant source of information. Many said they only used the map at the start of a journey or when stationary. Overall, the combination of AR and audio created a natural, balanced experience: the visual channel offered spatial orientation, while the auditory one reinforced timing and confirmation. This pairing minimized distractions and reduced the need to look away from the road.

Although the experimental design did not isolate the AR + Audio condition as a standalone group, qualitative feedback strongly suggested that this combination provided the most effective and user-friendly interaction. These findings confirm that multimodal integration, particularly through AR and audio, allows for safer, more efficient, and context-adaptive navigation.

### 8.1.2.3 Research Question 3

*Would the number of navigation output modalities during riding affect users' safety and user experience?*

The results show that the number of output modalities influences user performance and safety, but the relationship is not linear. Adding one additional modality generally improved navigation accuracy and reduced cognitive load. For example, dual-modality conditions (AR + Audio or UI + AR) outperformed the single-modality setups. However, when a third modality was added (UI + AR + Audio), the improvement became smaller, and cognitive workload slightly increased.

The three-modality configuration achieved the highest efficiency score but also resulted in marginally higher effort ratings. This suggests that while multimodal systems enhance performance, excessive sensory input may initially cause confusion. Several participants mentioned that it took a bit of time to get used to the signals, but after a few trials, they found the coordination clear and effective.

In conclusion, the findings suggest that two well-designed modalities—particularly AR and audio—offer an optimal balance between information richness and mental effort. Although the full three-modality setup can still be valuable in high-risk or accessibility-focused contexts, excessive cues may not always translate into better usability. Effective multimodal design should therefore prioritize clarity, coordination, and adaptability over quantity.

## 8.2 Process Discussion

### 8.2.1 Research Process

The research adopted a user-centered and research-through-design approach that combined qualitative and quantitative methods. This framework allowed iterative development and continuous feedback between empirical testing and concept refinement.

However, some methodological limitations should be acknowledged. The interview sample was relatively small and mainly composed of university students aged 18-30. This narrow demographic reduces representativeness and may not reflect the broader e-scooter user base. Furthermore, usability testing took place in a controlled VR environment, which provided consistency but lacked the complexity and unpredictability of real-world conditions, such as traffic flow, pedestrians, or weather.

These factors might influence how users perceive and respond to multimodal feedback in practice. Therefore, future studies should include field experiments or realistic simulations to verify how multimodal systems perform under authentic riding conditions. Despite these limitations, the research process effectively captured how different modalities interact and how users adapt to them, generating findings that are valuable for future mobility design.

### 8.2.2 Concept Process

The conceptual development primarily explored how AR could be integrated with mobile interfaces and auditory cues to create an interactive and safe navigation experience. However, the AR implementation relied on a screen-based projection rather than a head-mounted or integrated display. This limitation made the experience less immersive and required users to hold or mount their phones at specific angles. Participants mentioned that a head-up or helmet-mounted display would likely be more practical and natural for riding.

The prototypes fidelity was also limited. The AR visuals and audio feedback were simplified and not context-adaptive, meaning they did not adjust to lighting, noise, or environmental changes. Future iterations should improve these aspects by introducing adaptive brightness, dynamic positioning, and variable audio feedback based on speed and direction.

Even with these limitations, the concept successfully demonstrated how multimodal cues can improve navigation safety and usability. It provided a working model that can be further developed into a high-fidelity prototype for real-world evaluation.

### 8.2.3 Usability Test Process

The usability testing provided valuable insights into how multimodal feedback affects user performance and workload. By using both NASA-TLX and an efficiency-based

performance model, the study quantified cognitive demand and compared different conditions systematically.

However, there are areas where future testing could be improved. The simulated environment was relatively simple and did not include distractions like pedestrians, varying light conditions, or traffic noise. As a result, the cognitive demand measured may be lower than what would occur in real outdoor riding.

In addition, the tactile (vibration) modality was excluded due to hardware limitations. Including haptic feedback could offer further understanding of how physical cues support or replace visual and auditory guidance. Accessibility factors were also partly overlooked: a few participants experienced mild motion sickness, and some found the red/green AR cues difficult to distinguish. Adopting higher-contrast or shape-based indicators could improve inclusivity.

The A/B UI test was performed using static images instead of interactive interfaces, which limited the ability to evaluate gesture control or dynamic usability. Future research should employ interactive prototypes to capture user behavior more accurately. Nonetheless, the testing procedure used in this study remains reliable and provided meaningful data for analyzing multimodal design performance.

### **8.3 Generalizability**

The generalizability of this study's findings can be analyzed from three perspectives: quantitative, qualitative, and research-through-design (RtD). Each contributes differently to understanding how the outcomes can be applied to other contexts of micromobility design.

#### **8.3.1 Quantative Research**

The quantitative analysis, based on controlled experiments and surveys, revealed consistent differences between unimodal and multimodal conditions. These results confirm the effectiveness of multimodal interaction within the study's context and support internal validity. However, since testing occurred in a laboratory setting, real-world factors such as external noise, motion, and environmental unpredictability were not fully represented. Future studies should therefore include field experiments to verify these findings under natural conditions.

#### **8.3.2 Qualitative Research**

The qualitative research offered detailed insight into users' perceptions and experiences. Even though the participant number was limited, the data reflected typical user concerns such as safety, comfort, and navigation clarity. Themes like distraction from screens and the need for hands-free guidance are widely relevant to micromobility contexts. Thus, while the results cannot be generalized statistically, their depth and contextual richness make them transferable to similar environments.

### 8.3.3 Research through Design

From the perspective of research through design, this thesis contributes reusable design knowledge and conceptual frameworks rather than prescriptive rules. The proposed dynamic modality-switching model, in which braking triggers detailed UI display and coasting activates AR and audio cues, serves as a flexible design logic that can inspire future developments in other mobility or AR applications. These insights are not meant to define universal solutions but to guide design thinking in creating adaptable multimodal systems. The modularity of the proposed framework means that designers can selectively adopt components such as AR projection distance or context-based feedback timing according to different usage scenarios.

## 8.4 Future Work

Although the study provides valuable empirical and theoretical contributions, several limitations offer opportunities for future research.

First, the cognitive workload evaluation relied on the NASA-TLX with standard weightings. However, this framework may not fully capture the complexity of continuous motion tasks like e-scooter riding, where physical and mental efforts interact dynamically. Developing a domain-specific workload model for mobile navigation tasks could provide more accurate assessment.

Second, the AR prototype employed in this study was largely static and did not dynamically adapt to environmental changes. Real-world riding involves constant motion, varying lighting conditions, and unpredictable obstacles, which future AR systems should respond to in real time.

Third, although many participants favored the AR+audio combination, this pairing was not directly included as a separate test condition. Incorporating it in future studies would help confirm its effectiveness quantitatively and deepen understanding of multimodal synergy.

Lastly, the experimental environment was controlled and lacked the complexity of real-world conditions such as weather, road surface variation, or pedestrian interaction. Field testing under natural conditions and across longer time spans would provide more comprehensive data on learning effects, behavioral adaptation, and long-term usability.

Future studies should therefore focus on developing adaptive and context-aware multimodal systems, refining evaluation methods for dynamic cognitive load, and expanding inclusivity by designing for users with different sensory abilities. Addressing these aspects will help bridge the gap between prototype research and real-world application, contributing to safer, smarter, and more accessible micromobility navigation systems.



# 9

## Conclusion

This thesis explored how multimodal interaction design can improve safety and user experience in e-scooter navigation systems. By combining qualitative and quantitative research within a user-centered and research-through-design framework, the study investigated how different sensory modalities—visual, auditory, and augmented reality (AR)—affect rider perception, cognitive workload, and task performance.

The research process began with an examination of user pain points and needs related to shared e-scooter usage, revealing that existing systems often rely too heavily on visual input and require frequent manual interaction. These issues increase distraction and reduce safety during riding. Through iterative design and testing, a multimodal prototype was developed to address these problems by distributing navigation feedback across multiple sensory channels.

Results from usability testing demonstrated that multimodal systems significantly improve performance efficiency and reduce mental workload compared with single-modality solutions. In particular, the combination of AR and audio feedback was identified as the most effective and preferred interaction model. This pairing allowed users to maintain focus on the road while receiving clear, real-time navigation information through peripheral vision and hearing. The study also found that although adding a third modality can slightly increase cognitive load, it enhances overall system reliability and flexibility in specific contexts. The findings confirm that multimodal design not only improves the usability of micromobility systems but also contributes to safer riding behavior by reducing visual dependency. In addition, the research validated the use of cognitive workload evaluation methods, such as NASA-TLX, as an effective way to assess multimodal interaction performance.

From a design perspective, this work highlights the importance of balanced sensory integration. Rather than increasing the number of feedback channels, designers should focus on how different modalities complement each other and adapt to user context. The results also suggest that adaptive systems capable of switching between modalities according to environmental and behavioral factors can further enhance the riding experience.

Although the study was conducted in a controlled environment, its methodology and outcomes provide a foundation for future field research and product development. The proposed design framework—based on multimodal synergy, adaptive modality switching, and cognitive efficiency—can be applied to a wide range of mobility and

AR-based navigation systems beyond e-scooters, such as cycling, walking, or in-vehicle interfaces.

In conclusion, this thesis contributes both theoretical and practical insights into the integration of multimodal interaction within micromobility design. It demonstrates that carefully orchestrated sensory feedback can reduce cognitive demand, improve safety, and create a smoother, more intuitive navigation experience. The results offer a meaningful step toward designing future urban mobility systems that are intelligent, user-centered, and responsive to the real-world challenges of human movement.

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# A

## Appendix 1: Interview

### **Riding Experience:**

1. How often have you been using e-scooters for transportation?
2. What is the typical distance of your e-scooter rides?
3. What are the main reasons you choose to ride an e-scooter instead of other forms of transportation? (for what purpose?)
4. How comfortable do you find the handlebars, and foot-rest area of the e-scooter?

### **Safety Perception:**

1. Do you feel safe while riding an e-scooter? What factors contribute to your sense of safety (or lack thereof)?
2. Have you ever been in an accident or near-miss situation while riding an e-scooter? If so, could you describe what happened?
3. How important do you think it is for e-scooters to have safety features like lights, brakes, and helmets?

### **Navigation and Interaction:**

1. When using your e-scooter, do you rely on a navigation system? If so, what type (e.g., smartphone app, built-in display)?
2. Have you used any special features on your e-scooter for navigation, such as turn-by-turn directions or location-based alerts? How useful were they?
3. How do you feel about the different types of warnings (auditory, visual, vibrotactile) that could be used on e-scooters? Which one do you find most effective in getting your attention in potentially dangerous situations?
4. If an e-scooter had a more advanced interaction system, like touch-screen controls or voice commands, would you use it? What functions would you like to see in such a system?

### **Future Improvements:**

1. What do you think are the most important areas for improvement in e-scooter design or functionality?



# B

## Appendix 2: Survey

### Introduction:

Thank you for taking the time to participate in this survey. We are two students from Chalmers who are doing our master thesis and we really need your feedback. Your insights will help us better understand the experiences, preferences, and needs of e-scooter riders. All responses will be kept strictly confidential.

Google Form link: [https://docs.google.com/forms/d/e/1FAIpQLSfbkCsI5bc9btsCYhx1H\\_183FFG6YMPAvsSYK4BNuzbrUYxrw/viewform?usp=dialog](https://docs.google.com/forms/d/e/1FAIpQLSfbkCsI5bc9btsCYhx1H_183FFG6YMPAvsSYK4BNuzbrUYxrw/viewform?usp=dialog)

### Personal Information

1. **\*Age:**

- (a) 18 - 25
- (b) 26 - 35
- (c) 36 - 45
- (d) 46 - 55
- (e) 55+

2. **\*Gender:**

- (a) Male
- (b) Female
- (c) Non-binary / prefer not to state

3. **City/Area where you mainly ride e-scooters:** \_\_\_\_\_

### Riding Experience

1. **\*How often do you use e-scooters for transportation?:**

- (a) hardly ever
- (b) once a month

- (c) once a week
  - (d) more than twice a week
2. **\*What is the typical distance of your e - scooter rides?:**
- (a) Less than 1 km
  - (b) 1 - 3 km
  - (c) 3 - 5 km
  - (d) More than 5 km
3. **\*What are the main reasons you choose to ride an e-scooter instead of other forms of transportation? (Select all that apply) - Multiple Choice:**
- (a) Convenience
  - (b) Cost-effectiveness
  - (c) Leisure
  - (d) Avoid traffic congestion
  - (e) Other (please specify)

### Safety Perception

1. **\*How safe do you feel while riding an e-scooter on a scale of 1 - 10 (1 = very unsafe, 10 = very safe)?:**  
1   2   3   4   5
2. **\*What factors contribute to your sense of safety (or lack thereof) while riding an e-scooter? (Select all that apply):**
- (a) Traffic conditions
  - (b) Road conditions
  - (c) Other users' behavior
  - (d) Presence of dedicated bike lanes
  - (e) Other (please specify)
3. **\* Have you ever been in an accident or near-miss situation while riding an e-scooter?:**
- (a) Yes
  - (b) No
  - (c) If yes, please briefly describe what happened:

4. **\* How important do you think it is for e-scooters to have safety features like lights, brakes, and helmets:**
  - (a) Extremely important
  - (b) Very important
  - (c) Somewhat important
  - (d) Not very important
  - (e) Not important at all
  
5. **How comfortable do you find the handlebars, and foot-rest area of the e-scooter on a scale of 1 - 10 (1 = very uncomfortable, 10 = very comfortable)?:**
  - Handlebars:  
1   2   3   4   5
  
  - Foot-rest area:  
1   2   3   4   5

## Navigation and Interaction

1. **\*To what extent do you want to put your phones inside the phone-holder?**  
1   2   3   4   5



Figure B.1: Phone holder

2. **\*When using your e-scooter, do you rely on a navigation system?:**
  - (a) Yes
  - (b) No

- (c) If yes, what type of navigation system do you use?
- Smartphone app(eg. google map)
  - Built-in display on the e-scooter
  - Other (please specify)
3. **\*How do you feel about the different types of warnings that could be used on e-scooters (auditory, visual, vibrotactile)?:**
- (a) Auditory (beeping, voice prompts):
- Extremely effective
  - Very effective
  - Somewhat effective
  - Not very effective
  - Not effective at all
- (b) Visual (lights, text messages):
- Extremely effective
  - Very effective
  - Somewhat effective
  - Not very effective
  - Not effective at all
- (c) Vibrotactile (vibrations on the handlebars):
- Extremely effective
  - Very effective
  - Somewhat effective
  - Not very effective
  - Not effective at all
4. **\*If an e-scooter had a more advanced interaction system, like touch-screen controls or voice commands, would you use it?:**
- (a) Definitely Yes
- (b) Probably Yes
- (c) Neutral / Not Sure
- (d) Probably Not
- (e) Definitely No

- (f) If yes, what functions would you like to see in such a system? (Select all that apply)
- Adjusting speed
  - Changing riding modes
  - Checking battery status
  - Navigation direction
  - Other (please specify)

## Future Improvements

- 1. If in the future there is a helmet/handlebar that combines vibration and voice interaction, would you be willing to use it?**
  - (a) Extremely willing to use
  - (b) Very willing to use
  - (c) Somewhat willing to use
  - (d) Not very willing to use
  - (e) Not willing to use at all
- 2. What do you think are the most important areas for improvement in e-scooter design or functionality? (Select all that apply):**
  - (a) Longer battery life
  - (b) More comfortable ride
  - (c) Better safety features
  - (d) More advanced navigation systems
  - (e) Other (please specify)

## Additional Comments

Do you have any other thoughts, suggestions, or experiences related to e-scooter riding that you would like to share?

Thank you again for your participation in this survey. Your responses are invaluable in helping us understand the e-scooter riding community better. If you have any questions about the survey, please feel free to contact us at [yiongday@gmail.com](mailto:yiongday@gmail.com)