Enhancing Traffic Safety with Wearable Low-Resolution Displays

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ABSTRACT

Safety is a major concern for non-motorized traffic participants, such as cyclists, pedestrians or skaters. Due to their weak nature compared to cars, accidents often lead to serious implications. In this paper, we investigate how additional protection can be achieved with wearable displays attached to a person's arm, leg or back. Different to prior work, we present an extensive study on design considerations for wearable displays in traffic. Based on interviews, experiments, and an online questionnaire with more than 100 participants, we identify potential placements, form factors, and use-cases. These findings enabled us to develop a wearable display system for traffic safety, called *beSeen*. It can be attached to different parts of the human body, such as arms, legs, or the back. Our device unobtrusively recognizes turn indication gestures, braking, and its placement on the body. We evaluate *beSeen*'s performance and show that it can be reliably used for enhancing traffic safety.

Author Keywords

wearable displays; activity recognition; traffic safety

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation: User Interfaces - Graphical user interfaces; Input devices & strategies

INTRODUCTION

Enhancing the safety in traffic is an important challenge for our society. For example in 2013, 92,492 people were killed in road accidents in the European Union. Vulnerable traffic participants like pedestrians, cyclists and motorized two-wheelers make up 43 % of fatalities [21]. Especially in cities, accidents occur because cyclists, pedestrians, and athletes are not sufficiently visible while participating in traffic. At least 20 % of cyclist fatalities are caused by bad lighting [22]. In some countries, this number even exceeds more than 50 %. Wearable displays or lights attached to a person can help to increase visibility in traffic. In this paper, we propose a versatile system for enhancing traffic safety called *beSeen*. It combines a set of wearable displays equipped with motion sensors to achieve a fully customizable safety light for traffic participants. *beSeen*'s concept has been developed using the results of a design study presented in the first part of this paper. We answer questions on display placements, visibility, and communication between users and other traffic participants.

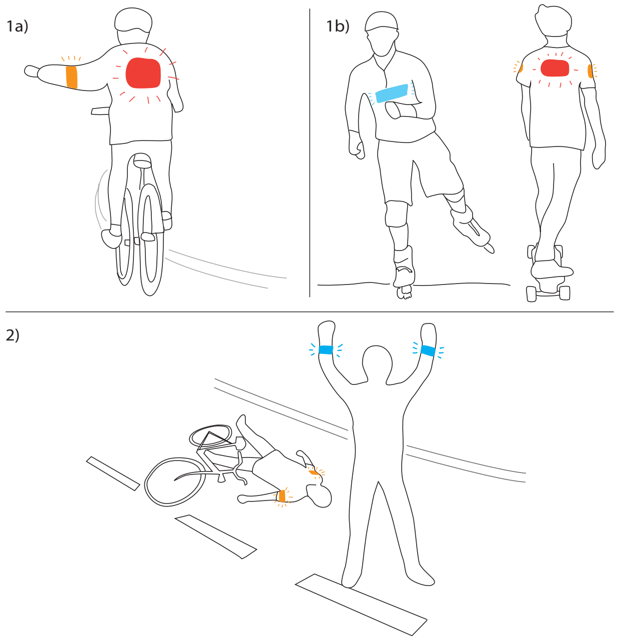

Figure 1. Wearable displays can be used in various use-cases while participating in traffic, such as 1a) indicating turns or deceleration, 1b) increasing visibility in sportive activities such as boarding or skating and 2) emergency warnings at accidents.

We also put a strong focus on usability, as any explicit action will draw attention from the traffic to the system. Therefore, interaction with a wearable display should be natural - requiring a certain amount of context-awareness. Each *beSeen* display senses a variety of physical parameters like orientation and acceleration to understand the user's actions without requiring explicit activation. Using this knowledge, customizable visualizations can be triggered on the wearable display.

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These range from brake lights, which detect deceleration, to blinking triggered by lifting the corresponding arm. Moreover, *beSeen* can be used as a front and tail light, as well as display information provided by smartphones.

In summary, we present the following scientific contributions: (i) We present a user study to identify common design considerations for wearable displays that enhance traffic safety, (ii) we introduce a versatile wearable display system called *beSeen* applicable for several traffic-related activities, and (iii) we conduct quantitative and qualitative evaluations to prove the feasibility of our proposed system architecture.

RELATED WORK

Previous works on wearable systems for participating in traffic are very widespread. They originate from research and do-it-yourself communities, or fundraising campaigns. In the following, we distinguish prior work in three main objectives: (1) Increasing visibility in traffic, (2) communicating information to oneself or other traffic participants, and (3) providing interactive experiences for traffic participants.

There are many commercial projects that aim at increasing the visibility of participants in traffic with wearable lights. For example, Veglo and Vega are LED-based strips that can be attached to a person's back or a backpack [30, 29]. While these lights do not offer interactive capabilities, BEACON introduces a wearable light strip which can be customized by smartphones [5]. Systematic approaches to design wearable systems were investigated in [18]. The authors present a design framework for e-textiles which comprises methodology for integrating LEDs and various types of sensors.

Besides increasing visibility, other projects also focus on communicating information about a measured physical or emotional state of the person wearing the device to either itself and others. Zackee is a wearable light integrated in a glove - it is able to indicate turning when pressing a button [2]. Very similarly, Carton et al. designed a smart glove that visualizes LED patterns on its surface based on different hand postures [6]. Visijax integrates LEDs directly into the jacket and recognizes arm movements, for example to trigger a turning light [31]. Sharing information about vital signs during group running was investigated by [19] and [26]. Mauriello et al. show that textile-based displays attached to a runner's back can raise group performance and motivation [19]. In order to raise social awareness during bike riding, [33] evaluated the use of helmet-attached display to share the rider's heart rate. LumaHelm takes the idea one step further and transforms the whole helmet into a display area [32]. This way, sensor data such as heart rate and acceleration (e.g. braking) can be visualized and shared to the surrounding. Besides communicating physical parameters, [17] and [34] presented a concept to share social information based on a wearable displays, for example integrated in a bag. Upcoming fashion companies like tshirtOS offer products able to display messages with LEDs underneath the fabric [3]. Materials like AmbiKraf will enable and forward the production of in-clothes-displays [23].

Providing interactive experiences while participating in traffic has been investigated for various activities and means of transport. For example, tactile systems can provide unobtrusive means for wayfinding. They have been realized as smartphone apps for pedestrians or vibro-tactile belts and handle bars for bikers [14, 25, 24]. Other modalities for supporting interactive experiences in traffic include acoustic or visual clues [9].

Different to prior work, we conduct an extensive study on wearable displays in traffic and investigate different viewpoints ranging from user preferences to visibility. While existing systems are strongly tied to a specific use-case or activity, we present generalizable design considerations for wearable displays in traffic. Our implementation *beSeen* provides increased visibility and means of communication with other traffic participants. We provide both implicit and explicit interaction opportunities, by integrating sensors and classification techniques that increase context-awareness.

DESIGN STUDY

Before designing the system, we had to investigate multiple design considerations in advance. We therefore carried out experiments and interviews with potential users. We considered the following information to be vital for the system design:

1. *Use-Cases*: What are the possible application scenarios for wearable displays in traffic? What are the scenarios people are expecting an increase in safety?
2. *Placement*: At which locations would users place a wearable display? Would they feel comfortable wearing these electronic devices on the body at all?
3. *Form Factor*: Which wearable display size would users prefer and how heavy may the device be?
4. *Feedback*: How would users like to receive feedback from a wearable display if they cannot see it? Do they require any feedback on its operation at all?
5. *Visibility*: How do other traffic participants, such as car drivers, encounter the visibility of different patch sizes, placements, and use-cases?

In order to evaluate the most suitable design approach for the goal of enhancing traffic safety, we first conducted an extensive online survey. To support the feasibility of our questions, we accompanied this process by personal interviews and experiments with 20 persons (55% male, 45% female). In the online survey, 104 participants took part, 45 % female, 53 % male and 2 % not specified. We invited persons to participate by posting an invitation on two facebook profiles and sending emails to friends, colleagues, and family. Most people (58 %) were between 20 and 30 years old, 23 % between 30 and 40, and 18 % between 40 and 70 years. This resulted in an average age of 31.87 years. Most persons (38 %) had a technical profession, while the others had a social (16 %), creative (9 %), scientific (14 %) or other (23 %) background. The results of the accompanying personal interviews supported the results of the online survey and helped us interpret the questionnaire's answers better.

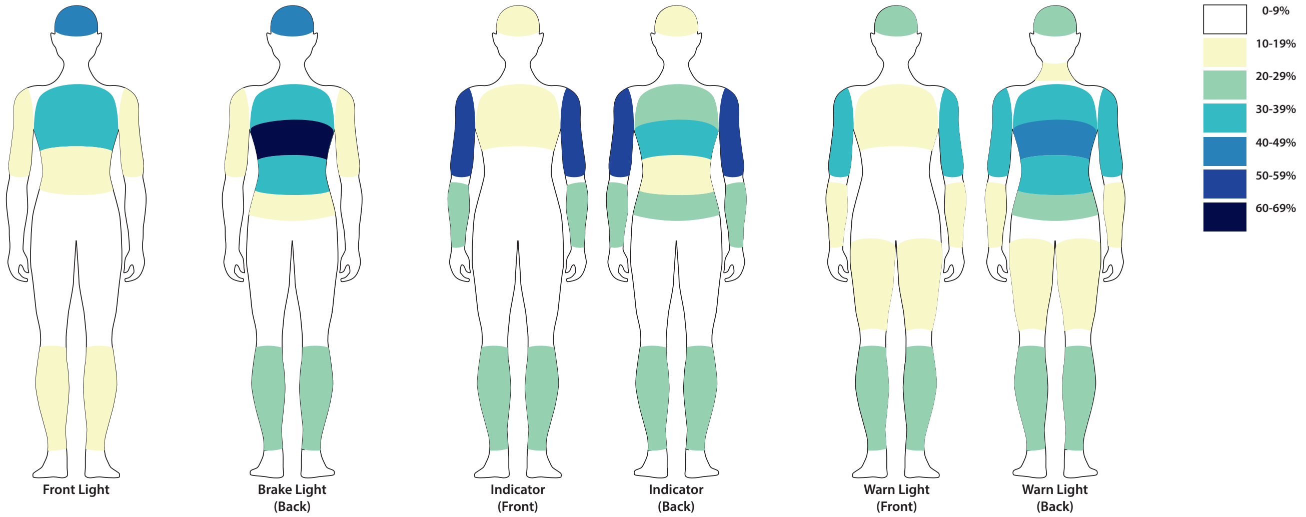

Figure 2. The placements favored by potential users depended strongly on the use-case. We could not observe any specific differences between genders.

The key findings of our study are that mainly faster sportive activities are relevant for wearing context-aware wearable displays, such as biking or skating. The participants favored placements at the upper arms for turning indicators, placements at the back for brake lights, and at the head and chest for front lights. An experiment with potential car drivers revealed that this goes mostly hand in hand with the users' visibility. The perceived visibility was better when placing the devices at the left side of the human body. A test with mock-up devices revealed the necessity to provide feedback on the proper functioning of the device. Here, a vibrational feedback was preferred over an acoustic feedback.

Use-Cases

There are several legal obligations concerning lighting of vehicles participating in traffic. For example, in Germany, a bike light must be mounted 60 cm above ground and must be directly attached to the bike's frame [8]. Moreover, brightness and battery power are regulated. Additional body-worn lights are not affected by those laws. Therefore, wearable lights are not suitable for replacing ordinary bike lights but are allowed to provide additional means of visibility and communication. Some colors should be avoided as they have determined meaning in traffic and may not legally be used. For example in many states and countries, a blue light is only allowed for emergency vehicles [20].

The surprisingly broad participation in our online questionnaire showed the relevance of increasing visibility in traffic. 49% of all participants could imagine using wearable displays in traffic. Increasing traffic safety with the help of light encountered a great acceptance, especially when performing quicker activities like cycling or jogging that partly take place on roads. Most participants did not see the necessity of increased visibility when carrying out slower activities like walking or hiking. 49 % of all participants stated that they go for walks, and 32 % go hiking regularly. 7 % of walkers and 12 % of hikers could imagine wearing an indicator or brake light. In turn, 63 % of walkers and 70 % of hikers could imagine wearing an interactive warning light. This consistent opinion and the existence of commercially available warning lights induced us to put our focus on use-cases for biking, jogging, and other sportive activities.

Besides increased visibility, some use-cases may require communication with motorized traffic participants. With 49 % acknowledgement, turn indicators and brake lights had a large acceptance when biking. In contrast, the two modalities were only accepted by 6% of our participants for jogging. For jogging and running, a simple front or tail light for increasing the overall visibility was considered to be sufficient. The live interviews also supported the applicability of warning lights, for example in cases of an accident. This impression was independent from the activity carried out.

Placements

In previous work, studies investigated possible places on the human body which are applicable for interaction [13]. In our study, we therefore did not focus on interaction, but rather on convenience and use-case dependent placement of remotely operable wearable displays. A study on placement of flexible forms on the human body [10] inspired the selection of placements proposed in our study. Therefore, we evaluated different display locations in the online questionnaire. They comprise placements on the upper body, lower leg, waist, forearm, upper arm, etc. In order to avoid possible confusions, we did not provide any information up front on how to use or attach the device. We asked for a placement where the people would feel comfortable wearing the device. In the live interviews, the participants were mainly concerned about the light's visibility for the different placements. Feeling comfortable could be observed as a less important consideration.

Figure 2 shows the participants' favored placements based on a number of use-cases. Our results indicate that these placements depend heavily on the use case of the device. Placements on the head or other moving body parts can be regarded as a special situation, as the wearable display can be delib-

Figure 3. Multiple form factors designed by potential users (left) include different shapes (like arrows and stripes) as well as various sizes. The variety of placements (right) is very large and depends on the use cases.

erately directed towards the movement direction. When it comes to visibility though, this can result in several disadvantages, as the display may be turned out of view. The location of a front light was favored on the head (48 %), on the chest (38 %), and on the waist (18%). Although interaction-related studies on projected displays show gender-specific effects on chest placements [13], we could not observe any differences among female and male participants. The brake light was favored on the back. While jogging, the placement was mainly considered relevant in the upper region of the back. The mid to lower section of the back was preferred when cycling. The reason can be seen in the users' visibility considerations for different postures while carrying out an activity.

The placement of a turn indicator is considered useful on the upper arms (50 %). Alternative placements on the back include the upper body between the shoulders (24 %), and a bit lower in the mid of the back (30 %). This ensures that car drivers can easily distinguish between the directions of the two turn signals. A warning light is mainly favored on the back (47 %) and arms (39 %) by bikers. Joggers have a comparable opinion - placements on the back (51 %) and upper arms (45 %) are appreciated. We were surprised that locations on the lower arm were not accepted greatly by joggers (14 - 21 %) or bikers (18 - 28 %). We expected that this placement would be very much appreciated because it allows users to warn other participants by gestural movements.

Form Factor

When asking our interview participants about the favored form factor of a wearable display, most persons answered that they would like the device to be as small as possible. The acceptance of the size also depends on the use case and the placement of the body. Across all placements, 35 % of the participants could imagine a size of 9 x 5 cm, while 50 % would like it to be smaller. While being placed on the head a size of 3 x 5 cm was favored, even a size of 15 x 25 cm was accepted by some people when placing it on the back. A similar line of argument applies for the display's weight: One quarter of all participants could imagine using a device weighing 100 g, but 65 % favored a weight of less than 100 g.

We also asked our participants to create their own wearable light by cutting it from colored paper. Some examples are depicted in Figure 3, showing very individual ideas, placements, and form factors. The preferred average device size was 13 x 7 cm for the brake light, and 18 x 7 cm for the indicator. The mock-up devices range from very large to very small displays to different shapes that are round, arrow- or stripe-like. Most users favored multiple patches and did not build a single patch with multiple functionalities.

Feedback

Especially when communicating information to other traffic participants, we expected a large benefit by providing feedback on the wearable display's state. The experiments were conducted at different locations, including busy roads and quiet parks. Previous works did not include additional feedback modalities besides the visual information provided by the display itself. In order to evaluate the impact of feedback we considered acoustic and haptic feedback modalities. A total of 10 participants rode a bike giving hand signals and turning as well as braking while wearing a mock-up device. The age of the participants ranged from 9 to 35. The experiment was conducted as a wizard-of-oz test, the devices actions were controlled via Bluetooth. This way it was possible to skip the expected action of the device, to evaluate its reliability.

We focused on obtaining qualitative information about the applicability, comfort, and expressiveness of the different feedback modalities. Therefore, the participants rode in various settings and used each feedback at least four times. The experiments took place mostly at night and sometimes at sunset. In total, each person used the device for at least 60 times in traffic. The corresponding activities were braking and indicating a turn. For acoustic and haptic output, we implemented three patterns consisting of continuous, recurring and singular triggering. The device was placed on the upper and lower arms as well as on the back.

We asked the participants about the usefulness of the provided feedback after each test run. A test run combines a possible output modality, the corresponding pattern and placement on the body. Each combination was randomly selected and the test persons rated their experience on a Likert scale ranging from 1 (best) to 6 (worst). In order to find out how a missing feedback is perceived, we skipped the execution for one time during each test run. The experiments were conducted at different locations, including busy roads and quiet parks.

The majority of participants perceived no feedback as unsatisfactory (M=3.9, SD=0.4). Independent from the rhythm, participants liked the vibration better (M=2.80, SD=1.43), than the sound (M=3.24, SD=1.46). Different to vibration motors, the expressiveness of providing sound is much higher, which has an influence on our results. In quiet surroundings like parks, people felt really weird carrying a beeping device which was perceivable by other pedestrians. A short beep on the start of the devices action was preferred for indicating turns (M=2.71, SD=1.31) over a long recurring sound until the turn was finished (M=3.47, SD=1.40). Differently to that, a lasting beep throughout the whole action was favored while braking (M=1.93, SD=0.45), instead of a short one (M=2.71, SD=0.49). The beeping sound we played had a fairly high frequency which was perceived as both annoying and easy to distinguishable from traffic.

Overall, vibration was favored by most participants but depends strongly on mechanical aspects. In cases when the mechanical coupling of the display to the body was too loose, the vibration could not be identified anymore. This can be regarded as a drawback for vibrational feedback, especially in winter when thick jackets are worn. The most problematic placement was at the back, where the feedback was not perceivable even when tightening the display with a belt. At this location, acoustic feedback performed better (M=3.01, SD=1.35) than vibrational feedback (M=5.05, SD=0.72). On the other hand, haptic feedback on the upper and lower arm could be identified clearly (M=2.40, SD=1.12). Acoustic feedback was perceived as more intrusive and annoying (M=3.42, SD=1.52). The acceptance of acoustic feedback at upper arm (M=2.92, SD=1.43) and lower arm (M=2.88, SD=1.42) is very similar. Comparable to acoustic noise, vibrational noise should be taken into account, for example when cycling on bumpy roads. It makes sense to adjust the intensity of vibrational feedback data provided by sensors, e.g. an accelerometer.

Visibility

To match the visibility expectations of potential users with the ones by car drivers, we recorded cyclists wearing a mock-up display in multiple traffic situations. In each recording, we attached the wearable display to the participant's favored placements, as previously shown in Figure 2. The selected placements comprise the lower leg, the lower and upper arm and the back. Each placement was recorded at least two times with different surrounding lighting. This resulted in multiple short video clips which were shown randomly in virtual reality glasses to 20 participants. All participants were asked to rate the visibility on a Likert scale from 1 (best) to 6 (worst). The results of this study are depicted in Figure 5.

Figure 4. We tested the visibility for wearable displays at different locations of the human body. Therefore, we recorded 3D videos and evaluated the visibility in virtual reality.

A cyclist's visibility with a wearable display (M=2.13, SD=1.12) was perceived much better than a cyclist without lights (M=5.40, SD=0.79). In general, placements on the upper body were perceived as better visible (M=1.99, SD=1.14) than placings on the legs (M=2.45, SD=1.00). The distance to the ground when placing the device on the leg was considered to be too low and the distance between the legs was not considered sufficient for identifying a turn's direction. When placing wearable displays on the leg, it was periodically occluded by the bike's frame. Some participants stated that this circumstance could be falsely identified as turn indication.

As we recorded the videos in right-hand traffic, the cyclist's left body part was usually closer to the road. This also lead to the fact that the right leg was partly occluded by the bike. Therefore, the participants rated the visibility as high when placing the device on the cyclist's left body part (M=1.90, SD=0.83). In contrast, a placement on the right hand side was considered to be less visible (M=2.30, SD=1.17). Some participants stated that it is also easier to identify the required distance to the biker when overtaking the biker. This indicates that the danger of accidents due to close passes of cars may be reduced. The visibility of tail lights placed on the back (M=1.71, SD=0.94) was favored over placements on the left arm (M=2.02, SD=0.86) or the right arm (M=2.29, SD=0.80).

Figure 6. The final set of applications comprises (1,2) a turn signal app that implicitly recognizes arm movements, (3) a brake light, and (4) a front light.

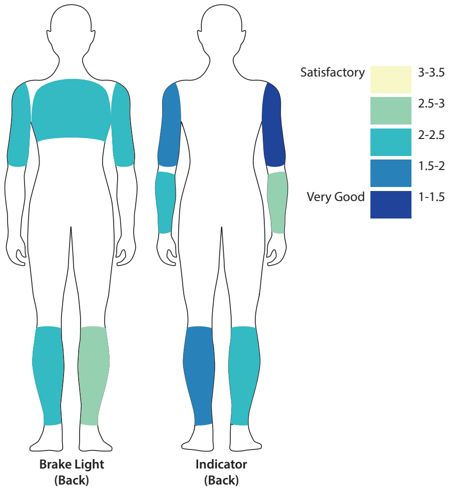

Figure 5. Potential drivers evaluated the visibility among different placements of a wearable display on the human body. A disbalance between left and right placements is caused by right-hand traffic.

We also compared turn indicator placements between the upper and lower arm. 55 % of all participants stated that the intended direction when turning was easier identifiable with placements at the lower arm. The reason can be seen in the greater distance between body and wearable display. However, the overall visibility of the upper arm (M=1.48, SD=0.79) compared to the lower arm (M=2.28, SD=1.32) is greater. This can be inferred from the fact that the indicator on the lower arm was not visible while the hand was placed on the handle bar. Instead, the indicator on the upper arm can be perceived at any time.

BESEEN SYSTEM ARCHITECTURE

Based on our design study, we created a prototypical wearable display system called *beSeen* shown in Figure 6. It is composed of multiple wearable display patches that can be attached to various parts of the body. Such flexible placements increase the range of possible applications.

Before designing the system, we considered different interaction possibilities - either on each device itself or centred around a smartphone. Obviously, the latter option is less time-consuming, but the feasibility is low when the smartphone has run out of batteries or users do not posses one. Therefore, we decided on providing independent features in each wearable display. Features that are not vital for normal operation, like adjusting feedback or brightness, can be controlled with a smartphone. Another challenge when interacting with the wearable LED-based display is its low resolution. Therefore, text is hardly practicable - it is necessary to implement pictograms to transport information and messages to the user.

When attached to an arm, lifting *beSeen* can trigger a turn indicator to blink. In case a traffic participant falls down due to an accident, *beSeen* can trigger a bright emergency signal to indicate the dangerous situation. Interaction can be based on body movements captured by each *beSeen* patch, or by direct control with a smartphone or smartwatch via Bluetooth. The latter approach can be used to control settings like a patch's brightness or feedback and launch different behaviours.

A number of input modalities can be applied for interacting directly with wearable displays and recognize activities implicitly [28]. For example, it is possible to supply buttons and knobs as in existing commercial products [2], or making the surface touch or proximity sensitive [7, 12, 11]. State-of-the-art projects often employ inertial measurement units to allow for both implicit and explicit interaction [6, 30]. Thinking further, skin buttons [16] or skin touch screens [1] would possibly create easy to use input methods. We decided on using a singular inertial measurement unit as its expressiveness is very high when participating in traffic.

Hardware

An overview of our hardware design is depicted in Figure 7. Each patch consists of an Arduino board featuring an ATmega328p running on 8 MHz. We also integrated an inertial measurement unit (MPU-6050), which combines an accelerometer and a gyroscope sampled at 100 Hz. The IMU includes a digital motion processor unit which disburdens the microcontroller from many signal processing steps. Furthermore, the design includes a BLE chip for wireless communication with a smartphone or a smartwatch. A piezo is used for acoustic feedback, while a vibration motor provides more subtle haptic feedback. A photodiode is used to adjust the light intensity to the surrounding area.

In order to be able to operate independently without any additional hardware device, we implemented gesture recognition features on the devices themselves. Depending on the body part the display is attached to, different behaviors can be recognized, such as a brake gesture when wearing at a person's back or a turn gesture when attached on the forearm. This is possible due to the autonomous placing recognition implemented. Optionally, the phone can be used as a control unit for custom animations and updates on the wearable display.

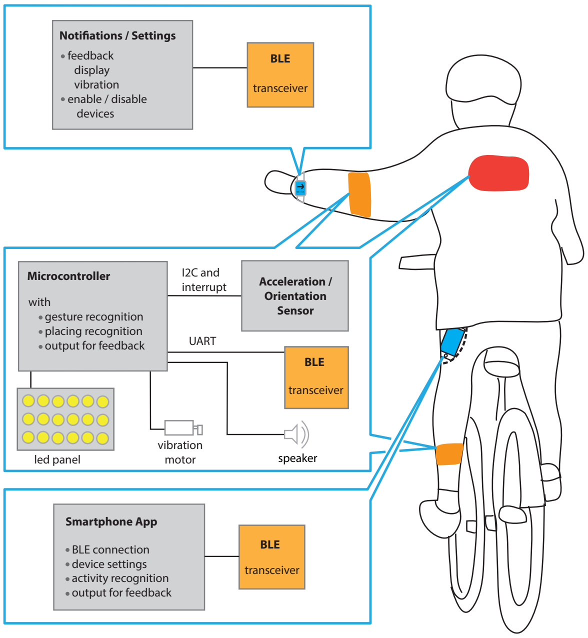

Figure 7. The beSeen architecture includes a variable amount of wearable displays attached to different positions on the human body. The displays are able to communicate to a smartphone or smartwatch using Bluetooth.

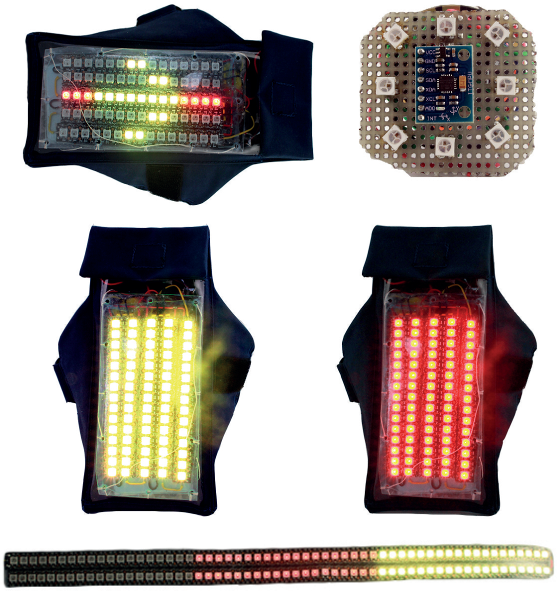

Figure 8. Photos of the different prototypes we developed: A display attachable to the arm, a small display for head placements, and a strip for back placements.

Visualizations & Form Factors

The RGB LEDs (WS2812B) give us the ability to create visualizations and pictograms that provide means for communicating with other traffic participants. As described in our design considerations, some colors should be avoided due to legal obligations, such as blue. A placement at the user's lower arm allows for indicating turns. An arrow is visualized on the display with yellow to amber color, toggling at a frequency of 1.5 Hz very similar to a car. We combined both a tail and a brake light. When no braking situation is detected, the display only activates a few LEDs with low brightness. On the other hand, all LEDs light up at high brightness when the user decelerates. When making use of deceleration parameters, the light can also progressively increase the brightness and the number of LEDs. This gives other traffic participants the ability to estimate how strong the deceleration is and react to it in the best possible way.

Based on the study's results on possible form factors, we implemented three prototypes, shown in Figure 8. One is a patch of size 15 x 5 cm, one a strip of size 100 x 4 cm, and one a small headlight with a size of 5 x 5 cm. The strip is mainly considered to be placed around the persons upper body, whereas the patch is intended for placements at both, the arms and the back.

Braking Detection

Detecting braking situations requires a carefully balanced detection mechanism. While braking maneuvers should be recognized at high accuracy, the device should not take action at slight decelerations. In our prior experiments we could observe many situations that were not immediately identifiable as braking activities. For example, when approaching an elevation or when turning, the bike also slows down. Therefore, the wearable display may observe all deceleration events, not just the ones caused by intentional braking. We implemented the braking detection for back-worn displays, as this placement was favored widely by our study participants.

Due to the limited memory and processing capabilities on our microcontroller, we had to be very restrictive in our implementation. Figure 10 shows a pseudo-code implementation of our brake detection algorithm. A corresponding example of the resulting variables is depicted in Figure 9. The algorithm uses two rolling mean values, one with a fast and one with a slow response. The slow rolling means for the y- and z-axis $s_{y,z}$ are used for neglecting longer-lasting changes, e.g. induced by the biker's posture. Building the difference to the fast rolling means $f_{y,z}$ enables to recognize situations in which the user decelerates. We apply δ_{min} to neglect very small differences between the signals, which is usually in the area of 0.02 g. As soon as a greater difference between fast and slow rolling mean is detected, it is accumulated in i and compared to a predetermined threshold $\sigma_{threshold}$. While analysing the data, we monitored a force shift in curves. In order to reduce this noise caused by centrifugal forces we adjust the integral calculation in real time by removing $\frac{1}{4}$ of the device's sideways trend.

In order to judge the performance of our implementation, we conducted an experiment with our 20 test persons. We asked them to cycle through various situations in traffic, including turns, braking, and straight riding on different surfaces. We recorded the resulting classification performance. The test persons conducted 400 braking maneuvers, with 99.75% cor-

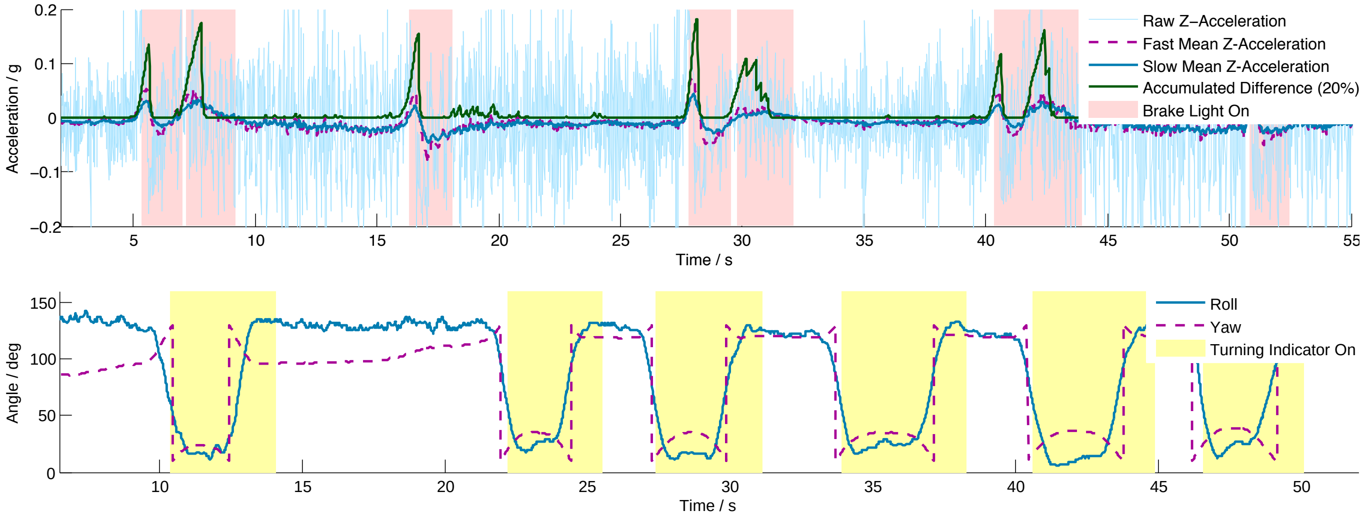

Figure 9. Top: A real world recording with our brake detection algorithm - it is very hard to draw the line between braking and other manoeuvres that induce deceleration like approaching elevations. Bottom: Turn signal gestures and waving gestures are recognized based on a state machine.

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for new acceleration measurement $m_{a,t}$ with axis $a$ at time $t$ do
    for axis $a \in \{y, z\}$ do                                          ▷ calculate features
        $s_{a,t} = ((s_{a,t-1} << 6) - s_{a,t-1} + m_{a,t}) >> 6$;        ▷ slow mean
        $f_{a,t} = ((f_{a,t-1} << 5) - f_{a,t-1} + m_{a,t}) >> 5$;        ▷ fast mean
    end for

    if $f_{z,t} < (s_{z,t} + \delta_{min})$ then                          ▷ if change is small
        $i_t = i_{t-1} >> 1$;                                             ▷ decrease accumulated difference
    else                                                                  ▷ else change is large
        $i_t = i_{t-1} + (f_{z,t} - s_{z,t}) - (\|f_{y,t} - s_{y,t}\| >> 2)$;
                                                                          ▷ accumulate difference
    end if

    if $i_t > \sigma_{threshold}$ then
        brakelight_on()                                                   ▷ Switch brake light on for 1s
    end if
end for
```

Figure 10. The brake detection algorithm poses low requirements on the hardware and can be executed independently on each *beSeen* light.

rectly recognized instances. There were also situations in which the algorithm led to misclassifications. These situations comprised the beginning of a cycling activity due to heavier movements of the upper body. For activities, in which the cyclist starts riding and pushes hard into the pedals, the error rate was at 64 %. We recorded 160 minutes of cycling with just two additional misclassifications. Depending on the threshold parameters and the strength of the braking maneuvers, the latency of braking detection is 250 -500 ms on average. A further improvement in latency can be achieved by estimating the road's parameters [4] to set different threshold levels.

Heavy upper body movements can also be observed while climbing up a curbside or while taking sharp curves. The corresponding false classifications depend on the cyclist's position while riding the bike, the curbside's harshness, and even the bike's suspension. A bad or non existent suspension causes the rider to whip forwards and backwards. This produces forces comparable to the ones used for detecting braking behaviour. Although the results for these upper body movements can be improved further, the overall outcome is very positive. Especially the number of true positives is vital for the system's operation. A reduction of misclassifications related to body movements can be achieved by reacting on heavy gyroscope drifts.

Gesture & Placement Recognition

As stated in the previous sections, we focus on recognizing gestures and placements independently from a smartphone on the *beSeen* displays themselves. In order to cope with the low computational abilities of our microcontroller, both classification tasks for gesture and placement recognition were realized with decision trees.

Using the results of our studies, we selected a set of four different placements: forearm, upper arm, lower leg, and back. The placement recognition is especially valuable when attaching the patch regularly to different locations on the body. For example, when wearing a rucksack, it is more feasible to quickly change the position from the back to the upper arm. In order to make the placement process as easy as possible, the user attaches the corresponding display to the body and then performs a short walking-like activity. Therefore, we recorded and annotated accelerometer and gyroscope information for different activities with 10 persons. This information was fed into the WEKA framework [27] to generate the corresponding decision trees using the J48-algorithm.

We evaluated the performance of our approach with our probands, with results shown in Figure 11. The matrix shows that the decision tree returns false classification when no movements are carried out. In order to filter these, we performed a majority voting within the placement recognition phase. Based on a weighted vote for dominant classes like *forearm*, we could achieve a perfect accuracy when applying a 4 second posture classification window.

Our set of recognizable gestures consists of two classes, lifting the arm for indicating turns and waving for triggering a warning light. We wanted the gestures to be as natural as

classified as → ground truth ↓	Forearm	Upper arm	Lower leg	Back	Reject
Forearm	4680	2	0	690	2628
Upper arm	0	7836	3	0	161
Lower Leg	0	3030	4660	0	310
Back	0	0	0	7134	866

Figure 11. Confusion matrix of the unweighted decision tree results of placement recognition. In order to sort out these misclassifications, we apply a majority voting with dominant classes.

possible to not draw to much attention from traffic. Gesture recognition is only carried out when wearing the patch on the upper arm and the forearm.

Possible gesture detection algorithms based on time-series classification like DTW and HMMs require a lot of processing power and memory on a 6-dimensional dataset. We abstracted from these approaches and designed a state machine with the states *lifted*, *waving*, *handlebars*, *hanging* with state transitions based on a small set of features. An example of a turning indication gesture in Figure 9 shows clearly distinguishable states. When carrying out this gesture, we assume that the arm is first located on the handlebar and then moved to a lifted state. Moving the hand back to the handlebar will switch off the turning indicator light after 1 second, as the arm is needed to operate the bike while turning. Based on this implementation, we achieve a recognition performance of 100%.

SUMMARY AND CONCLUSIONS

Wearable displays are very well-suited for increasing the visibility of non-motorized traffic participants. Besides increased visibility, interactive features allow communicating with other traffic participants, for example by automatically triggering a turning indicator when lifting the arm. Wearable displays can also be used for other activities like jogging or skating.

As our central contribution, we systematically evaluated design considerations for wearable displays in traffic. Our studies include the investigation of placements favoured by users, possible form factors, and use-cases. Moreover, we evaluated the visibility of different display placements for car drivers. Therefore, we used 3D recordings with virtual reality glasses to allow for evaluating a high number of participants. We also investigated the use of different feedback modalities comprising haptic, acoustic, and visual feedback. Based on our studies, we implemented a wearable display system called *beSeen*. It can be attached to various parts of the human body. Context-awareness is achieved by integrating an inertial measurement unit into each display, as well as linking it to a user's mobile phone via Bluetooth. Each display is able to recognize various placements with a simple initialization posture. Moreover, we implemented and evaluated front lights, turning indicators, and brake lights. Feedback about the device's state is delivered to the user by a vibration motor and a speaker. We could show that *beSeen's* recognition performance for turning gestures and braking manoeuvres is suitable for the sensitive use-case of participating in traffic.

In the future, we would like to refine our *beSeen* architecture and work towards more detailed context awareness by linking activity recognition on multiple devices. This could allow for recognizing situations like accidents, estimate road parameters, or derive information for personal health applications. Integrating *beSeen* into clothing requires investigating possible power supplies and recharging possibilities, as well as possible sensor and light placements. An integration of Vehicle-to-Vehicle communications, as proposed in [15] can also be considered for wearable displays. This would enable the biker to warn and locate approaching cars with an additional modality. A video of our work can be found here: `https://youtu.be/d-cGG1AvK1k`.

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