An Exploratory Physical Computing Toolkit for Rapid Exploration and Co-Design of On-Bicycle Notification Interfaces

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ABSTRACT

Cycling offers significant health and environmental benefits, but safety remains a critical issue. We need better tools and design processes to develop on-bicycle notification interfaces, for example, for hazard warnings, and to overcome design challenges associated with the cycling context. We present a physical computing toolkit that supports the rapid exploration and co-design of on-bicycle interfaces. Physical plug-and-play interaction modules controlled by an orchestration interface allow participants to explore different tangible and ambient interaction approaches on a budget cycling simulator. The toolkit was assessed by analysing video recordings of two group design workshops (N=8) and twelve individual design sessions (N=12). Our results show that the toolkit enabled flexible transitions between ideation and out-of-the-box thinking, prototyping, and immediate evaluation. We offer insights on how to design physical computing toolkits that offer low-cost, 'good enough' simulation while allowing for free and safe exploration of on-bicycle notification interfaces.

Author Keywords

Bicycle; situation awareness; road safety; physical computing; IoT; toolkit; human-bicycle interaction; co-design

CCS Concepts

•**Human-centered computing → Human computer interaction (HCI);** *Haptic devices;* User studies;

INTRODUCTION

Cycling is recognised as one of the most cost-efficient and sustainable forms of transportation and has been shown to lead to significant health benefits [17]. An increased uptake of cycling and a subsequent reduction in car use is expected to improve the general air quality of cities, reduce the level of noise pollution and generally lead to less congestion and fewer

Figure 1. Workshop setup to develop an on-bicycle UI in close cooperation with the target group utilizing an *Exploratory Prototyping Tool* (right) for rapid hands-on prototyping in a collaborative environment.

serious accidents [14]. Despite these clear benefits, there are still many significant barriers to the uptake of cycling in many countries. These include unsafe or badly maintained infrastructure, unsuitable terrain [10] and unsafe traffic conditions. Personal safety plays a critical role, showing that many people are afraid of taking up cycling, due to a perceived or real risk of accidents and an increased feeling of vulnerability.

From an design perspective, cycling poses a unique set of environmental, contextual, technological and methodological challenges that need to be taken into account to effectively

address the safety issue. Cyclists are vulnerable, susceptible to changes in environmental and road conditions, bicycles have a limited access to sensor information and limitations to display safety-critical information, as compared to cars. A more comprehensive understanding is needed about how interaction mechanisms and study methodologies can be applied to the context of cycling to improve rider safety.

While we have seen some isolated attempts to equip bicycles with safety technologies [1, 2, 18, 39], there is a need to better understand this problem both from a design and user interaction perspective. Our research contributes to mitigating safety risks by exploring how to support the design and exploration of on-bicycle interaction mechanisms that are specifically aimed at issuing time-critical notifications to warn cyclists.

Cars are instrumented with increasingly sophisticated sensing technologies to support autonomous driving and detecting potential hazards. They warn drivers through a range of on-board interfaces, for which detailed guidelines have been developed in fields such as Cooperative Intelligent Transport Systems and Advanced Driving Assistance Systems, based on decades of human factors research [24]. While significantly less advanced, there are attempts to implement sensing approaches for bicycles to detect adverse road or environmental conditions (i.e. detecting potholes, tree branches, animals [31]), identifying risky driving behaviour (i.e. measuring a car's approach speed and velocity), or sense pedestrians on collision course [26].

What is less well understood is how to design notification interfaces that then relay this safety-critical information to cyclists. We specifically consider the bicycle as an interaction platform itself, rather than the design of additional wearable devices, such as glasses or gloves. The physical design space for *on-bicycle* user interactions, with devices that are attached or integrated into the bicycle hardware, is limited and presents a number of challenges. There are a limited number of perceivable mounting points for interfaces on a bicycle (notably handlebar and handles, columns, pedals, frames and seats) some of which already contain basic bicycle functionality (for example, gear shifters, light switches, bells, tachometers, etc). While cycling has been the focus of Interaction Design research before [34, 35, 38], research on how to support the design processes of human-bicycle interfaces more generally has been scant to date. Physical computing toolkits are a natural fit to allow for the exploration of different interaction and notification modalities in this context.

Our main research goal thus is to understand how to support and facilitate co-design processes that allow participating cyclists to safely explore different on-bicycle notification mechanisms and modalities. We provide participants with a variety of on-bicycle interaction tools and modalities with the potential to increase awareness of their riding environments and allow them to interact with notifications about potential hazards or safety threats. While detecting hazards is enabled by sensing technologies, we specifically focus on the co-design processes of human-bicycle notification interfaces, rather than the technical challenges of building safety sensors and handling sensor data, which are addressed elsewhere [9, 26, 31].

To address our research goal we report on the design and evaluation of a dedicated physical computing toolkit, the Bicycle Exploratory Prototyping Toolkit (BEPT) which enables rapid prototyping, the exploration of different interaction modalities in the cycling context and supports the collaborative design of on-bicycle notifications mechanisms.

We present the findings of two studies that explored the use of the toolkit to support participants of design workshops to build tangible and ambient interaction mechanisms, delivering on-bicycle notifications. We finally discuss the results with the intention to offer insights into the design of physical computing toolkits specifically designed for the cycling context.

RELATED WORK
We review prior work on Internet of Things (IoT) sensor and design toolkits, on-bicycle feedback, interaction in motion and review the design space provided by bicycle simulators.

IoT Sensor and Design Toolkits
IoT sensor kits make physical computing more accessible to users who do not possess detailed knowledge of electronic components, circuit design and microcontroller programming. These kits often include plug-and-play electronic components, including single board computers or microcontrollers, sensors and actuators. Platforms like the Arduino board [3] have made microcontroller programming more accessible. While not a true plug-and-play platform in itself, the Arduino platform is a common building block for many plug-and-play IoT toolkits.

Greenberg and Fitchett [20] introduced the concept of Phidgets (physical widgets) as one of the earliest implementations of an IoT Design toolkit. The Phidget toolkit combines physical interfaces (sensors & actuators) with software needed to control the interface in order to support a plug-and-play physical computing platform. More recently, dedicated sensor platforms like the SmartCitizen Kit [15] have allowed citizens to set up participatory sensing projects using a fully-designed open source sensor platform and a data sharing platform.

While IoT sensor kits support exploring and building physical computing interfaces, they do not actively support the co-design of these interfaces with participants. A recent set of of IoT Design toolkits such as the Physikit [22], Un-Kit [5] and Tiles toolkit [19, 32] more explicitly support the design process and guide participants to explore different contexts. Physikit focuses on the ambient visualisation of environmental data, offering a web-based configuration tool and a set of custom ambient displays to support different output mechanisms (such as) movement, airflow, light or vibrations). The toolkit does not provide its own sensor platform but utilises the SmartCitizen kit. Un-Kit targets older people. The toolkit includes a set of sensors and actuators and a set of cards, explaining the capabilities of the IoT toolkit. The toolkit highlighted its role as inspiration to envision the use of IoT in everyday practices, rather than supporting an exploration of what was possible using the provided elements. The Tiles toolkit followed a similar card-based approach using a set of design briefs and criteria to evaluate design to facilitate experimentation / reflection.

Note that while some toolkits can be applied to a wide range of design contexts, the most commonly applied usage scenarios found in the literature are domestic settings. The toolkits here are inspirational in how they make the design of IoT accessible to a broader audience and foster user-driven rather than technology-driven design processes. However, we argue that the specific context of cycling requires further consideration of a range of design dimensions such as safety, limited space to mount devices, traffic and road conditions and interaction in motion that have not been widely considered to date.

On-Bicycle Notification Modalities
On-bicycle feedback modalities that notify cyclists and other road users have been researched in a variety of contexts [6, 12, 13, 36, 37]. One project reports on an automated vehicle detection system [9] using LED strips along the top tube of the bicycle frame. Others used wristbands equipped with vibration motors [23] to indicate right or left turn directions. Walmink et al. [38] designed a heart rate monitor placed on the back of a bicycle helmet to communicate the rider's current level of exertion between a group of cyclists. The team behind the project 'Oh Music, Where Art Thou?' [40] explored audio as a potential source of navigational feedback for cyclists. Our toolkits aims to allow cyclists to explore a selection and combination of multiple such modalities for on-bicycle warnings.

A related set of work explores bicycle-mounted and wearable notification mechanisms that are used to warn other road users, rather than cyclists themselves. For instance, Dancu et al. [13] used projections on the road to signal the cyclist's intention to take a turn and compared their usability to a signal pot, an off-the-shelf system with LED indicators. A context aware signal glove [8] recognises and extends the cyclist's hand gestures by activating directional LEDs placed on the back of the glove. Hands-free controls can be established using sensors placed on the helmet [25], such as accelerometers capturing head movements or gestures, or a microphone recognising a rider's voice to trigger events. Matassa et al. [30] explored wearable accessories, allow memories to be tracked while cycling. Lastly, Claes et al. [11] used interactive floor mats and public screens to poll cyclists' opinions.

There are several commercial bicycle-mounted sensors, most notably the Garmin Varia Rearview Radar [18] which measures the approach velocity and distance of cars overtaking bicycles from behind and the Codaxus LLC C3FT [4] which measures the proximity of passing vehicles. While technically mature, these are standalone devices featuring their own (visual) displays that neither integrate with a customised on-bicycle UI nor allow for decoupling sensing and notification.

Simulating Interaction in Motion
To cover a broader spectrum of the interaction process on bicycles, it is essential to consider interaction in motion. Most mobile systems are 'stop-to-interact' [29] or 'fast interactions' [27], since movement and exercise activities, such as walking, running, cycling and swimming are already intense experiences. Enhancing them through interaction bears the risk of drawing the user's attention away from identifying dangerous situations during such activities. Marshall et al. [28] summarized the risks of this type of interaction. Secondary

tasks (e.g. using a phone) while driving a car, divert the attention and reduce driving performance [7, 33]. This work is particularly relevant in the context of notifications that can draw cyclists' attention away from the road.

Bicycle simulators allow bicycle-related research to be conducted in a controlled and safe environment. Experiments can be planned and executed without exposing participants to hazards of real world setting. Such simulators are not common, but some examples can be found. Herpers et al. [21] developed an immersive game platform for physical activities. Their bicycle simulator provided visual and environmental feedback, processed from pre-recorded smartphone data. Kwon et al. [16] considered air drag, angular directions, braking forces or rolling resistance for a more realistic simulation.

Our paper positions itself uniquely at presenting a physical computing toolkit specifically designed to explore on-bicycle notification and interaction in motion on a budget bicycle simulator that can be easily replicated.

BICYCLE EXPLORATORY PROTOTYPING TOOL
In this section we introduce the design, motivation and technical setup of the Bicycle Exploratory Prototyping Toolkit (BEPT) in conjunction with a budget cycling simulator setup.

BEPT Design
The Bicycle Exploratory Prototyping Toolkit (BEPT) is an exploratory physical computing toolkit aimed at supporting the co-design of tangible and ambient bicycle interaction approaches. The toolkit enables participants of design workshops to experiment with placing combinations of interactive gadgets that support a range of modalities on different parts of a bicycle (handlebars, brake levers, stem, frame, seat, pedals, etc.) with a particular focus on interactions that are directly integrated into or placed onto the bicycle (on-bicycle).

The design context is to create on-bicycle interfaces that are suitable to alert cyclists of hazards via notifications using a range of different tangible and ambient interfaces. The toolkit allows for some instrumentation. However, it does not include actual sensor data that could trigger particular kinds of notifications, instead opting for a simulated set of hazards, that act as triggers for notifications. BEPT uses a low-cost bicycle simulator setup to allow participants to experience and evaluate their designs in a simple simulated environment.

The design of BEPT was motivated by three central design considerations. First, it supports a self-directed design process, allowing users to independently create diverse designs for on-bicycle notification systems. Second, it provides a medium-level of fidelity with fully functional gadgets that support users to flexibly change the functional behaviour of the system. Third, the toolkit was specifically designed to be used in the context of a bicycle simulator to encourage safe exploration.

In this regard, BEPT provides a middle ground specifically suited to early prototyping and rapid exploration. While in-the-wild studies, on one hand, would offer greater contextual depth, the in-situ exploration of untested gadget prototypes is likely to be neither safe nor allows for a rapid exploration of different designs. The use of more expensive fully-featured simulators

Figure 2. Example gadget and controller (vibration motor)

Figure 3. Visual, tactile and audible output modalities and a custom-built I2C-BUS constitute the *Bicycle Exploratory Prototyping Toolkit* for rapid exploratory prototyping.

Gadgets	Notification patterns
Vibration Motors (4 gadgets) Vibration motors for vibro-tactile feedback. A total of four vibration gadgets allow for simultaneous placements. Each individual gadget contains three vibration motors, all of which vibrate with the same pattern and intensity if triggered. Attaching three motors instead of one at the same time allows to either increase the size of the feedback area, or to increase the intensify of vibro-tactile feedback, if motors are placed next to each other.	1. Constant vibrations (at 100%) 2. Constant vibrations (at 33%) 3. Ramping vibrations (from 0% to 100%) 4. Fast interval vibrations 5. Slow interval vibrations
LED strip gadget (4 gadgets) For visual feedback, we included two different types of lighting, LED strips and LED rings (see next row). LED strips come at a fixed length with single LEDs aligned in a line with gaps of 5cm. The strips can be cut in between the single LEDs to the desired size. We provided four gadgets, one with 10 LEDs and three with 5 LEDs.	1. LED Strip on (constant) 2. Fast blinking 3. Slow blinking 4. Pulsing animation 5. Directional animation
LED ring gadget (1 gadget) An LED Ring, with 16 RGB LEDs aligned in a circular shape which offered a different form factor.	*as row above, but circular pattern for directional animation*
Smartphone gadget (1 gadget) A smartphone on a bicycle mount was used to connect to the Web server, but also acted as one of the gadgets. The smartphone offered both visual and audible feedback.	on-screen pictures & sounds

Table 1. BEPT gadgets and notification patterns

on the other hand would allow for a more comprehensive evaluation of safety-critical features of designed gadgets, but would be more costly and suited to later design stages.

BEPT Technical Setup

Components and connectivity

The toolkit consists of a range of custom-built electronic units, referred to as Gadgets. Based on our literature review, we chose different electronic components, in particular, various shapes of light emitting diodes and tactile actuators (LED strips and rings, vibration motors and sound emitters, see Figure 3 and Table 1). Gadgets use different electronic components to support different output modalities (light, sound, vibrotactile feedback). Each gadgets is connected via a short cable to its own self-contained controller unit that uses an Arduino micro-controller to manage control, data input/output and power delivery (see Figure 2). Gadgets (and their controller units) can be mounted on a stationary bicycle to form multimodal tangible or ambient displays.

Topology & Web Server

Controllers are connected to a home station via a custom BUS interface (I2C-BUS) by a long wire (>2 m). Plug-and-play functionality is achieved by adding microphone connectors to each controller and fitting control and power ports onto the BUS, allowing controllers (and associated gadgets) to be

connected and disconnected quickly. The network topology (Figure 4) shows how these components connect to each other and the other components of BEPT (web server, smartphone link, smartphone controller, and other gadgets).

A web server acts as the pivot for the communication. Web sockets are used to establish the communications between the controller and the system to exchange messages. The server further enables the addressing of non-Arduino driven gadgets (such as a projector).

A web interface acts as the controller. It provides the wizard with the ability to trigger all gadgets at once, to trigger single gadgets at will, to disable certain gadgets and to select different predefined patterns for each individual gadget on the fly.

An Android smartphone mounted to the cycling simulator is the link between the gadgets and the controller. The connection between smartphone and server is made using its integrated WiFi-protocol.

A Master-Arduino device (Arduino Uno R2) connects the gadgets with the controller via USB. The connections with each individual gadget/controller are established using the Inter-Integrated Circuit (I2C) Protocol.

A custom-made I2C Bus allows for plug-and- play functionality of the respective Arduino-driven gadgets. It supports a flexible set of Slave-Arduino devices (Arduino Pro Mini) to be connected onto the same bus and the communication between the parties.
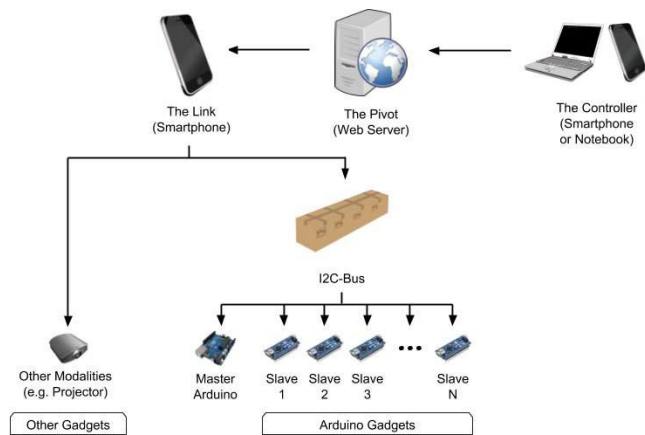
4

Figure 4. Network Topology for the Exploratory Prototyping Tool to enable controlling the individual output modalities as well as non-Arduino driven gadgets from an easy to understand user interface.
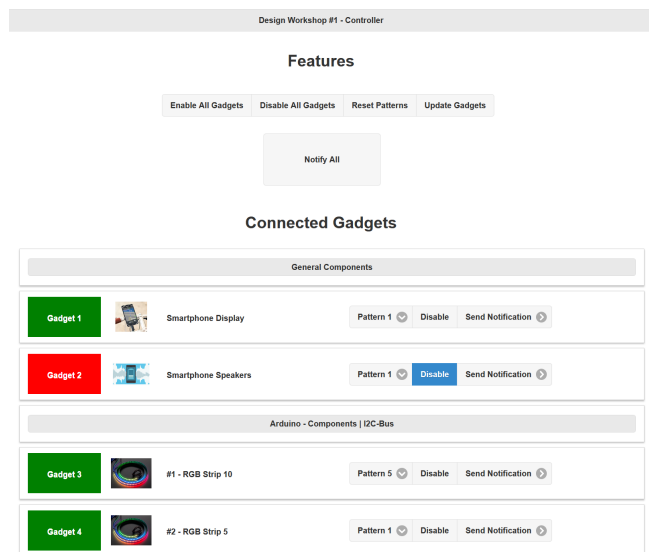

Figure 5. User Interface for the BEPT.

Orchestration User-Interface
To allow for self-directed exploration, the toolkit can be operated by a single user without specialised technical knowledge. Users are able to link and orchestrate different gadgets without further instructions, through an easy to understand web interface (Figure 5). The system automatically detects and lists all gadgets currently connected via the I2C-Bus interface. Users can choose from different predefined notification patterns (e.g. LED blinking pattern) and manually trigger a notification to be sent to a gadget. Users can also use a 'Notify-all' button to send notifications to all connected gadgets simultaneously. To enable quick adjustments without having to manually unplug gadgets, the interface allows gadgets to be disabled, which prevents notifications to be received. Further features include resetting all patterns, enabling or disabling all gadgets and manually searching for connected gadgets.

STUDY DESIGN AND APPROACH
To understand how BEPT could be used to facilitate the design process for on-bicycle interaction we conducted two studies.

Study I – Ideation & Exploration
Study I explores the suitability of BEPT as a co-creation tool to allow participants to explore a wide range of ideas for novel bicycle UIs. As part of this study we conducted a set of two exploratory design workshops (Figure 5). Participants were invited to collaboratively establish requirements, discuss ideas, experiment with different gadgets and explore the prototypical system they developed within the controlled environment of the cycling simulator. This process was enabled by the BEPT.

Apparatus
For the first study we created a lightweight indoor cycling simulator, consisting of a bicycle mounted on a bicycle training stand. A 50-inch flat screen was positioned in front of the bicycle (Figures 1 and 6). The screen showed video footage from the perspective of a cyclist cycling through different urban traffic conditions. This video did not focus on specific hazards, but rather provided contextual cues, giving participants the experience of cycling under naturalistic conditions and allowing them to focus on the "road" rather than on the gadgets.

To increase the sense of immersion, participants were provided with a range of tools, including a water spray can, a fan and audio equipment to simulate different environmental factors. Participants could turn off the lights in the room to simulate riding at night. Participants had direct access to the BEPT gadgets and web interface through which they could orchestrate multi-modal notifications (Figure 6, right). The interface provided a visual representation of each gadget, allowed users to select different patterns (e.g. light or vibration), switch gadgets on or off, send notifications and provided feedback on the selected options and status of the gadgets. Gadgets could be mounted freely, using Velcro strips and sticky tape.

Participants
Participants were staff and postgraduate students recruited from research groups within our university, all of whom were experienced cyclists. Eight participants (five male, three female) aged between 23 and 52 (m=31, SD=8.95) participated in two workshops. The first workshop consisted of three males and one female aged between 28 and 38 (m=30.5, SD=4.35) and the second workshop was attended by two males and two females aged between 23 and 52 (m=31.5, SD=11.89).

Procedure
Participants were instructed that their task was to create and explore different on-bicycle notification designs through multiple iterations during the workshop. The instruction included the introduction of a fictional *Hazard Sensing System* (HSS) that would automatically detect potential hazards and send out notifications to be displayed(implemented via a wizard-of-Oz approach). Two example scenarios were predefined to help participants better understand this departure point: a) a distracted truck driver, approaching a cyclist from behind; and b) the threat of swooping magpies attacking a cyclist from above while defending their territory. The sensing system precondition implied that there were no technological restrictions on

Figure 6. Exploratory Design Workshop (Study I): Participants collaboratively creating on-board interfaces (left). Exploring interfaces on the bicycle simulator (middle). The web-interface controlling the tool and simulating hazards (right).

what types of issues participants could be notified about. In this way we ensured that participants did not feel limited by the details of what could be sensed, but rather focussed on the design of how cyclists could be notified.

Open group discussions and collaboration between participants were encouraged. Lastly, participants were given a brief (5min) introduction to the bicycle simulator and the BEPT. Each workshop lasted for approximately 120 minutes.

The workshop was split into the following stages. Participants could freely work on, skip and come back to iterate over each:

1. **Conceptualisation**: participants were asked to think about general cycling concerns and potential ways for effective notification techniques on bicycles. Furthermore, additional features could be elaborated and discussed to improve the safety benefits of the desired on-board UI. Participants were provided with standard modelling tools like pen and paper.

2. **Prototyping**: Participants were given the opportunity to develop, prototype and discuss their design ideas directly on the simulator using the BEPT. They could set it up and see their propositions in action within a typical environment.

3. **Simulation**: the participants could install their systems onto the simulator as well as test and experience each other's design ideas in the simulated environment.

Members of the research team acted as facilitators during the workshop to prompt discussions and help with any issues related to using the BEPT. During exploring the first scenario, facilitators asked questions such as the following to guide the design process: "What information would you like the HSS to communicate with you? Why?" and "What additional information about nearby hazards is important to you? Why is it important? How would you use these gadgets to convey the information?". The purpose of these facilitating questions was again to move the focus of the study away from potential issues with collecting and processing hazard information and allow participants to focus on exploring on-bicycle notifications.

Study II – Customisation & Exploration
This study explored the suitability of BEPT to support user-driven evaluation of bicycle notification prototypes under simulated conditions. We provided participants with a prototypical notification system. consisting of a combination of gadget identified in Study I. Participants were invited to explore these

prototype in a controlled environment on an indoor cycling simulator (Figure 6). Gadgets were installed and mounted on the bicycle, based on preferences determined during previous workshops. The main difference between the simulator setups in both studies was how notifications were triggered. While Study I supported free exploration, allowing participants to trigger notifications whenever they wanted, Study II used a time-stamped video that simulated specific hazards and issued pre-defined notifications, allowing participants to assess the suitability of a gadget setup under semi-realistic conditions.

Apparatus
Study II used a variation of the previous simulator setup. The bicycle was placed in front of an approximately 70-inch projection screen (Figure 7). The screen showed a looped video which identified a given set of hazards (from a 1st person cyclist perspective), including pedestrians on collision course walking onto the road, an overhanging branch on a narrow cycle path which occluded oncoming traffic and a car passing from behind. The video was time-stamped to the BEPT and triggered a hazard notification when the event was about to occur within the video. The prototypes mounted on the bicycle were implemented and instrumented using the BEPT.

Participants
Twelve participants (5 male and 7 female) aged 23–52 (m=33.25, SD=10.64) took part in 12 individual prototype evaluation studies. All participants had previous cycling experience and indicated to feel comfortable using a bicycle. Three participants participated in one of the previous design workshops. The remaining 9 subjects did not know the project.

Procedure
This was an individual study and participants used the setup one at a time, accompanied by the facilitator. Participants were introduced to the setup and briefed about the context and purpose of the study. The facilitator demonstrated the prototypes and described how they issued hazard notifications.

Participants were asked about their general preferences when riding a bicycle. Based on the findings from the design workshops, they could choose what types of hazards they deemed to be a threat for their safety while cycling, and if they wanted to receive notifications for these occurrences. These occurrences included cars, other road users, animals, the environment and terrain, and the behaviour of others.
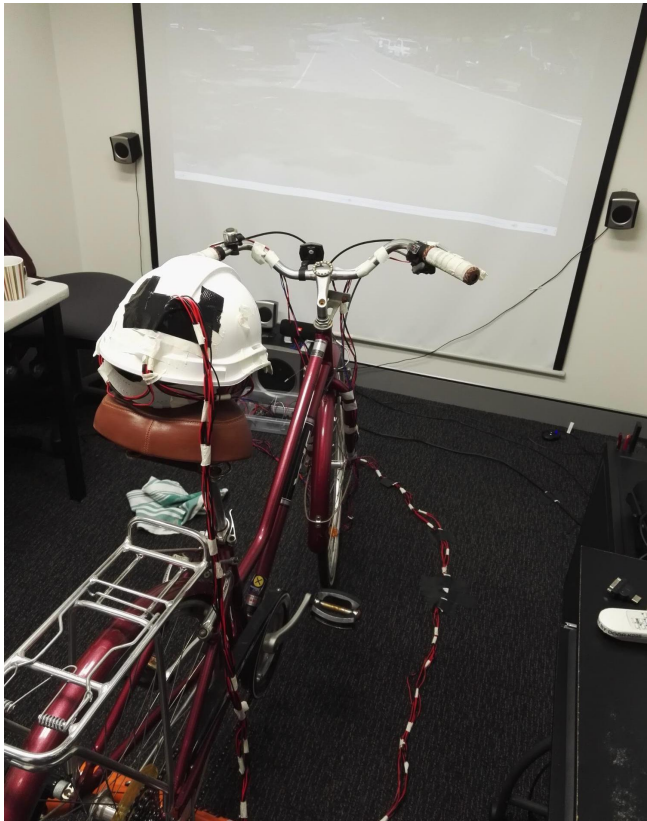
Figure 7. *Bicycle simulator* with a time-stamped video linked to BEPT.

To investigate the impact of the timing for each notification, participants could choose how many seconds in advance of the actual hazard they wanted to receive the notification. The selection ranged from 0 to 5 seconds (in steps of 1 second) before the hazard appeared in the played back video footage. Lastly, the attendees could choose which of the provided gadgets they wanted to use for the notifications. They could freely select any combination of the gadgets.

Individual participants could select their preferred hardware setup. They could also change the settings and they could adjust the individual gadgets themselves. Depending on whether a gadget was enabled or not, the participants could choose different colours, set the strength of the tactile actuators, choose between a set of predefined patterns and select, if they wanted to receive directional feedback or not. With regards to the video, our setup allowed participants to pause the video on the screen and change individual notification settings. They had the ability to turn off notifications for certain hazards, try out different combinations of gadgets for certain occurrences, tune the different tools and replay particular passages of the videos to re-evaluate the new setup.

The final step of the study was a semi-structured interview, participants were interviewed and asked to reflect on their experience with the designed on-board interface.

FINDINGS
The findings are based on observations, notes and the analysis of video footage taken during the design workshops (Study I & II) and the participants' feedback collected in the interviews.

Study I
Exploring the Design Space
Participants were encouraged to consider where to mount the provided gadgets on the bicycle and to explore whatever they deemed to be the most practical or impractical, and effective or ineffective location for this purpose. The messiness and playfulness of BEPT encouraged participants to simply plug & evaluate and explore designs they initially thought of as 'unlikely-to-work'. The use of the toolkit raised questions about the toolkit's fidelity and the role of the facilitator. These aspects are further discussed in turn.

Tangible Plug & Evaluate. The BEPT was designed to give participants direct control of the functionality through our web-based user interface and the tangible 'plug & evaluate' interface. The interface was easy enough to use to encourage initial trial and error. Participants got their hands dirty fairly quickly as they started to explore different design ideas themselves, independently and freely as part of the co-design process. Participants noted that they appreciated having the ability to engage in a process of trial and error and receive immediate feedback on design decisions.

From 'Unlikely-to-Work' to New Solutions. During the conceptualisation phase, participants were initially sceptical about some ideas. For example, all participants initially rejected the idea of placing tactile actuators on the pedals, as they did not expect vibrations to be noticeable through their shoes. As the BEPT allowed for rapid prototyping, this assumption was put to the test. Based on their small experiment, participants discovered that vibrations could indeed be felt through their shoes, hence expanding the design space. However, pedal vibrations did not seem to be effective in delivering directional information. Participants described them as "too remote". This experience led participants to explore vibrations in the saddle (this was not previously considered, and participants again found it difficult to perceive direction, i.e., left vs right bum cheek), and lastly wearables such as gloves or helmet (which were actually just provided as props and not considered to be part of the design space during the study setup). A finding of this exploration was that directional cues received via vibration inside the helmet were considered quite intuitive.

Toolkit Fidelity and the Role of Facilitators. To utilise the tool and bypass technical issues, participants were indicted into the use of the toolkit. The facilitator stepped in when necessary to help participants realise ideas more quickly or help to implement more advanced designs. The focus of the toolkit was on self-directed exploration. Therefore, the complexity of prototypes that could be built by participants themselves was limited (e.g. predefined LED lighting patterns to choose from, rather than developing their own).

Messiness & Playfulness. Another aspect that related to the toolkit's fidelity was the design choice to use physical cables for connectivity rather than implementing a full wireless setup. In the original design of BEPT, physical wires were considered a suitable choice to connect the individual output modules. Wires allow for relatively simple and cost-effective connectivity, in particular as they solve the problem of providing sufficient power to the output modules. By comparison, building

a wireless setup would not only require wireless connectivity (e,g. RF, Wifi, or Bluetooth), but also mean that each individual module would need to be battery-powered and charged for use during design workshops. However, our observations showed that the use of many long cables (cf. Figure 2) did pose challenges to participants and created a trade-off between flexibility and playfulness. Participants repeatedly struggled to mount interfaces in their desired spot, while still maintaining the ability to simulate cycling. This somewhat limited the design space. On the other hand, the messiness and creativity required to overcome those challenges did encourage team work and further encouraged the playful nature of the activity.

Discussing Context & Implications for Design
Intensive discussions and subsequent considerations and iterations emerged around the cycling-specific context. Participants included more obvious topics such as distraction, redundancy, environmental factors (such as bumpy surfaces), but also less apparent ones such as different cycling styles, and self-consciousness while cycling. The results indicate that the toolkit allowed participants to draw on their own experience of cycling and explore solutions that addressed their individual needs and preferences. The following examples demonstrate how participants used BEPT to explore different design options in relation to those topics.

Distraction and Discomfort. Participants discussed needing visual indicators near the line of sight and brightness to be adjusted to user preferences and environmental conditions. Visual feedback was primarily placed within the cyclist's front field of view, on the handlebar centre and grips as well as on the top of the front tire mudguard (see Figure 8). The closer LEDs were mounted to the line of sight, the more critical it became for LEDs not to be too bright, especially during night cycling as the glare could cause distraction. Using BEPT, participants were able to experience different levels of LED light intensity under different lighting conditions using BEPT.

With regards to vibrotactile feedback the toolkit allowed for a nuanced exploration of actuator placements, vibration patterns and intensities. Participants explored a range of different combinations of modalities and remarked that the strength of the tactile feedback needed to be both perfectly adjusted and individually configurable. This was seen as critical in order to avoid discomfort, prevent the rider from being distracted by notifications that were considered "too strong" and to compensate for environmental factors, like road vibrations. Overall, participants found notifications distracting when the strength of gadgets was not calibrated properly.

Exploring Perception Limitations & Redundancy. Other insights related to the placement of output modules, according to their modality. Participants wondered under which conditions LEDs mounted on the handlebar would be best perceived. Would they only work well if looked at directly, or would they also work if the cyclist's gaze would wonder to either side, such as during more casual cycling styles while enjoying the scenery? One participant acted out this scenario and found that handlebar-mounted LEDs were not sufficiently perceived, when the cyclist was not looking straight ahead. Participants noted that this constituted a critical failure of this

output modality when needed the most (not looking ahead) and would, therefore, require other modalities as redundancy. The potential to miss a handlebar-placed vibration warning when cycling hands-free or while indicating a turn was also noted. The toolkit did support the participants in physically exploring the limitations of output modalities in relation to their placement, intensity, appropriateness to relate critical information, and personal preference.

However, when participants tried to use BEPT to explore multiple redundant and concurrent notifications, they did immediately find this experience overwhelming. This raised questions about the concurrent use of gadgets and what constitutes an appropriate mix of output modalities.

Self-Consciousness. With regards to audible warnings, participants noted that adjusting to an appropriate volume on a bicycle can be challenging. The volume needs to be loud enough not to be missed and not too loud so that others get annoyed by it. In comparison, when exploring vibrotactile actuators, they were perceived as welcoming subtle and private in a way. Some participants felt that notifications should be discreet, to avoid them feeling "self-conscious" when cycling in public. Not only did they not want to capture the attention of others and potentially distract them, they simply did not want to broadcast to onlookers that they were being notified or warned about something, and draw any attention to themselves in any way, apart from being seen by other road users.

Specificity. Participants felt the visual feedback via LEDs on the handlebar seemed to be good enough to easily and intuitively indicate directional cues (at least forward, left and right). Participants used colour encoding and temporal patterns (e.g. blinking) to convey additional information (e.g. urgency or criticality). Participants felt that audible cues or warnings had the advantage of being potentially very specific, like "warning, car too close". However, it was noted that adjusting to an appropriate volume can be challenging, given that cyclists are exposed to varying levels of road noise. Participants also related sound warning to the issue of 'self-consciousness'.

Study II
During the study, participants individually explored and evaluated the application of a specific set of output modules composed by participants during Study I and identified as most suited for further evaluation: two LED strips, one mounted on the grips at each side of the handlebar, one LED ring in the centre of the handlebar, two vibration motors (one on each grip), and six vibration motors in the helmet (Figure 7). Gadgets were mounted in the same position for all participants.

Customisability & Individual Differences
The study found significant inter-individual differences in how participants interpreted notification cues through the on-bicycle interface. While Study I allowed for free exploration, Study II was based on a shared, fixed setup in order to link matching hazard notification from a video to the output mechanisms. Participants noted that multiple BEPT setups would be useful so that participants with similar preferences could cluster together to work on their respective design, rather than being limited by a consensus option.
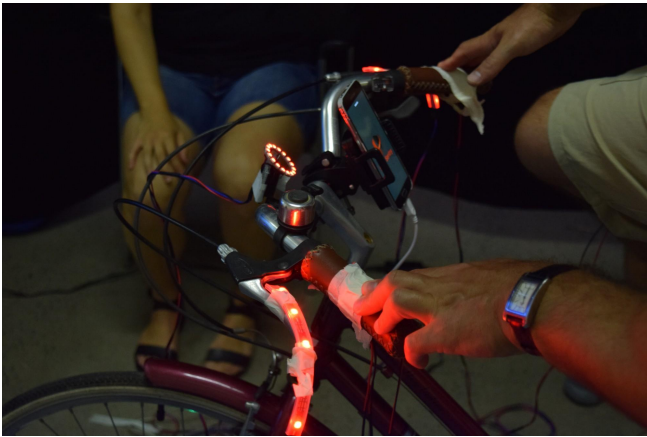
Figure 8. Example of an on-bicycle notifications.

Difficulties Embracing the Hazard Sensing System
Overall, throughout the co-design process, participants struggled to fully embrace the notion of a fictional Hazard Sensing System (HSS), that would act in the background to provide contextually relevant hazard information. While participants understood that the HSS was a fictional device, discussions repeatedly gravitated towards the trust of such a system in a safety-critical cycling context. Predictability and reliability were the two most commonly mentioned and recurring concerns. Since the system's main purpose was to warn riders about upcoming hazards, participants felt that the system should be able to determine potential hazards and predict whether they might actually threaten the safety of a rider. Participants also raised the issue that the systems might cause nuisance alarms, issuing alarms at the wrong time and place. However, due to the fact that the design of the HSS was not part of the study, participants did not explore further how predictability or reliability could be reflected in the design.

Two design aspects discussed were a) wanting to know what kind of hazard it is, to connect the warning with the actual hazard, and b) wanting to receive notifications "as early as possible", irrespective of the hazard. Participants then struggled to reconcile the balance between providing such information in a detailed manner without distracting, overburdening or annoying the cyclist, since cycling is perceived as an activity providing freedom and disconnectedness.

DISCUSSION
The results of the user studies provided us with insights into how an exploratory physical computing toolkit can facilitate the co-design of on-bicycle notification mechanisms. Results from the first set of design workshops (Study I) addressed to what extent a toolkit like BEPT can help workshop participants ideate novel bicycle user interfaces, specifically interfaces that relay time-critical information about potential hazards. Results from the second user study (Study II) revealed how a toolkit like BEPT in combination with a lightweight bicycle simulator and simulated hazards can be used to evaluate different designs and elicit rich feedback. Based on our findings we identified four themes that offer insights into the design and application of physical computing toolkits in the context of cycling. We discuss themes and study limitations.

Toolkit Fidelity and Complexity
Like other physical computing toolkits, the design of BEPT had to strike a balance between creating a toolkit that was simple and powerful enough for novice users to explore the design space and create interaction concepts that reflected their intended use, but was not too complex to overwhelm co-design participants with too many options or a setup that was too difficult to achieve in the timeframe of the user studies. This worked, but what was missing was the ability for the facilitator or participants to unlock additional settings in order to realise more complex design ideas. Co-design processes that use toolkits like BEPT need to be able to evolve with participants and their ideas and utilise facilitators to bridge the balance between usability and flexibility.

Challenges in Designing for the Cycling Context
The design space for human-bicycle-interaction is underdeveloped. There are few guidelines on how to utilise the limited physical space available to mount bicycle UIs and how to design interfaces that work in conjunction with each other (i.e., it is more common to find discrete standalone interfaces).

Designing interfaces for bicycles is non-trivial as sometimes dynamic conditions (rapidly changing environment, traffic, and cyclist attention) are at the focus of the warning system. These conditions are difficult to simulate. Here, there is room for extending BEPT in the future to cover such conditions.

At the same time, safety is a critical concern. We believe this to be a strength of using design toolkits and budget simulators like the one presented in this paper, to allow cyclists to freely explore and evaluate a wide range of bicycle interaction in a safe environment. There is a risk of such an approach creating solutions that might not work safely in real-world conditions. The approach does, however, lend itself for carefully staged deployments and gradual testing in increasingly realistic, uncontrolled and dynamic settings, e.g. using more sophisticated simulator setups and test tracks.

Interindividual differences
The fact that our results found strong individual preferences further makes evident that the design of on-bicycle interfaces to notify cyclists not only has to respond to complex environmental conditions, but also to deeply embed personal styles and preferences regarding cycling. The ability to explore different options through a toolkit like BEPT allows these differences to be explored. The group-based design approach in Study I proved to be both a promoter and a hindrance in this regard. On one hand, group interaction did promote further exploration of ideas that only some participants had considered. On the other hand, the fact that the exploration was eventually consensus-driven limited the expression of individual solutions.

BEPT Toolkit Challenges and Limitations
The technical design of the toolkit and simulator highlighted some challenges that need to be further addressed. Long wires were chosen as the main mechanism to connect gadgets & controllers to the master system. While this was a cost effective and simple option which made it feasible to build the toolkit

within a reasonable timeframe, there were issues with the reliability of the connections. Disconnects did occur during the workshop which caused stress to the facilitator and interrupted the flow of the design activity to some extent.

Study Limitations

The studies had a number of limitations. The approach supported early exploratory designs the validity of which will have to be tested under real-word conditions. The study was deliberately decoupled from the challenge of collecting and processing real-world hazard information. Integrating hazard events will pose additional challenges to the design of notification mechanisms that need to be further explored.

Another related dimension that has not been considered in our study design is the question how a diverse range of cyclists' riding abilities would be considered. For example, the decreasing vision of older cyclists could be simulated using special glasses. Similarly the simulator only offered a single generic type of bicycle. However, cycling styles the the experience of cycling differ significantly between different bicycles (e.g., road vs. city vs. mountain bike), potentially requiring different types of notifications and interaction modalities.

CONCLUSIONS AND FUTURE WORK

In this paper we presented an exploratory physical computing toolkit developed to support the process of co-designing on-bicycles notification interfaces with participants in a workshop settings. The aim of these interfaces was to relay information about potential hazards to cyclists. The toolkit supported self-directed exploration of different output modalities, placements of gadgets, and orchestration of different settings in order to support a rich exploratory environment.

Our findings showed that the toolkit encouraged the design of a diverse set of notification mechanisms and supported both, the initial exploration of a wide range of interaction concepts as well as the evaluation of the resulting concepts in the context of a lightweight cycling simulator setup. In particular, the work revealed that a physical computing toolkit like BEPT can support exploratory prototyping and self-directed exploration in the previously under-explored field of human-bicycle interaction. While design fixation, the predisposition of participants toward design materials contained in the toolkit, remains an issue, the toolkits' modular nature allows for easy extendability and supports the combination of different basic modalities (e.g. visual and tactile) creating a rich design space. Our studies also revealed that the toolkit's fidelity had to strike a balance between simplicity and richness. Strong inter-individual differences in preferences showed that the toolkit catered for the needs of individual participants, however finding consensus was non-trivial. The toolkit itself posed some technical challenges due to design decisions such as the use of cables rather than wireless connections. A move to a more sophisticated wireless setup is a likely direction for future work.

We believe that lightweight exploratory toolkits like BEPT offer a middle ground that allows designers to work with cyclists to safely explore early concepts of on-bicycle notification interfaces, without exposing participants to potentially hazardous conditions or unsafe gadgets. Future work will determine whether a toolkit like BEPT can create interfaces that could see a wider adoption in the wild. A natural progression would be to implement a version of the toolkit that works on restricted paths (e.g., test tracks) using real bicycles. Future toolkits could further extend the range of interactive components, move beyond notifications to include user input and bespoke notification profiles, utilise different bicycle types as well as consider different styles of cycling (e.g. sport, leisure, commuting).

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