# Grand challenges in CyclingHCI

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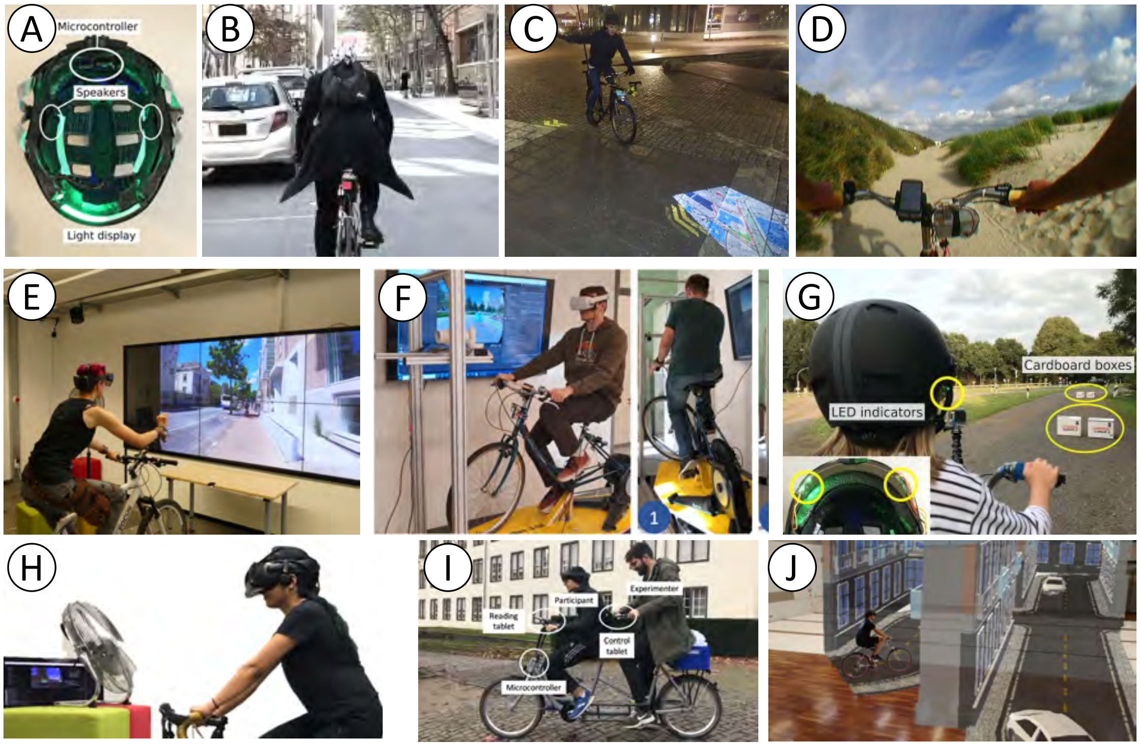


Fig. 1. Overview of CyclingHCI works that demonstrate current technological advances: augmented helmets and bicycles with visual, auditory, and vibrotactile feedback (A) [69], brain-controlled interaction between e-Bikes and riders (B) [12], hand and head tracking (C) [34], outdoor experiments to increase ecological validity of the results (D) [90], bicycle simulators with screens [59] and in Virtual Reality (E-F) [124], conducting CyclingHCI studies with particular user groups, e.g., children (G) [68], reducing motion sickness via airflow (H) [78], self-driving bicycles (I) [76], and cycling in Augmented Reality (J) [77].

Cycling Human-Computer Interaction (CyclingHCI) refers to the study and design of user interfaces and interactions between bicycles and riders in the context of cycling-related experiences. To date, however, there has yet to be a structured agenda for CyclingHCI to clarify the immediate challenges researchers should address next and facilitate the advancement of the field. We, three CyclingHCI researchers who collectively designed, developed, evaluated 18 CyclingHCI projects, reflected on our experiences to derive 10 grand challenges that we articulate with design opportunities and considerations grouped into: (1) Pushing the technological boundaries



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for cycling, (2) Understanding and protecting cyclists, and (3) Spatially situated cycling interaction. Our findings provide practical implications for research and practice in CyclingHCI, with which we aim to enrich the cycling experience through the safe integration of technology.

CCS Concepts: • **Human-centered computing → HCI theory, concepts and models**; **Interaction paradigms**.

Additional Key Words and Phrases: grand challenges, cycling, interaction, bicycle

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## 1 INTRODUCTION

Cycling Human-Computer Interaction (CyclingHCI) is concerned with the coming together of bicycles and interactive technology. CyclingHCI offers the opportunity to contribute towards addressing some of the world's most pressing issues, such as obesity due to a lack of physical activity and environmental pollution due to car use. Some of the most prominent examples from this research field encompass a diverse array of technologies, such as cycling in augmented [59, 76, 77] and virtual environments [18, 75, 78, 124], mobile phone-enhanced assistance [37, 61, 131], interactive bicycle helmets [68–70, 76, 123], projected surfaces around cyclists [34, 35, 68], and tracking of cyclists' behavior [70, 73]. Research and industry drive technological advancements offering bicycle riders additional functionality, such as smartphones with GPS for wayfinding, gyroscopes for sensing motion, and accelerometers for speed monitoring. These offer HCI researchers opportunities to study, improve existing, and invent new human-bicycle interactions.

CyclingHCI has come a long way in improving interactions between bicycles and riders. In the early 1980s, Steven K. Roberts was the first to augment a bicycle with a solar-powered portable computer and a keyboard for typing while cycling [96]. Almost three decades later, in the late 2000s, CyclingHCI has exploded into a rapidly growing body of novel interaction techniques, simulations, and applications by adding vibrotactile feedback on a handlebar [92], augmenting bicycles with connectivity and sensing [37, 61, 131], and image-based route generation [41]. Later on, research efforts contributed towards designing co-present [32], social exertion [123], cycling in groups [21, 44, 60], and supporting recreational activities [31, 129] through cycling experiences, augmenting environments around cyclists [34, 35], interacting with environment and other road users [1, 3, 20, 33] and on-the-go [30, 51, 72, 127], and assistance systems [19, 48, 95, 116, 118]. The invention of electrically powered bicycles, i.e., e-Bikes, has changed cycling [1] as they offer a sustainable and healthy alternative to cars, commuting for longer distances, promote an active lifestyle, and reduce air pollution and traffic overcrowding, and provide a platform for technological advances for cycling. For example, Boreal Bikes created a platform to augment cycling experiences by offering a power supply and an onboard computer [2]. These developments opened up research opportunities for improving interactions with e-Bikes [8–10], creating simulated experiences in extended reality [28, 59, 75, 77, 78, 117, 119], crowd-sourcing [25, 73, 99] and contextual [128] solutions, and self-driving bicycles [76, 125]. Although CyclingHCI has contributed a vast number of technological advancements and novel interactions over the last couple of decades, it needs a structured way for future advancements. With this work, we aim to accelerate the progress of CyclingHCI by presenting grand challenges to help the community enrich the cycling experiences through interactive technology.

[1] https://s3.eu-north-1.amazonaws.com/vmn-bike-eu.com/2022/06/deloitte-e-bike-sector-briefing-1.pdf, https://www.mordorintelligence.com/industry-reports/e-bike-market

[2] https://www.borealbikes.com/


Fig. 2. The grand challenges process was based on preparatory reflections and eight sessions held over four months.

In this paper, we describe 10 grand challenges for CyclingHCI, grouped into three categories: (1) Pushing the technological boundaries for cycling, (2) Understanding and protecting cyclists, and (3) Spatially situated cycling interaction. We derived these challenges through a community-focused approach [6, 40, 82] across eight sessions over a four-month collaboration between the authors who have collectively been involved in the design, development and evaluation of 18 CyclingHCI systems. Our work takes inspiration from previous compilations of challenges in HCI to advance different agendas, such as shape-changing interfaces [6], immersive analytics [40], tangible systems [121], SportsHCI [38], human-food interaction [85], and human-computer integration [82]. This work aims to bring together the growing CyclingHCI community, inform common research goals, help researchers new to CyclingHCI, and provide a coherent view to external stakeholders such as cycling companies and funding agencies.

## 2 CYCLING IN HUMAN-COMPUTER INTERACTION

This section provides an overview of efforts to establish the emerging field of CyclingHCI. We review these efforts and focus on recent results demonstrating the field's advancements and lessons learned from prior work.

### 2.1 Mapping a New Domain

We begin with a historical account of CyclingHCI efforts to date:

- **Lessons learned:** In 2009, Rowland et al. [97] presented eight lessons from designing two CyclingHCI systems. This work was the first one that went beyond individual point designs and tried to articulate a broader guide for CyclingHCI researchers. However, these lessons were articulated in 2009, and technological advancements since then necessitated a new effort to articulate the field's challenges. For example, the authors did not consider eBikes as they were not as commonplace at the time.
- **Conference workshops and a cycling event:** Several workshops have been conducted at major HCI conferences (German HCI Conference Mensch und Computer 2021 [120] and 2023 [103], MobileHCI 2021 [74], CHI 2021 [100], Augmented Humans 2023 [2], and CHI 2024 [71]). In 2021, there was a SIGCHI International Cycling Event connected with a MobileHCI 2021 Workshop [74] sponsored by the SIGCHI development fund [3]. This event facilitated an international exchange among researchers working in CyclingHCI from the USA, Canada,

[3] https://sigchi.org/resources/sigchi-development-fund/

India, the Netherlands, and Germany, which included the systematic development of interactive prototypes over three months, invited talks from experts in the field, and networking. The research agendas at these workshops focused on augmenting cyclists, understanding cyclists' behavior, novel cycling interfaces and their social impact, safe evaluation of novel interfaces, e.g., the use of simulators and extended reality methods, understanding of mobile interaction, and joint efforts to work towards developing a future research agenda. Although these efforts created a good foundation to advance the field, they contained limited research directions discussed over a short period. However, these workshop discussions have inspired us and paved the way to continue the CyclingHCI community's efforts in shaping the research agenda by deriving grand challenges.

### 2.2 State-of-the-Art in CyclingHCI

Since the bicycle's invention in 1817, a series of improvements have occurred around the design and types of interactions available for cyclists, ranging from equal-sized wheels and a low center of gravity to make the bike more stable and safer [52], the introduction of pneumatic tires, chain drives, gears, and the more recent development of materials for bicycle frames, adding electric motors to ease of riding, and additional interactive technologies for riders (Figure 1). These recent efforts include the augmentation of helmets, cyclists, and bicycles to provide warnings, navigation instructions, or traffic behavior recommendations using visual [69], auditory [4, 69], or vibro-tactile feedback [55, 67, 69, 90, 105, 109]. Since E-Bikes provide "power assistance" to riders [43, 56, 102] to go farther and faster with less physical effort, new interactions between e-Bikes and riders has emerged, e.g., to adjust to cyclists' movements or peripheral awareness [8, 10]. Hand and head tracking [35, 70, 105] is used to understand cyclists' actions on-the-go, e.g., hand gesture or shoulder look. Series of outdoor experiments were conducted to increase the ecological validity of the results and understand cyclists' behavior under real-world conditions [12, 19, 90, 129]. To simulate cycling experiences in safe and controlled indoor conditions, researchers have built bicycle simulators with screens and Virtual Reality headsets [18, 59, 67, 118, 124]. Several experiments were conducted with child cyclists [68], given their developmental differences compared to adult cyclists. Recent attempts were focused on reducing motion sickness in bicycle simulators via dynamic airflow [78]. Researchers introduced tandem-based simulators [76, 125] to replicate futuristic cycling on self-driving bicycles and interaction with other users [122, 123]. Lastly, cycling in Augmented Reality [77] was focused on balancing the safety and realism of simulated cycling experiences. The works not shown in Figure 1 also include navigation [4, 69, 90, 109], safety systems based on crowd-sourcing [12, 42, 58, 66, 79, 93, 98], and interaction with other road users [122, 123].

Inspired by the current developments in the field, we conducted discussion sessions to derive grand challenges. In the following sections, we outline the methodology used to derive the challenges, provide a list of the challenges, and a discussion.

## 3 METHOD

Our research method centred on expert sessions [39, 87, 110] to collect insights. Over sixteen weeks, we discussed our learnings from prior work and experience designing, implementing and evaluating 18 CyclingHCI systems (Figure 2). The analysis resulted in initial thematic areas that we refined over multiple sessions to converge into 10 grand challenges, grouped into three categories: (1) Pushing the technological boundaries for cycling, (2) Understanding and protecting cyclists, and (3) Spatially situated cycling interaction. We accompany each grand challenge with associated design opportunities. Our approach is motivated by previous efforts in HCI [40, 87, 110] to pinpoint key challenges through extensive multi-day workshops and discussion sessions.

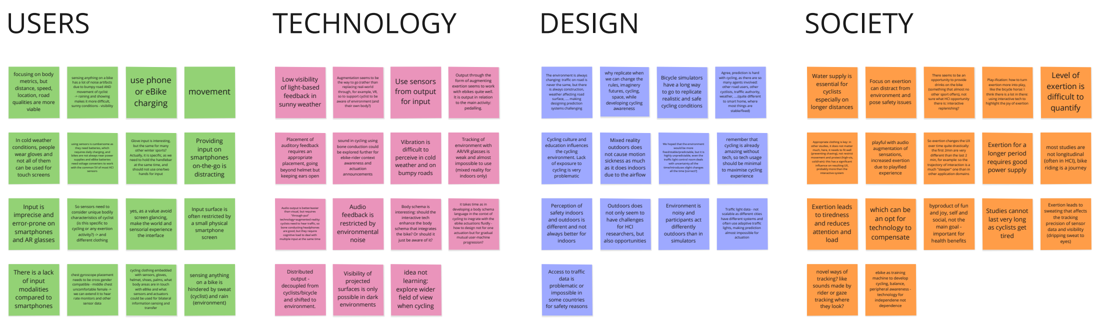


Fig. 3. Digital whiteboard for the initial ideation of Grand Challenges in CyclingHCI.

### 3.1 Participants

We reflected on our spectrum of seniority levels and having worked in academia, industry and industrial research settings, and how this affected our view on CyclingHCI. We also reflected on our varied cycling-related projects, from developing novel CyclingHCI prototypes to providing consultancy for a large city's urban cycling infrastructure. The second and third author worked primarily in two Australian cities (Melbourne and Canberra), while the first author is in Sweden but has worked on CyclingHCI projects in Germany, with 55 years of combined experience designing interactive systems (10, 15, and 30 years, with an average of 18.33 years). We have CyclingHCI experience across various settings, populations, and technological interventions, from enhancing cycling safety and navigation, understanding cycling behavior through mixed methods, creating playful experiences and promoting exertion, facilitating social cycling, and employing virtual and augmented reality for both skill development and athletic performance. This diverse expertise highlights the broad CyclingHCI coverage and deep understanding of different cyclists and technology relations for our study. We present the first account of grand challenges for CyclingHCI, acknowledging that future work could involve more experts. However, we note that prior work on grand challenges has employed expert numbers as small as one [17], two [91, 115] and three [112] to contribute to other grand challenge articulations.

### 3.2 Procedure

The development of the grand challenges was initiated by starting with a short introduction to the grand challenges activity, including examples from past grand challenges papers in other areas of HCI. Throughout eight sessions held virtually and in face-to-face settings, we presented and discussed the number and type of grand challenges. We considered the main overarching categories under which grand challenges were clustered in prior publications: those related to users, technology, design, and society. Prior to each session, we tasked ourselves to reflect on our CyclingHCI designs individually. Each documented their contemplations of challenges and then shared them amongst the collective. This strategy aimed to ensure that diverse viewpoints were adequately acknowledged and represented. During each session, every participant presented an articulation of the challenges facing our investigations. These challenges were added to four flip-over sheets, initially clustered in the four aforementioned overarching categories as a starting point. Through the presentations, a comprehensive list of challenges was collated, consisting of challenges identified by the authors in their preparation for the seminar and challenges identified while listening to other presentations, providing a foundation for steering discussions during the later activities.

| Categories | | Challenges |
|---|---|---|
| Pushing the technological boundaries for cycling | C1 | Reducing cyclist's reliance on technology |
| | C2 | Creating cycling technology to withstand weather and road conditions |
| | C3 | Providing cycling technology for exertion |
| | C4 | Creating realistic, safe, and motion sickness-proof bicycle simulators |
| Understanding and protecting cyclists | C5 | Understanding how to support environment-related cycling behaviour |
| | C6 | Supporting data privacy collected by a smart city |
| | C7 | Understanding cyclists' body movements to optimally support the cycling experience |
| | C8 | Interpreting and protecting data collected by cyclists |
| Spatially situated cycling | C9 | Facilitating cyclists' interactions with other road users |
| | C10 | Maintaining cyclists' connection to surroundings |

Table 1. An overview of grand challenges in CyclingHCI.

Based on the gathered challenges, an initial clustering was made by the first author (Figure 3). Extending on the four clusters derived from previous exemplary grand challenges papers [6, 40, 82], the author grouped the challenges across "users", "technology", "design", and "society". This clustering was discussed with everyone at the start of the next session to reach a consensus before deriving grand challenges from the resulting collection of materials. Out of all the challenges gathered in the initial stages to determine what constitutes a Grand Challenge in CyclingHCI, the following inclusion criteria were discussed after the initial clustering based on the questions used in the work by Elvitigala et al. [38], as we aimed to omit common challenges that are not specific to CyclingHCI purportedly:

(1) Is the challenge specific to CyclingHCI? If not, does it play out differently in CyclingHCI than in other fields?
(2) Is the challenge important for the field and not easily solved?
(3) Is the challenge feasible, i.e., solvable in the next ten years?

We discussed a list of potential grand challenges based on the collective difficulties gathered according to the criteria. This included cyclists' reliance on technology, cycling technology for different weather and road conditions, cycling for exertion, simulating and replicating cycling activities, cycling culture, data privacy for cyclists, cyclists' body movements, data collection, behavior and interaction of other road users, and maintenance of cyclists' connection to surroundings. Those topics were all identified in the group discussions as being potentially "grand" challenges. Afterwards, we elaborated on the proposed grand challenges. We revisited the proposed grand challenges by following previously published HCI grand challenges methodology [6, 40, 82] which recommend specific instructions for what we wanted to achieve at the end of this step, such as "what additional challenges are missing?". This allowed us to cast new questions over the challenges and their overlaps to refine them. Our intermediate results are depicted in Figure 3 that includes a Miro board with ideas/challenges grouped in four categories: "users", "technology", "design", and "society". This way, we arrived at the broader grand challenges that can inform future research opportunities. After identifying grand challenges (Table 1), we looked back into the literature to identify state-of-the-art related to each grand challenge to provide a better understanding of which of the challenges are already being worked on and which are still in their infancy. Additionally, we discussed potential paths forward with these challenges (marked bold in the next section) and summarized in Figure 4.

## 4 PUSHING THE TECHNOLOGICAL BOUNDARIES FOR CYCLING

### C1: Reducing cyclist's reliance on technology

It has been discussed during the sessions that, in cycling, creating technology that does not lead to cyclists' reliance on it is challenging [11, 106]. Reliance on technological support does not imply a decrease in cycling accidents, and outsourcing the decision-making process to technology does not mean higher safety. The challenge lies in harnessing technology to enrich cycling while ensuring safety and determining the right balance of technology: to improve cycling experience and safety. However, cyclists' reliance on technological assistance has been shown to be dominant [77, 117, 119], making them follow more what a system is telling them to do rather than relying on their judgments. This can lead to a loss of skills, decreased awareness, an inability to make decisions, and a decrease in road safety [14, 36, 49].

One way to address this challenge is by turning technology into a coach or using it for educational purposes. For example, sensing technologies focusing on cyclists' safety motions [47], such as indicating turns with their arms and doing shoulder checks, could support in-the-moment notifications or reflection logs about increasing one's safety motions. Likewise, for assistance systems based on Augmenting Reality [77, 117, 119], cyclists can learn which road aspects have to be considered for a decision-making process and possibly presented on demand after recognizing that a cyclist was distracted. In these cases, ***technology can be a coach*** that helps develop a skill, such as learning to perform the range of movements that signal intent to other cyclists, vehicles, and pedestrians. Often, these motions can differ across countries; signaling that one will stop in Denmark means placing one hand in front and then slowing down - in Australia, cyclists stop without signaling. The coaching system must be socially situated to support the cycling motions in a given country. Importantly, coaching systems could create power dynamics in which the cyclists obey the technology rather than harnessing their cycling skills. Gradual technology for hands-off coaching is needed in system design to support skills practice. Additionally, cycling systems need to ***consider cycling context and assess cyclists' intentions***, such as environment, cyclists' attention, physiological state, and skill level, before offering assistance.

### C2: Creating cycling technology to withstand weather and road conditions

While technology has the potential to improve the cycling experience, it still needs to be mature enough to withstand a wide range of weather and road conditions. For example, cycling technology needs to withstand heavy rain during a full-day cycling trip. Unfortunately, there is not much guidance about creating such technology. We note that advances have been made, for example, there are now sealers and nanotechnology-based water-repellent sprays that can protect HCI prototype hardware [4]. Moreover, there is little guidance on making interactive devices shockproof to withstand rough roads or physical impacts due to accidents. Lastly, exposure to ultraviolet (UV) radiation is another aspect related to weather conditions since UV rays hitting the bicycle during long cycling tours can easily damage plastic casings, and the battery's performance of the prototype is severely affected by too hot temperatures, which results in a shortened battery life and e-waste. Although waterproofing knowledge exists in the form of IP ratings [5], for CyclingHCI, it is important to balance waterproofing and weight.

During the sessions, it has been discussed that the IP rating system can be useful for CyclingHCI researchers, but only to a limited extent. For example, the IPX7 rating (colloquially referred to as waterproof) means the device will stay functional if fully submerged in 1-meter deep water for 30 minutes. What this means for cycling technology needs to be clarified. Will it withstand heavy rain during a full-day cycling trip? The IPX6 rating (colloquially referred to as

[4] https://www.lexuma.com/products/x2o-water-repellent-spray-for-electronic-devices
[5] https://www.audioreputation.com/ipx7/, https://www.audioreputation.com/ipx6/

water-resistant) is also used with cycling accessories. This implies that a device will stay functional when sprayed with a 15 psi strong water jet at any angle from 3m distance for 1 minute. Similarly, this does not tell us whether the device will withstand heavy rain or even hail during cycling [6]. Furthermore, the lack of the necessary equipment to test the prototypes against such environmental impact often leads to broken equipment that results in e-waste. If this challenge is solved, CyclingHCI researchers can more easily develop ***durable and weather-resistant cycling prototypes***. Progress exists, though, and we point to the emerging wide availability of capacitance-transparent smartphone cases that allow mounting on bikes that now feature ultraviolet and shock-resistant surfaces.

### C3: Create cycling technology suitable for intense exertion

Smartwatches [7], rings [29], and in-body prototypes [62] capture, amongst others, heart rate variability, body temperature, blood glucose, and oxygen levels to provide cyclists with a better understanding of how their body responds to the exerting activity. However, sweat can affect data from the responding body and lead to overexertion while training, influencing the accuracy and durability of these cycling sensors. Such skewed or incomplete data affects the tracking of bodily responses during cycling activities, limiting opportunities to help facilitate safe training, for example, by decreasing exertion, improving training effects, and preventing injury and overexertion. Unfortunately, creating technology that provides accurate and sweat-resistant data from the responding body in a durable form is challenging.

As we have discussed during expert sessions, there is a need to design and develop mechanisms and materials that ***prevent overheating and overexertion*** by, e.g., notifying cyclists and trainers to limit further exercising based on current bodily responses. These can include cooling mechanisms, applying aerogel, or adding mechanical solutions that prohibit cyclists from cycling faster.

### C4: Creating realistic, safe, and motion sickness-proof bicycle simulators

Bicycle simulators are an imitation of cycling and play a vital role in maintaining cardiovascular health, improving physical shape through gamification [15, 50, 111], and provide a safe and low-cost evaluation platform for researchers [114]. Due to the advances in VR technology and its advantages in enabling a high degree of presence and immersion in 3D environments, most of the existing bicycle simulators [23, 63, 64, 107, 114, 119, 130] are placed on stationary platforms and use a VR headset to present a virtual world to users [46, 108]. While such a setting of simulating cycling experience is considered safe since users do not encounter real physical danger, i.e., encounters with real cars, they lack balancing and physical movement through space. While research in this area is ongoing and new approaches based on Extended Reality and tandem-based simulations are introduced [75–77], simulating safe and realistic cycling experiences without introducing motion sickness is challenging.

During the sessions, we discussed the challenges of realism, safety, and motion sickness and needed a better understanding of how to balance these three aspects of cycling simulators. One way of addressing this issue would be to ***redesign bicycle simulators*** and possibly go away from existing construction consisting of a bicycle placed on a fixed platform towards immersive environments that allow redirected cycling [77] or even minimalistic setups that do not necessarily need a whole bicycle [75]. Some strategies to navigate these challenges can include outdoor bicycle simulators with safety assistance, such as tricycles [70]. As for reducing motion sickness in VR bicycle simulators, possible solutions can include ***adding external countermeasures that reduce motion sickness*** that do not necessarily belong to cycling experiences, e.g., reduction of the visual field of view or vibrotactile on-body feedback.

[6] https://www.audioreputation.com/ipx6/
[7] https://www.apple.com/watch/

## 5 UNDERSTANDING AND PROTECTING CYCLISTS

### C5: Understanding how to support environment-related cycling behaviour

Designing interactive systems that protect cyclists from the harsh elements while preserving tight engagement with the environment is challenging [113]. Researchers have already begun to support cyclists dealing with the elements through ultraviolet protection devices and body cooling systems. However, these advancements are not (yet) very interactive. We believe that interactivity can significantly progress how design can support the cyclist dealing with the elements. Cyclists might consider riding in incremental weather unpleasant, and if they have the choice, wait for better weather, for example, when intending to cycle for pure enjoyment. However, prior research has found through interviews with dedicated sports enthusiasts that they can regard the weather's impact on their experience as a challenging aspect that contributes positively [113]. In particular, previous research has suggested that exercising in challenging weather conditions can highlight the adventure aspect of an exertion experience [7, 13, 81, 83, 84], e.g., to turn an everyday exercise activity into a "mini-adventure" [83]. Unfortunately, there is not much knowledge available that could aid with designing systems that balance cyclists' desire for comfort and adventure. For example, should a system, upon detecting rain, unfold a retractable hardtop that encloses the rider, like in a convertible car, with the advantage of protecting the rider from the elements, or would riders feel disconnected from their environment? The limited popularity of velomobiles (bicycles with an enclosed body) suggests that cyclists might favor a closer connection with the environment [5].

Previous research has begun to paint a picture of how weather impacts cyclists. For example, Bean et al. [16] found that people cycle even in wet weather in cities such as Dublin, Seville, and Valencia. In contrast, in places like Melbourne, Chicago, and Vancouver, people avoid cycling when it rains. These findings indicate that people are more accustomed to precipitation, as Dublin is notoriously rainy, but, at the same time, Seville and Valencia are rather dry. Still, rain there does not make much of a difference to the cyclists [16]. Research also highlighted that cyclists vary their behavior depending on the season, suggesting that interactive technology might need to consider what season it is [16]. Furthermore, research found that cyclists are affected by inclement weather, for example, cycling in winter in the dark [86], and that any cycling support should consider global warming [22], as "global warming is likely to lead to ridership increases in colder climates and declines in warmer climates" [16]. This underdeveloped understanding makes it difficult for HCI researchers to support cyclists, as it is unclear what type of interactive support they would benefit from and how regarding inclement weather.

During our sessions, we discussed that more user studies, mainly using qualitative approaches such as ethnography, could help address this challenge. CyclingHCI needs to not only find out what context to consider, such as seasons but also how to utilize this data, in particular, how to design interactive systems, e.g., using shape-changing solutions, that can protect the rider from any harsh elements while preserving the tight engagement with the environment. ***Adaptive shape-changing bicycles*** is a possible solution for this challenge, given that there are solutions that protect cyclists from rain and sun, which employ a housing around them or even umbrellas. However, there is a need for mechanisms that would enable transformations from a regular bicycle to one with a protective roof, and how to create such mechanisms poses challenging design and engineering problems.

### C6: Supporting data privacy collected by a smart city

While cyclists would benefit from improved safety if bicycles could seemingly exchange information with infrastructure in today's smart cities [104], for example, how busy a road is with trucks, such communication raises ethical questions about privacy. Do cyclists want to share their data with other road users? What data will be shared, e.g., location information or more personal data from the heart rate monitor? Is the data shared only with road users nearby or beyond that, and is it stored beyond the immediate moment, for example, for long-term diagnostics? Could insurance companies use this data to deny a cyclist health insurance? How to balance the benefits of sharing bicycle data, such as increased safety, with privacy issues is still an open question.

The challenge of handling privacy around personal data is familiar to HCI [53, 89]. Here, we highlight that large amounts of data will be captured through CyclingHCI systems, allowing for a fine-grained understanding of the cyclist, often coupled with very personal data, e.g., from biosensors. Furthermore, cyclists need to focus on their cycling activity. Hence, they do not have an easy option to consent to individual data-sharing options. Potential paths forward with this challenge include ***local on-device data collections*** during cycling to maintain the focus on the exercise. The communication with the cloud services and pushing the data to the cloud can be confirmed by a cyclist at a different point in time, with the possibility of deleting the data at any time. Alternatively, solutions encompassing ***an ecosystem of local devices that help cyclists collect, store, and analyze their data*** can be proposed. This way, cyclists do not necessarily have to share their data with third parties.

### C7: Understanding cyclists' body movements to optimally support the cycling experience

While it is technically possible to map the moving body beyond its natural capabilities due to technological developments such as gears and e-Bike electrical engines, we do not yet understand how to design the "superpowers" we give people through interactive cycling systems. It is a technical challenge to map the movement of the legs to the engine support that an e-bike should support. Moreover, there is still an open question of how to engage with kinesthetic understandings of body movement and create the associated models.

A key technological invention in the history of cycling was the introduction of gears [8]. The gears facilitate dynamic mappings of cyclists' leg movements to different distances the cyclist covers. The system determines how a cyclist's leg revolution is mapped to a covered distance differently than without the system, allowing them to climb steep mountains and reach high speeds. Initially, gears were a purely mechanical improvement. However, new electronic shifting systems allow faster shifting under full load, but many technical challenges still need to be resolved. These new electronic shifting systems still rely on mechanical parts, limiting the number of gears they can support. Possible solutions discussed during the sessions include extending the knowledge ***to create kinesthetic models of cyclists***. However, unlike camera-based systems suitable for the living room context, such as the Kinect, we assume the cycling kinesthetic model toolkits would probably use IMU sensors attached to the cyclist's body. For example, while cyclists can enjoy the ability to reach speeds that they would not be able to do without a bicycle [54], there is also a risk that they might go too fast, endangering them and other road users. This is particularly pertinent today with the rise of e-Bikes. This has led to discussions that cyclists are not used to these speeds and might cause accidents, resulting in legislation on how fast such system support should go. That there is no consensus on how to design such enhanced movement abilities best is evident by the fact that different countries imposed different speed limits for e-Bikes [9].

### C8: Interpreting and protecting data collected by cyclists

As cyclists are often very conscious of their role in society, such as reflected in their choice to cycle for sustainability reasons [26], they can feel strongly about being tracked by technologies such as cameras, as they could use face

[8] https://www.bikeradar.com/features/when-were-bicycle-gears-invented
[9] https://en.wikipedia.org/wiki/Electric_bicycle_laws

recognition to identify each cyclist. Cyclists' tracking technology is often invisible to the cyclist, possibly raising fears that being tracked without their knowledge is not something the organization is trying to convey, such as count of cyclists by "change comes from numbers". Prior work already highlighted that bodily data is often considered more private and hence needs to be considered particularly sensitive regarding storage. For example, if the bicycle collects data and stores it inside the bicycle, e.g., on a memory card embedded in the frame, what happens if the bicycle gets stolen? Moreover, cycling can be a very social activity when riding in groups, and such data is often shared to discuss performance and enhancement opportunities. These groups can be online, sharing large amounts of data, such as promoted through apps like Strava. This can have advantages, like the ability to inform cycling infrastructure decisions by councils as advocated for by Strava's big data approach [94]. The question with this challenge is how to keep cyclists' data secure.

Current cycling systems already capture a wide range of data, such as cadence and heart rate. Yet, user models around this data that could help predict what cyclists should do next to achieve their cycling goals still need to be updated and expanded. This makes data representation and interpretation challenging. We note that with additional sensors, increasingly both on the cyclist's body and their bicycle, we will gain even more data. Using this data and presenting it to the cyclists, if they wish, to interpret and make sense of it, is challenging. The question of how to use this data and present it to the cyclist to help them interpret and make sense of it is still unanswered.

Possible strategies for these challenges discussed during the sessions include ***personalized and simplified visualization*** tools ranging from minimalistic, abstract, and customized visualizations that only the cyclists can understand to more detailed visualizations that require big screen or mixed reality headsets. Another way of addressing this issue is to enable ***data protection mechanisms*** beyond consent forms that users rarely read in detail.

## 6 SPATIALLY SITUATED CYCLING INTERACTION

### C9: Facilitating cyclists' interactions with other road users

Cyclists interact with other road users via hand signals when turning, ringing the bell to increase pedestrians' awareness of them, or talking and gesturing with car drivers or even self-driving vehicles. However, these relationships are challenging to understand [45]. If we understand these relationships better, we can design better interventions, such as ***interactive systems promoting prosocial behavior on the road***. Understanding cyclists' relationships with other road users still needs to be developed since cyclist's hands are busy holding the handlebar, making touch or gestural interactions impractical. Voice-based interaction is often limited by the speed at which most road users pass each other, and the noise of the air stream and the limited ability to convey speech into a car make voice interactions difficult. As discussed during the sessions, existing interaction is typically unidirectional, i.e., from cyclists to other road users, and we envision future systems which notify car drivers about the approaching cyclist [101, 132]. The question is how to design such ***bidirectional interactions***, e.g., should both the cyclist and the road user be warned of each other, and should this include awareness of each other's warnings?

Prior research found that assertive cycling behavior relates to drivers perceiving cyclists as aggressive [57]. Another study identified that "the perceived attitude of drivers to cyclists" is the primary factor restricting more cycling, not cycle lanes or petrol prices [126]. Related research found that cyclists who cycle often blame car drivers more for accidents than cyclists who cycle less [88]. If we understand these relationships better, we can design better interventions, such as interactive systems promoting more prosocial behavior on the road. However, generating an enhanced understanding of the cyclist's relationship with other road users is challenging. Another work proposed

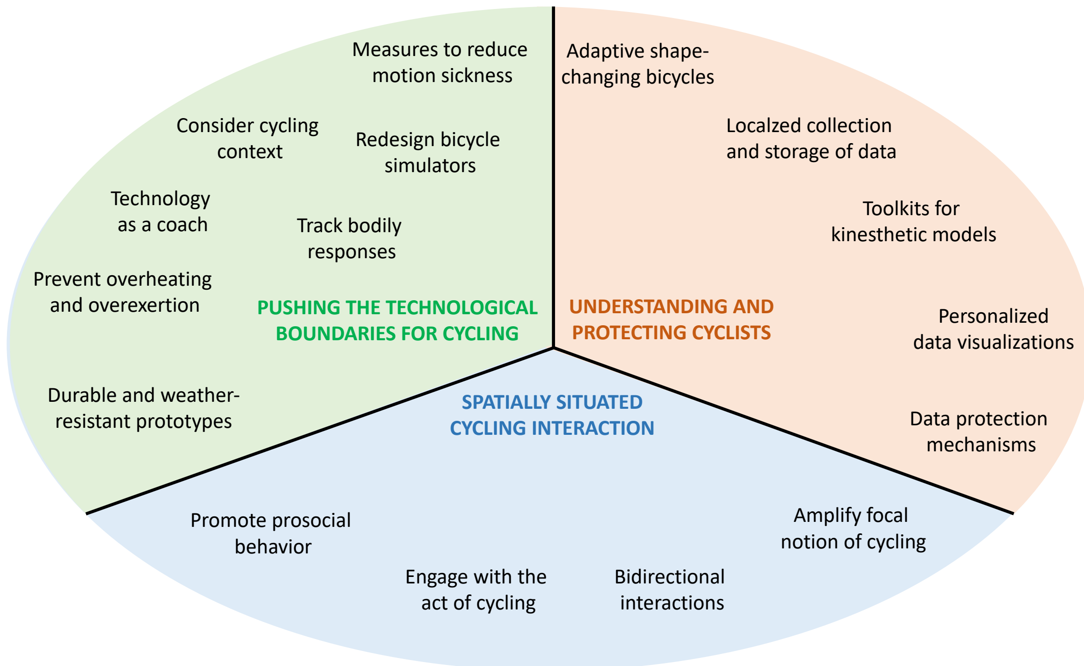


Fig. 4. The summary from the expert discussions of potential paths forward with three categories of grand challenges for CyclingHCI.

brain-computer interfaces to understand cyclists [12] by sensing their peripheral awareness. Knowledge about how useful it can be to understand cyclists' relationship with other road users still needs to be developed. We believe that bicycle simulators [23, 63, 64, 107, 114, 119, 130] could help produce such an enhanced understanding. These bicycle simulators can simulate dangerous situations to get visceral responses from road users without exposing the cyclist to real danger. However, how transferable resulting understandings are to real-world cycling still needs to be discovered. Thus, our understanding of cyclists' relationships with other road users still needs to be improved, and we phrase it as a grand challenge.

### C10: Maintaining cyclists' connection to surroundings

Reliance on technology can cause a detachment from the place, the time, and the community the user is engaging with [24, 65], resulting in the user not profiting from the associated health and well-being benefits of cycling. This detachment hinders a deep engagement with others and the world around the user, diminishing opportunities for social connection. For instance, car drivers detach from the place they are traveling through, the time, and the community they are passing by [45]. They use air-conditioning and air-filters to experience a different temperature and air quality in the car than outside. The same applies to the time since cars allow traveling at much faster speeds than our ancestors experienced, and the community since cars have sound-isolating windows to prevent conversations with the communities we drive by. In contrast, although allowing us to travel faster than by foot, bicycles do not detach us from the place, the time, and the community, at least not to the same extent. We feel the same temperature and air quality of the area we travel through and can hear and speak (or shout if we travel fast) with the community around us. Bicycles can be seen as focal vehicles that require focus, i.e., cyclists need to ***engage with the act of cycling***, both in terms of investing physical effort but also in terms of paying attention to balancing and the environment, especially if we compare this to self-driving vehicles, where the goal is to allow for disengagement and not being present in the act of driving, e.g., level 5 autonomous cars. Furthermore, bicycles generate focus. We might focus on the nice place (and air) we cycle through, the time and effort it takes to climb a hill, and say hello to the people we cycle by.

We note that certain technological developments for bicycles are underway that work against the "focal" notion, resulting in a detachment of the place, the time, and the community. For example, researchers have been making more enclosed bicycles [10] that detach cyclists from the place and the community they are cycling through. This trend may also carry over to interactive technology, with more technology used on bicycles [59, 76–78, 124]. For example, design research suggested self-balancing bicycles, requiring less focus on bicycle-riding activity [125]. Furthermore, a self-driving bicycle has been proposed [76], suggesting that less focus is required on the bicycle-riding activity in the future if everyone has such a self-driving bicycle. To overcome this challenge of detachment, based on the discussions we propose two ways designers can achieve this: (1) they can either ***highlight the focal notion of cycling*** or (2) ***amplify it***, allowing cyclists to experience a stronger attachment to the place, the time, and the community they are experiencing. However, how to design for highlighting or amplifying the focal notion is still an open question.

## 7 LIMITATIONS

Our work has limitations, as does all research that aims to advance a particular field based on past experiences. In particular, we acknowledge that our selection of the grand challenges is derived from a perspective that represents a particular view on cycling, in our case, that cycling is the future of mobility and interaction design can advance this future. As such, additional insights from a wider view could complement our grand challenges. Furthermore, we acknowledge that our grand challenges are based on our attitude toward the future, and we see them as the ones that can address major challenges such as sustainability, health, and traffic congestion. Therefore, other, more critical voices could complement our approach. We also acknowledge that our perspective could be further complemented by bringing in expertise from other areas, for example, from bicycle engineers, sports scientists, urban planners working with bicycle infrastructure, cycling coaches, physiologists working with cyclists, etc., and other geographical locations since the cities in which we live and conducted studies probably impacted the challenges we identified, e.g., cycling in Europe is different to cycling in the USA [27]. Furthermore, prior work on grand challenges in other subfields of HCI has previously stressed that any such investigations should also consider "dark patterns" [80], where a potential misuse of technology is envisioned to warn of potential shortcomings. Here, we can envision that technology could be marketed to cyclists in a way that promises safety to a level that makes riders overconfident, facilitating taking unnecessary risks. Therefore, we point to the need for future work that investigates what undesirable systems could be designed to highlight potential pitfalls that could hinder the advancement of the field.

## 8 CONCLUSION

In this paper, we presented 10 grand challenges facing CyclingHCI. The challenges emerged from sessions where we reflected on having collectively designed, developed and evaluated 18 CyclingHCI systems. We identified three categories for the derived challenges: (1) Pushing the technological boundaries for cycling, (2) Understanding and protecting cyclists, and (3) Spatially situated cycling interaction. Solving these challenges will be difficult since they are multifaceted and include factors like people, infrastructures, environments, and weather conditions. Therefore, we

[10] https://www.better.bike/, https://www.podbike.com/

invite HCI researchers to move this emerging field forward to improve cycling safety, help people reap the benefits of the associated physical activity, and contribute to sustainability. To do so, we must follow a multidisciplinary approach by involving other fields, such as infrastructure design, urban development, sports, transportation, ergonomics, human-factors engineering, policy-making, cycling training, and education. Morever, bicycles offer a unique opportunity for HCI researchers to have an impact on a global scale, as there are approximately one billion bicycles worldwide [11]. Cycling promotes a healthy lifestyle, offers a sustainable alternative to other forms of transport, and improves social connections. With this work, we invite researchers to contribute to the future of CyclingHCI, inform common research goals, and help researchers new to CyclingHCI.

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