# Wearing Awareness: Designing *Pedestrian-Wearables* for Interactions with Autonomous Vehicles

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(a) (b)

**Figure 1: Two examples of participant-proposed *pedestrian-wearables*, (a) a stretching facemask and (b) a shape-changing scarf.**

## ABSTRACT

Fully autonomous vehicles (AVs) are said to become part of our streets, however, their introduction raises certain challenges for vulnerable road users when it comes to making confident street-crossing decisions. To mitigate such concerns, researchers have proposed novel external human-machine interfaces (eHMI) that transmit vehicle intent and awareness information to pedestrians. However, many proposed eHMIs are limited to being deployed on vehicles or street infrastructures, and therefore offer limited opportunities to provide more personal forms of feedback to diverse pedestrians. In this work, we introduce a new category of eHMIs, *pedestrian-wearables*, which include clothing- and accessories-based devices that provide information about AVs directly to pedestrians. We report on a study wherein participants proposed designs for *pedestrian-wearables* that provide relevant alerts to wearers and help them make safer street-crossing decisions. Informed by our participants' designs, we discuss three main facets of *pedestrian-wearables*: their perceived strengths and potential for inclusiveness and social acceptability.

## CCS CONCEPTS

• **Human-centered computing → Empirical studies in HCI**; **Empirical studies in interaction design**.

## KEYWORDS

*pedestrian-wearables*, AV-pedestrian interactions, communication.

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## 1 INTRODUCTION

As the world transitions towards a more technologically inclined future, it is important to recognize and prioritize the safe integration of large types of machinery, such as autonomous vehicles (AVs), into our daily lives [7, 36, 44]. The introduction of AVs promises several benefits for society including increased traffic efficiency and mobility, fewer traffic collisions, and positive impacts on the environment [1, 6, 8, 19, 25], however, their introduction also results in the loss of driver cues [1, 8, 19, 33]. This absence leads to pedestrians experiencing increased levels of fear towards AVs, and decreased levels of trust and comfort in them [1], which motivates the need to provide pedestrians with information regarding oncoming vehicles [1, 2, 34].

Outside of driver cues, pedestrians currently receive information from traffic and pedestrian signals at intersections, however, such mechanisms are not accessible to varied pedestrian demographics [12, 24]. For example, visual signals only help sighted individuals [12] and audio cues can be easily missed at busy intersections. While cellphones and their related technologies such as augmented reality present an opportunity for individualized alerts [25, 26, 49], not all pedestrians carry cellphones, they may not always be accessible, and such functionality-rich devices can


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become quickly overloaded, causing alerts to be missed, ignored, or become annoyances [20].

We build on current efforts towards designing interactions with AVs [50] by brainstorming and analyzing possible clothing- and accessories-based wearables, as proposed in recent literature [48, 57], as always-available devices for communicating information to pedestrians [32]. We name these devices *pedestrian-wearables*, and define them as a subset of wearable technology devices whose primary purpose is to alert pedestrians of relevant information such as oncoming AVs and their intentions. Such devices can provide adaptable and intimate communication mechanisms. They also present opportunities for creating sensory disability-friendly devices that activate multiple senses for any given alert [54] by not only sensing changes in their surroundings, but by communicating, making decisions, and actuating accordingly [21]. In this paper, we analyze a set of design ideas for future *pedestrian-wearables* and present an extended understanding of pedestrian preferences for wearable devices (beyond smartphones and smartwatches [47, 55]) that serve as alerting mechanisms in AV interactions. Our current efforts focus on exploring an initial design space for *pedestrian-wearables*. In the future, we aim to develop prototypes and conduct user studies to explore people's reactions to using *pedestrian-wearables*.

## 2 RELATED WORKS

This section briefly discusses the current literature on interactions between AVs and vulnerable road users and highlights the potential for personalized communication between AVs and pedestrians.

### 2.1 Interactions Between Autonomous Vehicles and Vulnerable Road Users

Researchers have explored several questions related to pedestrians and other vulnerable road users' safe interactions with AVs. For example, Adnan et al. highlighted the importance of sharing vehicle intent and awareness cues with pedestrians [1] and discussed how the loss of driver cues led to increased levels of pedestrian fear and decreased levels of pedestrian trust and comfort in the vehicle [1]. This sentiment was also emphasized by Amini et al., who discussed the importance of ensuring pedestrians know they have been seen by vehicles [2]. In response to increasing awareness for pedestrians, many types of interfaces (commonly referred to as eHMIs), such as vehicle-mounted devices [15, 16, 18, 36–38], personal cellular interfaces [36–38], and projections [11, 27] have been proposed. Through exploration of such eHMIs, researchers have found that (1) pedestrians value intent cues more than awareness cues [36–38], (2) while eHMIs help convince pedestrians of vehicle intent, pedestrians do not blindly trust them [15, 16, 18], and (3) visualizations from a vehicle itself increase pedestrian trust [10]. In the case of other vulnerable road users such as cyclists, interfaces such as handlebar vibrations and laser projections have been explored, finding that interfaces situated on the vulnerable road user yielded the fewest tradeoffs when it came to usage and safety [27]. More broadly, Bazilinskyy et al. found that text- and colour-based eHMIs were most persuasive for pedestrians [5], however, as visual representations, these also present concerns regarding feasibility, accessibility, and legibility. Beyond such interface-centric studies, Dey et al. also presented a taxonomy for eHMIs in which they categorize alerting systems by state and message [14]. Lastly, researchers have also compared pedestrian treatment towards AVs to that towards manually driven vehicles and found that vehicle distance and speed were crucial factors that pedestrians pay attention to when making crossing decisions [17, 52].

### 2.2 Wearables for Autonomous Vehicle Interactions

Wearable technologies aim to incorporate functional computer and electronic components into individuals' daily lives without being intrusive, distracting, or excessively controlling [54]. They are already used by many individuals in the forms of fitness trackers [23, 53, 54] and personal health monitors [30, 47, 56] to help aid day-to-day stresses through their communicative abilities. Prior research has explored the use and integration of technology on street corners [46, 55], and further encouraged exploring the use of wearables as communication mechanisms between AVs and pedestrians [48, 57]. Wearables for drivers, like headset-mounted audio sensors for detection and location of surrounding vehicles [55] as well as vehicle-integrated devices such as cellphones and smartwatches for safer-driving [47] have been explored as part of intersection-wide communication networks. Both examples demonstrate the ability to acquire and communicate required information to facilitate safer intersection interactions. Beyond intersection-wide explorations, Tabone et al. discuss and support the possibility of using wearables to complement other eHMI forms of AV-pedestrian communication [48], and Zhou et al. encourage the exploration of various cue types, particularly haptic cues through wearables, to help people develop trust towards AVs [57]. Finally, Mahadevan et al. encourage the exploration of interfaces that exist beyond the vehicle for the purpose of communicating with pedestrians [37]. We expand upon these works to begin exploring potential pedestrian-based wearables that can aid communication with AVs.

## 3 VIDEO PROTOTYPING STUDY

We conducted a remote, two-phase prototyping study to gather insight, brainstorm ideas, and explore possible designs for *pedestrian-wearables* (Figure 2). Prior to conducting the study with participants, the research team underwent a brainstorming session to individually reflect on street-crossing scenarios and propose a set of possible designs.

### 3.1 Study Methodology

We adapted the PICTIVE [40] and video prototyping methods [35] for a virtual study setting. Using these methods and a set of provided prototyping tools [40], participants were asked to design ideas for *pedestrian-wearables* based on task scenarios. Following, they demonstrated how their wearable would function [35].

*3.1.1 Study Procedure.* At the start of every study session, conducted 1-1 with a participant, the researcher provided background of the study. This brief introduction was followed by a short discussion about their street-crossing experiences, with question prompts such as *Do you look towards drivers or vehicles regarding their intent towards you and awareness of you? Are there specific cues that you look for when determining whether to cross an intersection?* and

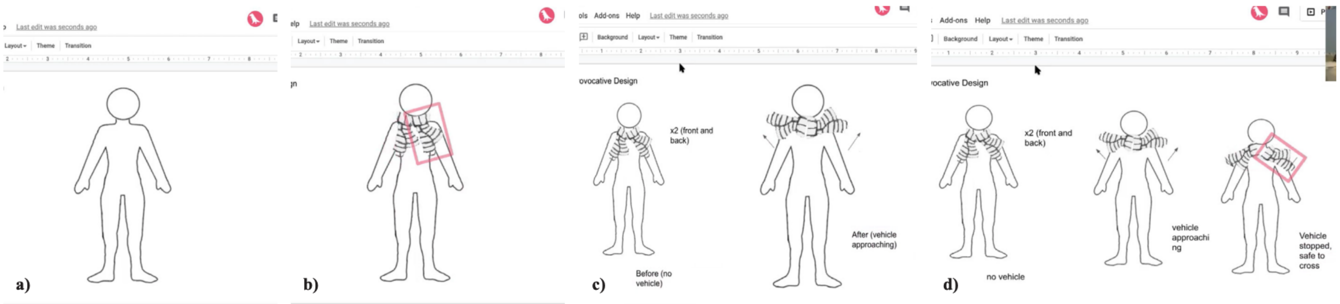


**Figure 2: An example of a participant going through the design process: a) the blank 2D human model, b) drag and drop nature of platform and components, c) and d) demonstrations of interaction and actuation of their designed *pedestrian-wearable.***

*Which cues are more important to you - those from a driver or a vehicle?*. Next, the participant completed two phases of our study in a 60-minute session. In each phase, participants were asked to produce at least three *pedestrian-wearable* designs. In phase 1, participants proposed directed designs (i.e., more conspicuous or realistic ideas), and in phase 2, they proposed provocative designs (i.e., 'out-of-the-box' and futuristic ideas). Contrasting phases were chosen to encourage creative thinking to produce a broader spectrum of design ideas. Each phase was broken into three sections: (1) Inspiration: participants were first shown examples (researcher-created sketches or existing artifacts from fashion and entertainment industries) to provide context and help identify the difference between the two phases. (2) Brainstorming: participants were given 15 minutes to design wearables using a think-aloud protocol (see Figure 2). These designs were created on Google Slides using a 2D human model and various draggable clothing and accessory templates to position on the model and edit as they saw fit. Participants were also free to create their own wearable templates using Google Slides drawing tools. The 15 minute session ensured participants explored multiple ideas without being overly critical of their thoughts. (3) Discussion: following the design phase, participants were asked a set of questions, like *How effective do you feel this wearable would be generally, in various weather conditions, in noisy or busy intersections, and in other situations?*, to gauge the usability and wearabiliy of proposed solutions, as well as user needs for *pedestrian-wearables* [19].

Upon completion of the two phases, participants were asked to rank their designs in order of their overall design, their perceived aesthetic nature, effectiveness, comfort level and wearability, and alerting stimulus. We recorded each session for posterior qualitative data analysis.

*3.1.2 Participants.* Five participants, two upper-year undergraduate and three graduate students took part in our design study. We recruited participants who had prior design experience (i.e., backgrounds in art or HCI), as well as many years of street-crossing experience as pedestrians. P1 completed the two phases over two days, while the remaining participants completed the two phases in a single, continuous session. To evoke different thought processes, three participants were asked to initially complete phase 1, followed by phase 2 (P1, P4, P5), and the remaining two participants (P2, P3) were asked to complete the phases in reverse order.

## 3.2 Video Prototyping Analysis

The collected qualitative data were transcribed, then analyzed, to find emerging common themes by performing a thematic content analysis. First, we coded by alerting mechanisms, then by garment type, and finally, by wearability. To code for alerting mechanisms, we referenced existing eHMI frameworks such as those suggested by Mahadevan et al [36, 38]. For garment type, we used terminology that is used in fashion and clothing catalogues. Lastly, for wearability we looked to the Design for Wearability Guidelines as they provide a well-rounded set of principles that cover functional, technical, and aesthetic details [22]. We selected these three sets of concepts because collectively they provide a holistic view of understanding the role of *pedestrian-wearables*. By coding for altering mechanism type, we hoped to learn about how information would be conveyed to the wearer. For such alerts to be effective, it would depend on where they exist on the human body and how they would be used, determined in our analysis by looking at garment style. Lastly, the likelihood of people (e.g., social acceptance) using such devices was looked into using the wearability guidelines.

# 4 RESULTS

Figure 3 presents a collection of the unique design ideas proposed for *pedestrian-wearables* that is categorized into three groups by type of alerting mechanism. The figure includes both, a subset of the proposed designs from our study as well designs produced by the research team. In total, our study discovered 36 designs (30 participant-proposed, 6 researcher-proposed), of which 21 were unique (15 participant-proposed, 2 researcher-proposed, 4 proposed by both). In Figure 3, those marked with an asterisk (*) were proposed by both participants and the research team, while those marked with a (1) were proposed by only the research team. Designs that were repeatedly proposed by different participants have been combined into single sketches in the presented diagram.

Overall, participants noted that they were likely to wear all the designs they produced in the directed designs phase (e.g. *"the more subtle designs are what I think we could most likely see in the future"* [P1], *"these are the most easily removable accessories, and the most subtle"* [P5]), but were hesitant about the more obtrusive and obnoxious designs from the provocative phase (e.g. *"it's drawing that line between they will notice and this will disrupt them..."* [P3]).

### 4.1 Most Commonly Recurring Designs

We found that the most commonly proposed designs by participants included a pair of squeezing socks, constricting bands, and alerting headphones. Such devices were said to be desirable due to their hidden and unobtrusive nature and their adaptability to different individuals and environments. For example, the squeezing socks (P1-2, P4) make contact with a large surface area of the wearer's skin, providing greater possibilities of tactile alerts (e.g. *"you could add different materials to the sole… it would feel different"* [P1]), while also being an article of clothing which is worn in many climates and across many regions. The constricting bands (P3-5) have the potential of integrating into existing garments and accessories such as watch-bands or belts (e.g. *"constriction can be extended to socks or gloves"* [P4]), and were described as flexible in terms of possible variations for customization and personalization (e.g. *"different points of constriction could translate to different things"* [P3]). The alerting headphones (P2, P4-5) were identified as a common accessory that many people are already familiar with (e.g. *"they're a day to day thing that you already use"* [P2]), and it provided opportunities for audio, visual, or tactile alerting mechanism integrations (e.g *"I like the addition of vibrations or pulsing to make it more accessible"* [P5]).

### 4.2 Alerting Mechanisms

As seen by the range of designs, participants were most inclined towards physical, or tactile, alerting mechanisms. They reasoned that physical alerts would result in the most effective communication devices, followed by visual alerting mechanisms, and concluding with audio alerting mechanisms (e.g. *"sound and light are already so overloaded… you already have crosswalks that alert both of those senses"* [P3]). Participants suggested that tactile feedback was perhaps the least annoying (e.g., *"Squeezing is an effective and least annoying way to alert the user"* [P1]), hard to miss (e.g., *"Touch because skin is very sensitive"* [P2], was more inclusive (e.g., *"Touch really does include more people."* [P5]), and served as the least overloaded sense (e.g., *"Sense of touch... you're already overloading sight and sound so much"* [P4]).

### 4.3 Garment Styles

All the garments in our set of designs can be categorized into two high-level concepts: essentials and accessories. Essentials contain garments that are worn daily and that individuals own multiples of (e.g. *"you're always wearing some form of it"* [P1]), and typically constituted of artifacts that came in contact with a relatively larger area of the individual's body such as jackets, shirts, socks, and shoes. Accessories, on the other hand, while could be used daily, typically constituted items that individuals typically only own one or two of and would be worn on top of some essentials, such as scarves, glasses, and headphones. Participants noted that essentials such as shirts and socks being closer to the skin would make alerts through these garments more prominent. Socks and shoes were particularly of interest as participants noted that these are the primary limbs used when walking (e.g. *"individuals use their feet as their main source of walking"* [P1]). Conversely, participants mentioned that accessories such as bands and headphones are usable in multiple situations and can be placed on various parts of the body (e.g. *"it's an accessory, I don't have to go out of my way to put it on"* [P4]), implying an increased willingness to wear the devices, and potentially more consistent usage.

### 4.4 Wearability Considerations of *Pedestrian-Wearables*

Our analysis highlighted that participant designs considered the following wearability guidelines [22]:

**Human Movement.** Being always on the body, participants proposed easily moldable devices that conformed to the shape of the human body (e.g. *"it's a part of the movement of the body"* [P1]) and the dynamics of its movements, while maintaining contact with a large surface area of the wearer's body for flexibility in performance.

**Form.** Devices were designed to be smooth to touch and easily moldable for seamless integration onto the wearer's body while maintaining comfort and allowing for dynamic mobility (e.g. *"it's something that can always be worn under your clothing"* [P4]). They were also placed close enough to the body to maintain effectiveness and allow for flexibility in design (e.g. *"it's very close to your skin… it doesn't matter how many layers you have"* [P2]).

**Sensory Interaction.** Participants ensured devices successfully alerted at least one of sight, hearing, or touch, and that activations were a result of communication received from AVs. For example, P3 suggested color-changing glasses as they could incorporate multiple alerting mechanisms in order to assist a diverse group of pedestrians.

**Placement.** As user comfort is a driving factor in the success of *pedestrian-wearables*, participants suggested their placement might determine how well they will be received and adopted. For example, P3-5 suggested forms of constricting bands due to their variability and inconspicuous nature (e.g. *"it's something you can hide under your clothes... usable in multiple situations."* [P3]). Similarly, P5 was cautious about incorporating multiple alerting mechanisms on devices placed on sensitive areas (*"because it's on the face I wouldn't want to use heat or movement"* [P5]).

**Accessibility.** Participants were cognizant of ensuring devices were placed in a somewhat conspicuous location (e.g. *"it's an accessory that you can put wherever"* [P4]) while remaining accessible to the wearer at all times to ensure alerts could be easily recognized. For example, P2 and 4-5 proposed a set of alerting headphones as an already commonly used accessory whose ability to integrate audio, visual, and tactile alerts made them desirable.

**Proxemics.** Participants were not explicitly asked to focus on proxemics, however, some proposed designs, such as an inflating jacket, had implicit implications on shared spaces amongst road users. For example, participants considered dual-purpose *pedestrian-wearables*, such as an LED-lined jacket or a light-projecting necklace, wherein they alert both, the wearer and those around them (e.g. *"it would be beneficial to have it alert other people too, just so everyone's aware and cautious"* [P1], *"it's not only a visual cue for yourself, but also for everyone around you"* [P4]).

**Attachment.** Since *pedestrian-wearables* are based on clothing and accessories, participants argued that the way in which they are worn should follow similar rules to that item of clothing (e.g. *"it's an accessory… I don't have to go out of my way to put it on,*

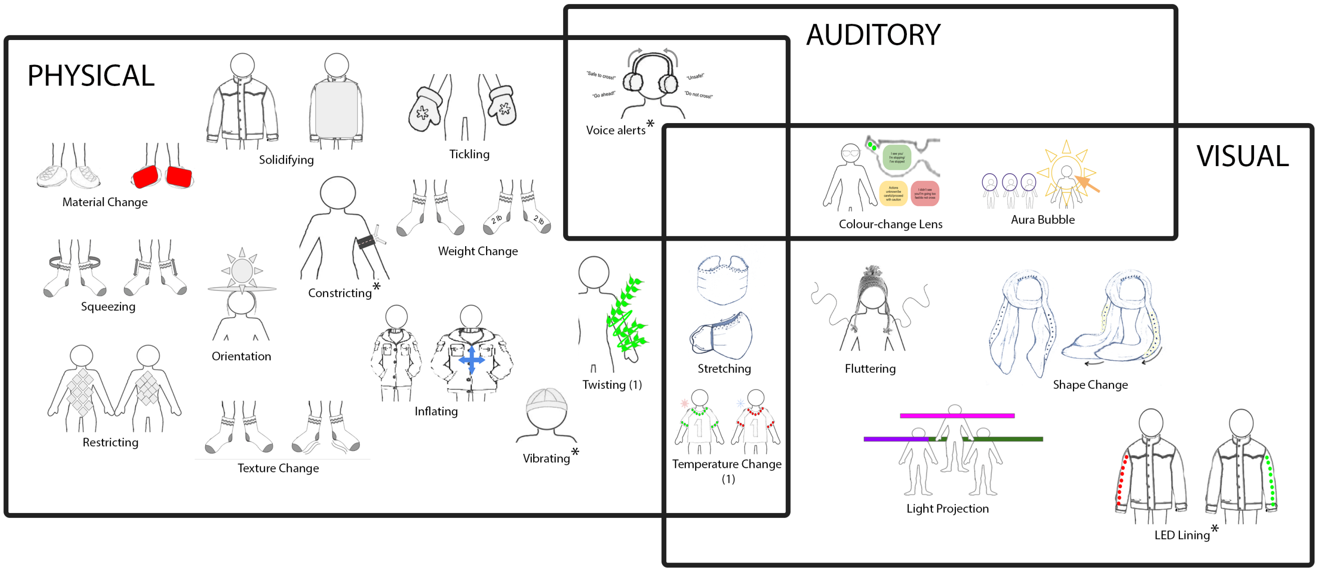


**Figure 3: A venn diagram showing all unique initial results from the video prototyping study. Designs are classified as follows: (*) proposed by researchers and participants, (1) proposed by only researchers. Remaining designs were proposed by participants. The presented designs do not include the additional alerting mechanism integrations that participants described during the discussion.**

*it just goes on top of everything"* [P4]). For example, scarves are worn in some unique styles that could be considered as the options for attachment, and their alerting mechanisms could be designed accordingly.

## 5 DISCUSSION

Based on our findings, we think *pedestrian-wearables* hold promise as technologies that serve to communicate between AVs and pedestrians. As a starting point, in this section we discuss several benefits and limitations of *pedestrian-wearables.*

### 5.1 Perceived Strengths of *Pedestrian-Wearables*

*Pedestrian-wearables* introduce certain trade-offs, such as device comfort, cleanliness, and washability, as well as advantages, such as flexibility of use, customizability, and accessibility when compared to devices such as cellphones. For example, the ability to have different shapes and sizes of wearables can offer opportunities for people to place these devices on different parts of the body, thereby enabling customizations such as receiving feedback in more sensitive parts of the body for more high-importance alerts. Building on our proposed designs, we can consider the simplistic nature, unobtrusive placement, and to-be-worn nature of some items such as a constricting armband or squeezing socks, characteristics that make them accessible, customizable, and convenient options for *pedestrian-wearables* that would not require users to carry additional items. These characteristics, along with the multi-modal nature of *pedestrian-wearables* also enables flexible use cases, making them more suitable for safety-critical contexts, such as when pedestrians may be in danger of getting too close to a fast AV that might not be able to stop in a timely manner - a situation that would be difficult to customize with phones and smartwatches given their reliance on visual and auditory feedback, and relatively restricted (non-)placements on the body. Similarly, items such as a facemask offer opportunities to provide contact with more sensitive body parts such as the cheek, and can be used for bringing attention to an immediate concern. In contrast however, options such as the shape-changing scarf, while offering limited options for being invisible, offer alternative advantages such as holding a number of predefined shapes and forms and communicating more than binary-level information [9, 28, 51]. The moldable shapes of wearables also provides opportunities to incorporate and use these wearables more easily, especially for pedestrians such as children who either do not carry smartphone-based wearables or may not have them accessible at all times to reference. Further, any obviously actuated physical device such as an inflating jacket or a light-emitting necklace could also be noticed by others to ensure the group's safety. For example, parents can immediately take note of an inflating jacket that may be worn by their children and quickly indicate to them to be safe [13].

### 5.2 Inclusion of Diverse Vulnerable Road-Users

Like the proposed benefits of wearables [30, 32, 46, 56] in general, we think *pedestrian-wearables* can serve as a more inclusive medium for interactions with AVs. As shown in Figure 3, *pedestrian-wearables* can take several forms and communicate with pedestrians using varied modalities, ensuring a more diverse range of pedestrians, including those with sensory and physical disabilities [3, 4, 11, 12, 17, 38], can benefit from the information and make safe street crossing decisions. These can also serve as complementary to the standard street infrastructure, such as cross-walk signals.

For example, a cyclist or skater could continue to use street signals but may also want to use *pedestrian-wearables* that offer more non-visual cues to avoid the need to regularly shoulder check for an oncoming vehicle on a busy road. Similarly, a wheelchair user might be more inclined to use multi-modal *pedestrian-wearables* like a scarf that can alert them visually and physically, leaving their arms free for mobility purposes [3, 39]. The introduction and exploration of multi-modal alerting wearable devices [39] aims to address such user groups by considering artifacts like scarves that can alert users visually, leaving their arms free for mobility purposes, and headphones which are innately sound-based.

Lastly, due to their varied modalities as seen in Figure 3, *pedestrian-wearables* can be made more culturally-specific by fine-tuning their behaviour to suit the environment, and this could offer an alternative solution to the challenges of traffic signal comprehension based in different scenarios [41, 45]. Non-verbal cues are often culturally-specific, and thus, a single set of alerts or communication mechanisms cannot be applied to all situations [31, 43]. Further, there are many scenarios that need to be accounted for beyond the simplistic scenario of street-crossing that literature currently explores in-depth, such as many-to-one AV-pedestrian interactions, and multi-state communication needs [33]. We propose that *pedestrian-wearables* introduce a multi-modal approach with a breadth of opportunities for embedding situation-specific information and alerts in all AV-pedestrian interactions.

### 5.3 Social Acceptability of *Pedestrian-Wearables*

Koelle et al. discuss the concepts of subtlety, unobtrusiveness, and avoiding negative attention, along with impression management and the maintenance of familiar shapes and devices when designing socially acceptable devices [29]. They further discuss how a device's acceptability is positively impacted when its audience is aware of its purpose [29]. We previously discussed a set of wearability considerations and trade-offs which impact social acceptability, and combined with our participants willingness to wear their proposed directed designs, we believe subtle versions of *pedestrian-wearables* could be adopted in the future. This belief aligns with earlier findings wherein researchers argue that the social acceptability of wearable devices depends on a multitude of factors such as wearer comfort, subtlety of actuation, and device familiarity [29, 42]. However, as the norm for what is considered socially acceptable is constantly changing, it is difficult to formulate a deterministic scope for social acceptance [29].

## 6 LIMITATIONS AND FUTURE WORK

As a first study considering *pedestrian-wearables*, we provide insight towards preferred alerting mechanisms and wearable styles, and some wearability considerations for wearables that support AV-pedestrian interactions. We acknowledge that our work presents limitations due to a small participant sample. This limitation may have influenced the choice of garment or accessory ideas collected in this study.

In the future we aim to expand our work by 1) gathering perspectives from other common pedestrian groups such as the elderly, young, and people with diverse-abilities, as well as industry professionals, 2) conducting a study without provided templates, 3) conducting a study with physical materials, 4) placing an explicit emphasis on communicating complex information and many-to-one interactions, and 5) developing prototypes and conducting in-the-wild evaluations to gain a more in-depth understanding of these devices and how they are meant to work.

Beyond acting as alerting mechanisms for AV-pedestrian interactions, *pedestrian-wearables* could be extended to other domains and contexts with similar requirements. For example, in safety-critical contexts such as factory floors, machine workers could use adaptions of wearables similar to the ones we propose to get alerts from the machines (e.g., the hand of a worker being positioned very close to a cutting machine could be warned against using constricting armbands) to make appropriate decisions.

## 7 CONCLUSION

In our work, we introduced a new category of eHMIs, *pedestrian-wearables*, that are meant to support and promote safe AV-pedestrian interactions. We analyze a set of design ideas for *pedestrian-wearables*, including devices that go beyond smartwatches and phones and containing physical, visual, and audio alerting mechanisms. Informed by this project, we present an extended understanding of pedestrian preferences for wearable alerting devices, and discuss three primary aspects of *pedestrian-wearables* - their perceived strengths and potential for inclusiveness and social acceptability - which we believe lay the groundwork for many future studies and adaptations.

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