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Cyclist Warning Systems: Design and Evaluation

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Abstract

Cyclists belong to the group of vulnerable road users and, thus, need particular protection in road traffic. One way to enhance cyclists' safety is to use urban data (e.g., infrastructure data, accident statistics) to inform cyclists about potentially dangerous areas, allowing them to better adjust to the situation and elevate their self-protection. However, the question is how to inform cyclists about such dangerous areas. In this paper, we present the results of two field studies, investigating two wearables (headphones vs. smart glasses) and different signal options to inform cyclists about dangerous areas. Study participants were cycling along a predefined track and could experience the different wearables and signals. The main aim of the studies was to find out how cyclists perceive and experience the different approaches. Participants' impressions were captured with questionnaires and interviews. Our results show a clear preference of the headphones over the smart glasses and signaling with intermittent audio while being in the dangerous area. However, we also found that participants' acceptance of the approach was influenced by the additional perceived benefit the respective wearable would have in daily life. Using a wearable solely to be warned, although this would increase safety, was less acceptable. We discuss the implications of these findings for the design of cyclist warning systems.

Keywords

Cycling, Safety, Wearables, Design, Evaluation, Field Studies

1. Introduction

As traffic shifts more and more to car alternatives, the bicycle has become one prominent means of transport [1]. Especially in urban areas, where space is sparse, conflicts between motorized vehicles and bicycles increase and are often unfavorable for the latter [2]. This leads to an increasing number of accidents with cyclists. As bicycle accidents are a type of accident involving vulnerable road users (VRU), this topic is gaining importance as a research area. Consequently, safety considerations regarding cycling shift into focus on saving lives ([3] [4] [5]). This paper contributes to cyclists' safety 1) by introducing a classification of road safety systems and 2) by providing results and implications from two field studies investigating different approaches to warn cyclists in uncertain or dangerous situations.

One way to increase safety for cyclists is to warn them of dangerous traffic areas, as investigated by the FFG-funded project SINUS. The project explores the feasibility of matching wearable physiological sensors indicating stressful traffic situations with data interfaces of urban data ecosystems, such as infrastructural information or accident statistics, for predicting risk situations for vulnerable road users. For these formerly isolated data sources, semantical interoperability is established. They are then used to train a machine learning model that predicts potentially dangerous areas within an urban road network and is dependent on temporal (day of week, time of day, season) and situational (road characteristics, weather, stress measurements) characteristics. The trained model is deployed as a service, which takes a location and timestamp as input and provides a prediction whether an increased risk for cyclists is prevalent for the respective location and time. Consequently, the question is how cyclists should be informed that they encounter a potentially dangerous area.

We approached this topic by investigating different wearables (headphones vs. smart glasses) and signals to inform the cyclist. We focused on wearables as means of communication since they are easily accessible, popular, and all-purpose devices, which are easy to integrate into various situations and systems. Following an iterative design approach, we conducted two field studies. The main research question was how to best communicate to the cyclist that they are in a potentially dangerous area, thus, how cyclists experience the different approaches in terms of perceptibility, usefulness, and acceptance. Thereby, the first study focused on varying signal intensity, while the second study investigated enhanced signal options based on study I results.

In preparation for the studies, we investigated different warning systems and, as result, introduce a classification for road safety systems in Section 2. Section 3 introduces our study procedure, including the technical infrastructure, signal design, and participant description. Subsequently, the studies' results are presented in Section 4, and we conclude this paper with a discussion of the results in Section 5.

2. Related Work

Previous work shows that there are a few studies focusing on how to warn cyclists. For example, Matviienko *et al.* [6] conducted a bicycle simulator study, using visual, vibrotactile, and auditive cues to warn cycling children. They found that unimodal signals were better suitable for encoding directional cues, while multimodal cues seemed more appropriate for priming stop actions. Prati *et al.*, [7] evaluated an on-bike system, warning about potential collisions with motorized vehicles, by comparing driving behavior with and without the system in a field study. They found that participants tended to reduce their speed when warned by the system. Other approaches for the protection of VRUs on two wheels, are, e.g., a bike handlebar that vibrates when a vehicle approaches from behind [8], the cyber-physical bicycle system, detecting rear-approaching vehicles and warning the cyclist [9], or the approach by [10], using projections to while cycling to predict and understand cyclists' intention.

To broaden the perspective on road safety systems, we further considered literature focusing on new technological developments, such as IoT, automated interventions, and cloud-based solutions, and literature examining human aspects (e.g., user acceptance, reaction time). Based on this, we derived a classification of road safety systems along seven safety characteristics. This classification allows to compare and identify important features of road safety systems in a clearly represented way. **Table 1** provides an overview of the classification and

Table 1. Seven safety characteristics for on-trip road safety systems, including manifestations and examples. The placement of the investigated approach in this classification is printed in bold.

Safety characteristics	Manifestations	Examples
Physical position	On-device	[11]
	Wearable	[12] [13]
	Cloud	[14]
Protecting road user	Cars	[15]
	VRUs	[16]
Protected road user	Self-protection	[17]
	Protection of others	[13] [18] [19] [20]
Level of concreteness	Situation awareness	[21] [22]
	Concrete dangers	[11] [13] [15] [20]
	Automated	[11] [23] [24] [25]
Prevention approach	Situation prevention	[14]
	Live preventions	[15] [16]
	Behavior changes	[26]
Source of information	Individual-based	[16] [26]
	Community-based	[13] [14]
	Environment-based	[23] [27]
Addressed sense	Visual	[6]
	Auditory	[6]
	Somatosensory	[6]

highlights the approach pursued in our studies.

The *physical position* describes where the physical implementation of the safety risk concept is located. Although not strictly separable, three main manifestations can be identified: on-device-systems, wearables, and cloud/IoT systems. Traditionally when talking about an on-device-system, one might think about an in-car navigation system guiding the driver with static data stored on the device. Although easily separable from the car, it can be considered an on-device-system since its usage is strictly linked to the car. Other systems, such as embedded systems might be harder to separate from the car [11]. Wearables are devices which are carried or worn by the road user and feature also other use cases than those focusing on reducing road risks. A prominent example is the smartphone [12] but other wearables, such as smart glasses [13], are discussed more and more often in this context. Cloud services/IoT are characterized by multiple (smart) devices interacting automatically to deduce useful information which is used to reduce road risks [14].

Protecting road user describes which road user uses the on-trip application to reduce road risks. Here, we differentiate between cars [15] [25] and vulnerable road users (VRU). This class of road users consists of non-motorized road users, which include pedestrians and cyclists but also includes motorized road users, such as motorcyclists [18].

The *protected road user* describes the road user who receives the advantage of the on-trip application use. One can distinguish between applications for self-protection and the protection of other road users. Hereby, the nature of the protected user is judged based on the protection from physical and psychological harm caused by traffic accidents. Such self-protection applications are, e.g., used in situations where no other road user is involved, such as automated parking [17]. For the protection of other road users from physical harm, the focus could be on a road safety-system gathering information in one vehicle to warn other vehicles of possible dangers [13]. Other approaches are directed towards VRUs, since they are in danger of critical injuries in a traffic accident including cars [18] [19] [20]. Approaches, gaining more and more attention recently, focusing on keeping both, the system user, and others safe while using the on-trip application by utilizing communication between involved road users, that is IoT [14] [15].

The *level of concreteness* refers to the interventions used by the on-trip application and comprises interventions increasing situation awareness [21] [22], interventions concerning concrete dangers, and automated interventions. The first two interventions aim to trigger a reaction of the road user to prevent a critical situation. When working with tangible information about the current danger one can trigger concrete intervention [11] [13] [15] [20] [25]. This, however, might not always be possible since this tangible information is not always available. In situations where, for example, one only knows that there is a danger, but the source or form of danger is unknown one must fall back to interventions increasing the situation awareness [28]. Although not hinting at concrete source of danger, the road user is prepared to react to a general danger [23] [29]. A special form of intervention, when working with tangible information about dangers, is automated interventions. Those interventions do not aim at triggering a reaction of the road user but trigger this reaction automatically. This could be, e.g., limiting speed, disabling the car in case of alcohol consumption [11] or automated braking [24]. These automated interventions are gaining more and more importance, especially when considering autonomous driving [25].

The *prevention approach* describes by which means the on-trip application aims at reducing road risks. This can be done a priori using situation prevention methods, via live prevention techniques, and a posteriori by using driver statistics for long term behavior change. Situation prevention methods use information gathered by other road users or smart devices to avoid risky routes [14], while an approach applicable when already in a risky situation is live prevention [15] [25]. In contrast to these two short-time approaches, long term behavior change uses individual driver statistics collected continuously to identify dangerous driving patterns and, in turn, to eradicate them in the long-term [26].

The *source of information* considers that each risk reduction measure is based on information and distinguishes between possible sources of this information. Two prominent sources of information are the individual driver or the community [13] [14] [26]. The information source environment is mostly considered implicit when talking about smart highways, smart cities or alike [23] [27]. In this scenario, smart devices collect data and share them with interested parties, such as road users.

The *addressed sense* distinguishes safety approaches based on intended sense to receive the relevant information for reducing road risks. Considered senses in this context are visual, auditory, and somatosensory. These three senses are also addressed by traditional road risk reduction measures, such as visual displays, auditory horns, and somatosensory rumble strip. Besides these traditional uses, all three senses are also analyzed, separated, and combined, in regard of their usefulness in modern safety approaches [6].

Our study focuses on wearables for self-protecting VRUs in a live prevention approach with visual and auditory signals. The level of concreteness and the source of information are not addressed in this study since we focus on how signals are perceived. This allows the investigated safety system to be used with different levels of concreteness (situation awareness and concrete dangers) and different sources of information (individual-based, community-based, and environment-based).

3. Method

As outlined, main aim of our studies was to investigate how to best inform cyclists about potentially dangerous areas. A prototype cyclist warning system was developed and investigated first in an exploratory study providing indications for implementation and testing of an improved system in a second study. Note that the study design and procedure were the same in both studies and only differed with respect to the investigated signal options.

3.1. Wearable Choice and Signal Development

We focused on wearables as means of communication since they are easily accessible, popular, and all-purpose devices, which are easy to integrate into various situations and systems. More concrete, we compared two wearables: 1) smart glasses as they allow for multimodal output (*i.e.*, auditory, haptic, visual), and 2) headphones since they are inexpensive, lightweight, and widespread (see **Figure 1**). Note that we decided to go for bone conduction headphones to ensure that cyclists' environmental perception is not concealed.

For each wearable, two signal options were developed and compared (see **Table 2** for an overview). The objective was to understand which combination of wearable and signal best conveys information related to danger to the cyclist.

In the first study, we were primarily interested in finding out how well different alert signals can be perceived during a bicycle ride at all. For the design process, we took several assumptions into account. Based on the objectives in the project SINUS, we assumed that we will be able to alert cyclists about a danger

Figure 1. Wearables used in the studies: Vuzix Blade smart glasses and WANFEI bone conduction headphones. Bone conduction headphones do not conceal ambient noise.

Table 2. Signal options per wearable investigated in the field studies. Options in study II were developed based on the findings of study I.

Wearable	Option	Signals in Study I (n = 6)	Signals in Study II (n = 8)
Smart Glasses	1	**Subtle** onset signal (visual) + Offset signal (visual) + continuous visual signal during danger area	Strong **visual** signal at beginning and end of danger area + continuous visual signal during danger zone
	2	**Strong** onset signal (visual) + Offset signal (visual) + continuous visual signal during danger area	Strong **visual + audio** signal at beginning and end of danger area + continuous visual signal during danger area
Headphones	1	**Subtle** onset signal (audio) + Offset signal (audio)	Subtle **audio** signal at beginning and end of danger area
	2	**Strong** onset signal (audio) + Offset signal (audio)	Subtle **audio** signal at beginning and end of danger area + **intermittent** audio signal during danger area

area but without providing information about what is causing the danger. We further assumed that cyclists need to be alerted when entering and informed when leaving the danger area. Furthermore, we decided to make a clear differentiation between which sensory channel will be targeted by the respective wearable. Hence, in study I, we went for visual signals only for the smart glasses, although they could also provide audio and haptic feedback. In addition, any signal design should keep cyclist's distraction at a minimum.

Based on these considerations, we implemented two different signal intensities per wearable (subtle vs. strong) for alerting the cyclist when entering the danger area (see Figure 2). For the smart glasses, a red rectangle would pop up in the field of the view of the cyclist (subtle onset), was scaled down in size and then moved to the upper right corner, where it would be visible while being in the danger area. When leaving the area, the rectangle was minimized until it disappeared (offset). For the strong onset, the size of the pop-up red rectangle was enlarged, while the continuous signal and offset signal remained the same. For the headphones, we came up with a rising tone (subtle onset) when entering the danger area and a descending tone (offset) when leaving the area. For the strong onset, the rising tone was played twice, while the offset tone remained the same.

During the study, the volume of the audio signals and the brightness of the visual signals were preset. The signals were iterated and pretested several times before the study started. Based on the results of study I, we chose the preferred options and further enhanced them for study II. A detailed description of the changes is provided in section 0.

3.2. Study Design and Procedure

Both studies were realized as 2 × 2 within-subjects design with *wearable type* (smart glasses vs. headphones) and *signal type* (option 1 vs. option 2, see Table 2) as independent variables. As dependent variables, we were interested in user's

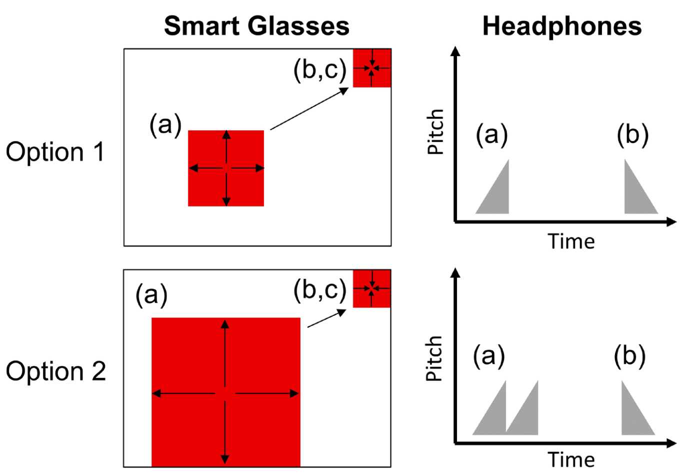

Figure 2. Signal options in study I: visual signals shown for the smart glasses: (a) onset, (b) continuous signal, (c) offset; audio signals for headphones: (a) onset, (b) offset.

perception, experience with, and acceptance of the different approaches. Note that in the studies there was not yet a real link between the warning and the riskiness of the situation. This was also pointed out to the participants.

Figure 3 provides an overview of the procedure. The study was accompanied by two experimenters, one leading the participant through the procedure, and the other managing the technical setup.

Participants were welcomed outside our research institution and after receiving a general and safety briefing about the study, were asked to sign an informed consent. They then had to fill in a demographic questionnaire, including questions about their bicycle usage, cycling behavior (CBQ, [30] [31]), previous use and experiences with headphones and smart glasses, and technology affinity (TA-EG, [32]). Participants were then introduced to the route they should ride along (Figure 4). It was first shown to them on a map and, after properly adjusting the seat of the provided research bicycle and putting on a bicycle helmet, they once rode along the route together with the experimenter to familiarize with it.

Afterwards the participant was introduced to the respective wearable and signal options. At this point, participants were also asked to rate how well they

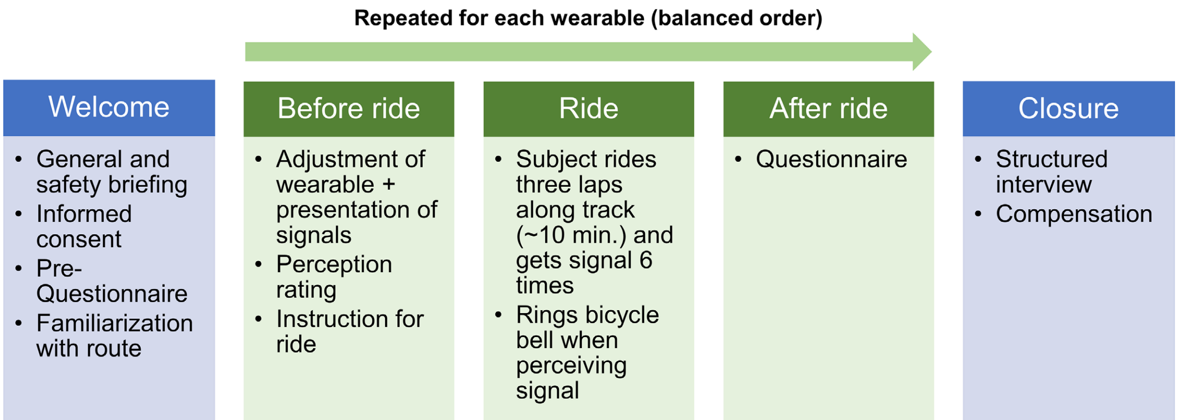

Figure 3. Study procedure for both field studies (total duration 75 minutes per participant).

Figure 4. Track used for the study. Circles with numbers show the area in which we presented a warning. The number represents the corresponding lap in which we presented the warning.

perceive the signal to gain an estimate of subjective perceptibility without being in motion. The participants were instructed to ride three laps (about 3.5 km) along the track and to ring the bicycle bell whenever they perceived a signal and when it was safe to do so (the bell was recorded with a GoPro in order to determine later whether participants perceived the signal during the ride). On pseudo-random locations in each lap, we exposed them to each of the two signal options (see Figure 4).

In total, the signals were presented six times per wearable in three laps. The order of wearables was balanced, and after each ride, participants filled in a questionnaire concerning their perception of and experience with the signals and devices. In the end, a structured interview was conducted to gather more detailed insights about participants' preferences and acceptance. Finally, the participant was compensated and sent off. The overall study duration was approximately 75 minutes. The studies were conducted in August and September 2021 and only during rainless weather conditions.

3.3. Technical Setup and Further Materials

Figure 1 provides an overview of the used wearables in the study and Figure 5 an overview of the implemented software architecture. This software architecture includes, besides the wearables, a smartphone running two applications (connector application and the headphone application) and a server. The connector application fetches the danger information (danger or no danger) from the server by supplying the GPS coordination and forwards it via a WebSocket connection. The wearables software then receives this information, either the application running on the smart glasses or a separate application on the same smartphone serving the headphones (headphone application). The wearable then conveys the signal, either over Bluetooth via the headphones or the smart glasses output devices.

Study participants were asked to bring their own bicycle helmet to the study if

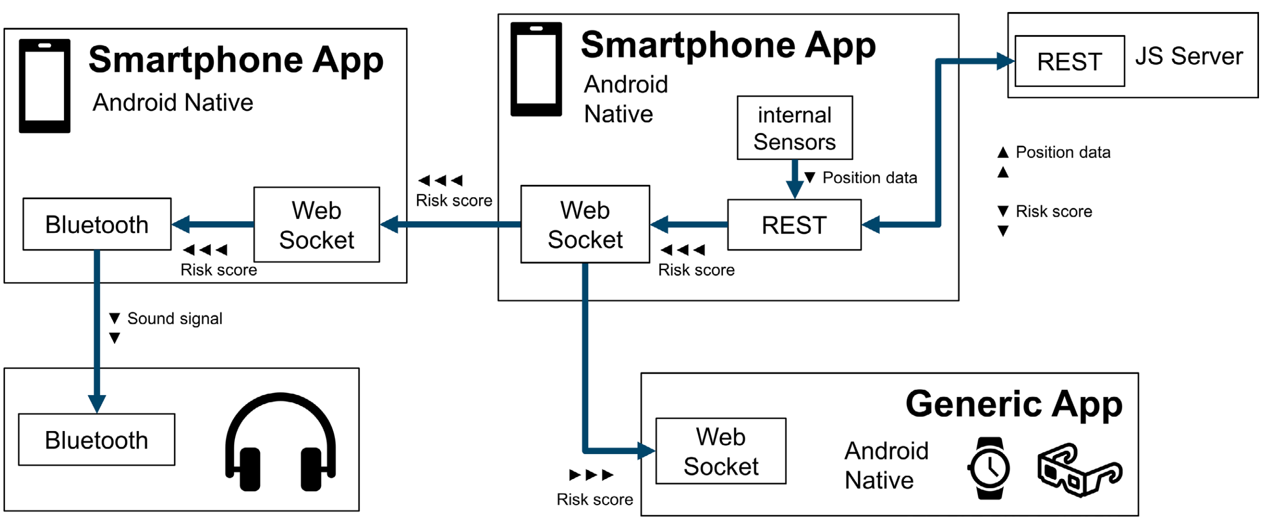

Figure 5. Software architecture used in the study.

available or were otherwise provided with a helmet by us. Participants rode a bicycle provided by TU Graz, which was equipped with a GoPro Hero to record the ringing of the bicycle bell for later analysis, and a OnePlus 8T KB2003 smartphone for controlling the wearables on track. All questionnaires were prepared in LimeSurvey and had to be filled in on a laptop. The interview guideline was prepared on paper and participants' statements were later transcribed.

3.4. Participants

We had two independent participant samples for the two studies. In total, six subjects (3 male, 3 female) with a mean age of 26.8 years (SD = 3.9) participated in study I. Two of them indicated to cycle daily, the other four several times a week. Five of them stated to primarily cycle in the city, whereas one person indicated to cycle in the city but also the countryside. Two participants had been previously involved in cycling accidents with minor injuries. Half of the participants stated to never wear a helmet, two do that mostly, and one person always. One person stated to sometimes listen to audio content via headphones while cycling. Four participants were aware about what smart glasses are but never tried them, two already tried them once.

In study II, eight subjects (4 male, 4 female) with a mean age of 34.2 years (SD = 5.5) participated. Two of them stated to cycle daily, five of them several times a week, and one person claimed to cycle several times a year. Three of them stated to primarily cycle in the city, four in the city and countryside, and one at the countryside only. Six subjects had been involved in bicycle accidents previously, one of them with major injuries. As accident cause participants named road conditions, tramway tracks, weather conditions, and own driving mistakes. Three participants stated to always wear a helmet while cycling, four most of the time, and one seldomly. Two participants stated to sometimes listen to audio content via headphones while cycling. Six participants indicated to know what smart glasses are, but have never tried them before, while two tried them once.

Both participant groups were characterized by high scores in positive cycling behaviors, and medium scores regarding cycling errors and violations (CBQ). Also, a rather positive attitude towards technology could be determined in both groups (TA-EG).

4. Results

In this section, we provide an overview of the results of both studies. Note that for study I we will present the outcomes and conclusions in a nutshell, since the outcomes of study I guided the refining of the signals for study II. Results of study II with the enhanced signals will be presented in more detail.

4.1. Study I

The first study (n = 6) was mainly concerned with varying signal intensity and, thus, comparing strong vs. subtle signals. We found that all participants could perceive all signals during the ride, no matter which intensity. However, based on the participants' statements and ratings, we found different signal preferences for the different wearables, as described beneath.

In general, the headphones were preferred over the smart glasses by four participants. As main reasons, it was stated that the signals were in general well perceivable and differentiable. Also, usability ratings for the signals were high. However, we also found that participants preferred the subtle over the strong signal, since the strong one was experienced as too strong and distracting. Furthermore, participants pointed out that they missed an intermittent signal, which indicates that they are still in the risky situation. It was also outlined that warning about a dangerous situation would be an additional benefit to the current use of headphones.

As for the smart glasses, participants had more concerns. Here, participants had problems to differentiate between the signals and to properly and timely perceive them, especially in bright light conditions. Hence, participants preferred the strong signal over the subtle one due to better visibility, while the continuous intermittent signal was considered as generally helpful. Also, the wearing comfort of the glasses was criticized, as they were experienced as, e.g., heavy and limiting the field of view. In terms of improvement suggestions, participants pointed out that combining the visual signals with audio when entering or leaving the dangerous area could be helpful to mitigate problems in visual perceptibility.

Based on these results, we adapted the signals for the second study accordingly (see **Table 2**). For the headphones, we used the subtle signal as onset signal, since the strong one was experienced as too distracting (audio). Furthermore, as enhanced option, we added an intermittent beep (every 2 sec.) as clearer indication that the cyclist is still in a risky situation (audio + intermittent). In contrast, we used the strong onset signal for the smart glasses as this was judged as better perceivable and kept the continuous signal, since it was judged as helpful (visual). As enhanced option, we added an additional audio signal for entering/leaving the danger area to increase perceptibility (visual + audio). These signals were investigated in study II with another sample of participants.

4.2. Study II

For the results of study II (n = 8) we outline four aspects: signal perception, experience, (dis)advantages of the wearables and signals, and acceptance. Due to the small sample size, we report median values. As for the statistical comparison of quantitative measures, we calculated 2-factorial non-parametric ANOVAs for repeated measures (analysis of variance of aligned rank transformed data) with the factors wearable and signal option.

4.2.1. Signal Perception

Regarding the perception of the signals during the bicycle ride (indicated by ringing the bicycle bell), we found that both signals of both wearables could be perceived by all participants (n = 8) without exception. We also asked participants to rate on a scale from 1 = not at all to 10 = totally, how well they perceived the respective signal before and during the ride. In general, signals provided by the headphones were perceived significantly better (median = 10) than the smart glasses (median = 8.5, $p < 0.001$). Both signal options for the headphones were perceived equally well before and during the ride (median ratings > = 9; n.s.). For the smart glasses perception ratings for option 1 (visual) were in general lower than for option 2 (visual and audio), and the perception of option 1 (visual) was rated even lower during the ride (median = 5.5) compared to before the ride (median = 7.5, $p < 0.001$).

4.2.2. Experience Ratings

After the ride with a certain wearable, participants had to fill in a questionnaire, where we asked them to rate different aspects concerning their experience with the respective signals and wearables, which were formulated as statements. Figure 6 provides an overview of the questionnaire results. For distraction ("*The signaling distracted me*") we found low median ratings for both wearables (n.s.), however, it is apparent that there is a larger variance in the ratings for the smart glasses, and particularly option 1 (visual), indicating that at least some participants felt more distracted.

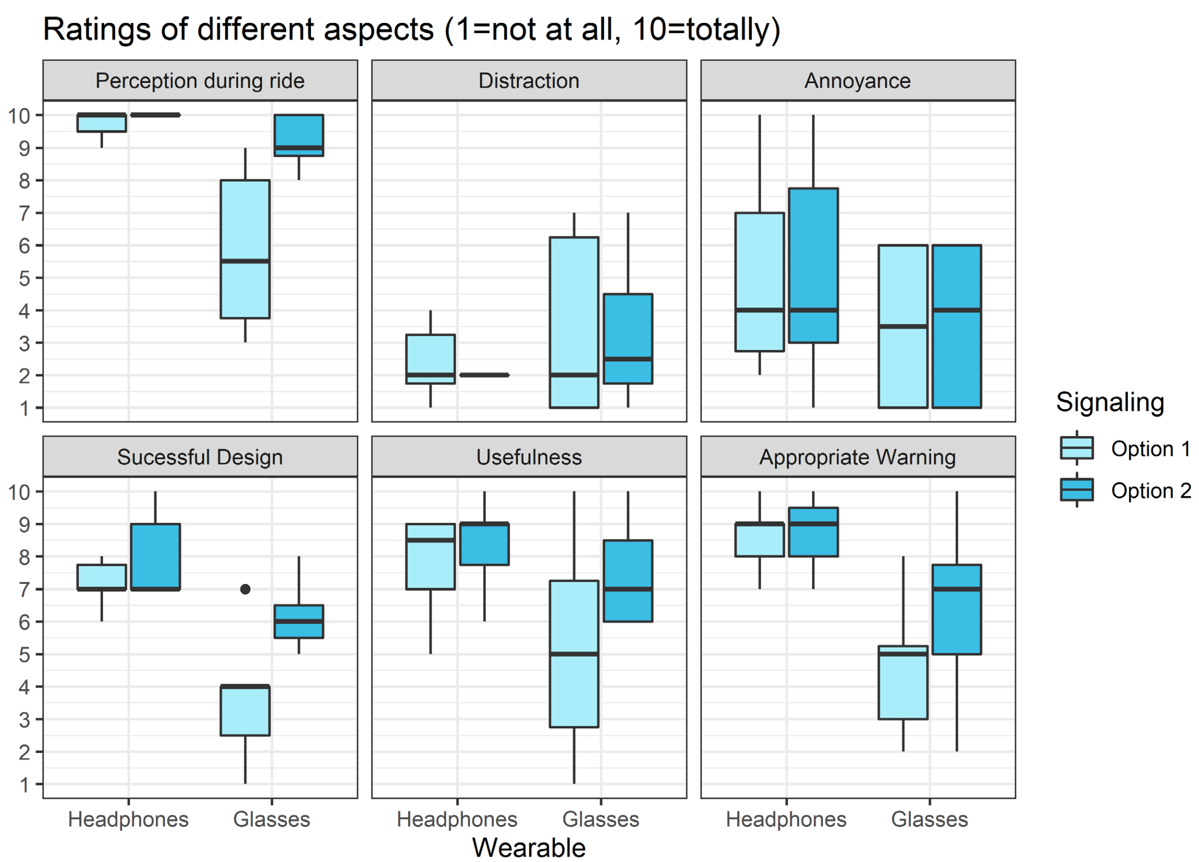

Figure 6. Questionnaire results from the second field study. Participants had to rate the different aspects (formulated as statements) on a scale from 1 = not at all to 10 = totally after the ride with the respective wearable.

For annoyance ("*I found the signaling annoying*") the median ratings are comparable for both wearables at a lower/middle spectrum of the scale (n.s.), however, we can also see a larger variance for the headphones in the upper scale spectrum, indicating that the sounds did not appeal to everyone.

Regarding the statement "*I thought the design of the signaling was successful*", we found significantly higher median ratings for the headphones compared to the smart glasses ($p < 0.001$). Thereby the ratings for option 1 (visual) are particularly low. As regards usefulness ("*I found the signaling useful to indicate potentially critical situations*"), the ratings are significantly higher for the headphones ($p < 0.001$), and in general significantly higher for option 2 ($p < 0.05$).

Furthermore, participants had to rate the statement "*I felt appropriately warned/dis-warned by the signaling*". Again, we found significantly higher ratings for both signal options provided by the headphones compared to the smart glasses ($p < 0.001$). For the smart glasses, option 1 (visual) received the lowest ratings ($p < 0.05$).

4.2.3. (Dis)advantages of the Wearables and Signals

In the final interview, we asked participants about the advantages and disadvantages of the wearables and signals, and improvement suggestions. As advantages of the headphones, it was stated most often (n = 4) that the signals were clearly perceivable, e.g., "*The signals were best recognizable*". Furthermore, the better wearing comfort was outlined (n = 3; "*Headphones do not bother me much—they don't comprise the sight.*") and that the headphones do not lead to further distraction (n = 3). Also, two participants outlined that the signaling would be compatible to listening to music while cycling.

As regards disadvantages, three participants found the sound to be annoying "*The sound was annoying as it got very high*". Two participants stated that particularly signal option 1 (audio) could be a distraction "*It could be distracting if you only have the sound at the beginning and the end—because you are waiting for it*". One participant stated that a disadvantage is that "*the headphones are something additional you need to put on*". As for improvements, four participants stated that the sound could be improved. Three participants pointed out that the sound warnings could be integrated in the headphones they normally use or that it would be useful to integrate the sounds in a bicycle helmet instead of needing to use extra headphones.

As for the advantages of the smart glasses, it was outlined most often (n = 5) that the combination auf audio and visual was clearly perceivable "*With the audio, the perception of the beginning and end of the situation was better*". Three participants also pointed out that extra information could be shown with the smart glasses "*If you could also show navigation advice, it would be a double benefit*". Regarding disadvantages, it was stated most often (n = 7) that the visual signals were difficult to detect or there were problems with glare: "*Even if they were better to wear, I would not like them—there was always a glare, which I could perceive*"; "*You could easily overlook the signal if there was direct sun-*

light". Furthermore, it was outlined, that the glasses limited the field of view (n = 3) and that the wearing comfort was not good (n = 3). Two participants stated concerns about distraction "*I would not use it—I don't like the idea that something pops up in front of you if you are supposed to pay attention in a dangerous situation*". As for improvements, participants pointed out that wearing comfort should be increased (n = 2), or that further information could be integrated (n = 2; "*You could show further information like speed, or which kind of danger it is*"). Further comments were about increasing contrast, use of another color, or use of another symbol, like, e.g., a warning triangle (n = 2 each).

4.2.4. Acceptance

In the final interview, we also asked participants which of the two wearables, respectively signals, worked better for them and they would prefer. In addition, participants had to indicate in the questionnaire provided after the ride with a wearable, which of the two signal options they preferred and why. We found that the headphones were preferred by six out of eight participants (75%). Out of the six participants, five preferred option 2 (audio + intermittent) over option 1 (audio), while one participant considered both options as equally good. As main reason for choosing option 2, all participants stated that the intermittent sound was a helpful reminder that they are still in a risky situation "*If the warning area lasts too long, the beeps in between help me reminding that I'm still in at risk...otherwise I might forget it*". "*The second one helps me to be aware that I am still in a dangerous situation*". "*You must 'think' less whether the risky situation is already over*". The two participants, who preferred the smart glasses, both preferred option 2 (visual + audio). Here it was stated that option 2 helped to overcome problems with perceiving the visual signal, and that "*A multi-modal signalization is more effective*".

Finally, we asked participants, whether they could imagine using their first-choice wearable in everyday cycling to be warned about a risky situation. For the six participants, who chose the headphones, three answered this question with a clear yes, stating that the headphones worked properly, that wearing comfort was high, or that they already wear headphones while cycling and this would be an add-on. Two participants stated that they would use headphones only conditionally: in unfamiliar situations or provided there is additional purpose for them "*I would wear them if I can do something else with them—I would not use them solely for the purpose of being warned*". One participant stated that she would not use them since "*I never use headphones*". For the smart glasses, one participant could imagine using them without conditions, while the other stated "*I would only use them if they would also show navigation information—if there is an additional benefit. Otherwise, no*".

5. Discussion

Our results show a clear preference for the headphones over the smart glasses and signaling with intermittent audio while being in the danger area. As main reasons for these choices, participants stated the clear perceptibility of the signaling in contrast to the smart glasses, higher usefulness, better wearing comfort, and less distraction. Moreover, the intermittent signal was valued as a cognitively effortless reminder that they were still in the dangerous area. However, our results also show that the sound design itself could be improved since some participants perceived the sounds as annoying.

As for the smart glasses, we found that multimodal signaling (visual and audio) could help to overcome the problems in perceiving the visual signals, however, our results also show that there are still further issues like low wearing comfort, a limitation of the field of view, glare/sunlight, and potential distraction by the visual signal. Hence, at the current stage of technical development, smart glasses do not seem suitable as a cyclist warning system. We are aware, though, that this also depends on the specifics of the respective smart glasses model.

On a more general level, our results also revealed other issues. Both studies indicate that participants' acceptance is influenced by the additional perceived benefit the respective wearable would have in daily life. Using a wearable solely to be warned, although this would increase safety, was less acceptable. Also, further conditions, like familiarity with the route, may play a role in using such an approach. Our results showed that in the end, only half of the participants would use their preferred wearable unconditionally. Hence, a key question for future studies certainly is, how such an alert system could be better integrated in the daily routines of cyclists, and/or how to increase the benefit of a wearable for cycling. Here, different options are imaginable. For example, for the proportion of cyclists who regularly wear a helmet, it could be a feasible approach to integrate an audio warning system into the helmet. On the other hand, combining navigational information with dedicated warnings for cyclists, could enhance the overall usefulness and, thus, use of the approach. Also, allowing for individualized settings could increase the subjective usefulness, e.g., by only receiving alerts when cycling on an unfamiliar route. Still, the question remains, how to alert cyclists, who are reluctant to safety precautions or use of technology? Here, a smart infrastructure could be one way to go, e.g., by having dedicated signs or signals for cyclists on bike lanes.

From a methodological perspective, our iterative approach proved to be successful. We found that in study II all participants chose the enhanced signal options (option 2) over the basic ones (option 1) for each wearable. This confirms that the adaptations based on participants' feedback in study I, were also approved by participants of study II, thus strengthening our results even though the number of participants was low in each study. However, we are aware that there are also some limitations. One challenge we had from the outset was that the possibilities are manifold when it comes to signal design. In our case, we chose to go for abstract signals and tried to make them as intuitive as possible. However, our study results suggest that there is still some room for improvement. For example, it was stated for the smart glasses that displaying a warning triangle instead of the rectangle could be more distinct. Also, we found for the headphones that our sound design was perceived as annoying by some participants. Here also the question remains, whether speech feedback instead of an audio tone could be beneficial. For the preferred option 2 (audio + intermittent) for the headphones, a further question is, whether the intermittent signal may need to be adapted to the duration of a danger area in the future.

One further limitation of our studies is the fact that we did not yet have a real link between the riskiness of a situation and the signals cyclists received, as our main aim was to first find out more about the general perceptibility, usefulness, and acceptance of the approach. As next step, we intend to investigate the approach in the field, thereby establishing this link based on the main objective of the project SINUS to determine the riskiness based on different factors.

6. Conclusion

In this paper, we presented the results of two field studies investigating how to best communicate to cyclists that they are in a potentially dangerous area by comparing different wearables and signals. Our results provide an overview of the advantages and disadvantages of the investigated wearables and signal options and outline respective room for improvement. We found that audio signaling with intermittent sound via headphones was preferred among study participants, while using smart glasses comes with several limitations. We further identified limiting factors when it comes to the daily usage of wearables for warning cyclists. A wearable must offer an additional benefit apart from being warned, while route familiarity seems to be a further factor to be considered for risk prediction.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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