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Gapeau: Enhancing the Sense of Distance to Others with a Head-Mounted Sensor

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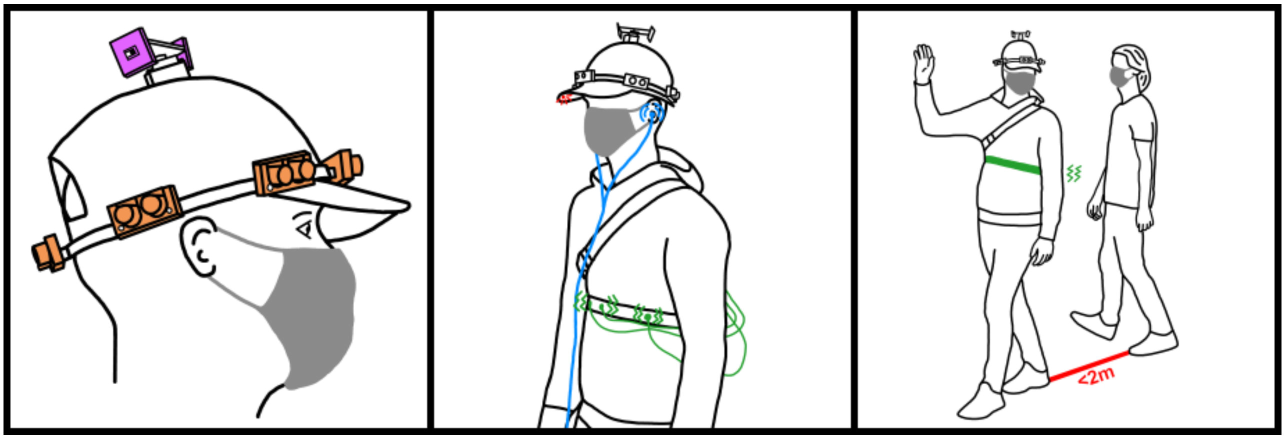

Figure 1: Gapeau augments the sense of distance to others using head-mounted sensors integrated in a hat. We designed three versions of Gapeau with three feedback modalities: visual, vibrotactile and auditory. Our prototype was evaluated in a controlled experiment and during an in-the-wild study.

ABSTRACT

Human perception lacks the capabilities to accurately assess distance. The recent Covid-19 pandemic outbreak rendered this ability particularly important. Augmenting our sense of distance can help maintain safe separation from others when required. To explore how systems can help users maintain physical distance, we designed, implemented and evaluated Gapeau—a head-mounted system for augmenting the sense of distance. Our system uses proximity sensors and thermal sensing to detect and measure the distance to other people. We conducted a validation protocol, an experiment, in which we compared different feedback modalities, and an in-the-wild study to evaluate Gapeau's performance and suitability for use in social contexts. We found that our system enabled users to more accurately determine whether they were maintaining a safe distance from others. Vibration and auditory feedback were found most effective and usable. Gapeau was perceived as socially acceptable. Our work contributes insights for augmented sensing systems with social relevance.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

sensory augmentation, head-mounted sensor, physical distance, wearable computing

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1 INTRODUCTION

Human perception lacks the capabilities to accurately assess distance, which is desirable in a number of casual and professional contexts. The sense of distance allowing us to precisely analyse our proximity would prove useful whenever our other senses are obstructed or insufficient, e.g. in industrial human-machine cooperation [70] or rescue operations [79].

Recently, physically distancing from other people has become a necessary part of our daily lives, due to COVID-19 pandemic outbreak. Staying far enough from those with whom we do not share a home is one of the key measures needed to contain the transmission of the virus [46]. However, as humans, we are not fully equipped to effectively assess and maintain a safe distance. It is difficult for us to judge the physical distance between ourselves and other people. As different governments recommend $1.5m$, $2m$ or $6ft$ distance guidelines, it is up to everyone to ascertain how far is far enough. In fact, different perceptions of distance may lead to conflict [59].

Concurrently, the field of Human-Computer Interaction (HCI) has recently begun investigating the possibilities for interactive systems to amplify our perception of the outside world through sensory augmentation [74]. Past research found that humans can be effectively provided with an enhanced sense of awareness of their surroundings [22], orientation [41], or even WiFi traffic [31]. However, the ways of providing an enhanced sense of distance have drawn limited attention.

A hypothetical enhanced sense of distance could help users navigate the difficult definition of safe distance. Effective distancing would no longer be an arbitrary number, but rather a sense of not being too close to anyone. While such a solution could be effective in helping users obey safety rules, it could also cause negative social implications. Past work on body-worn sensors and cameras has shown that the acceptability of such devices is often a challenge [18]. Yet, past work examined systems that offer benefits primarily to their users and we are not fully aware if a wearable that helps enforce public safety rules would face similar difficulties. Consequently, HCI should study the social context of body-worn devices for personal safety.

To explore the feasibility of providing users with an enhanced sense of distance and its practical and social consequences, we conducted a user-centred design process in which we created Gapeau. Our system is a hat (chapeau) equipped with ultrasound and thermal sensing in order to assess the distance from other people. First, we conducted an initial survey to limit the number of possible design alternatives for Gapeau. We then designed three alternative versions of the system using vibration, auditory or visual feedback. Next, we validated that the system performed as required. In a controlled experiment, we found that Gapeau allowed users to judge whether they maintain a safe distance to others significantly better than without using the system. Next, we conducted an in-the-wild study where we explored the social aspects of the system.

This work makes the following contributions:

(1) demonstration of effective augmentation of the user's distance perception with use of Gapeau — a head-worn system for distance assessment,
(2) insights on social acceptability of wearable systems for social good, based on the in-the-wild exploratory study conducted during the pandemic,
(3) insights on providing enhanced spatial awareness in sensory augmentation systems (as considered in [74]), especially concerning various feedback and communication modalities.

While our investigations are settled within the exceptional context of pandemic, the findings of our study are, to a certain extent, generalizable for other contexts where enhanced distance perception is desired.

2 RELATED WORK

Here, we review past research that contributed to the concept and design of Gapeau. First, we discuss earlier systems which provided the users with an enhanced perception of the surrounding space. Then, we report on past research that focused expressly on sensing distance. Finally, as we focus on the pandemic-driven context in this paper, we review related technological attempts to confine the COVID-19 outbreak.

2.1 Increasing the Users' Awareness of Their Surroundings

Augmenting users' senses to increase their awareness of surroundings is a recurrent theme in HCI. A number of systems inquired if and how human vision could be augmented. For instance, SpiderVision [22] used a head-mounted display (HMD) to add additional 'layers' of vision when moving objects were detected outside the user's field of view. They found that users managed to quickly adapt to being able to sense visual information on the back of their head. HindSight [75] was a similar system, but it used a 360-degree camera and audio feedback, thus eliminating the need for an HMD. The system enabled users to react to approaching vehicles in adequate time. Similarly, Shen et al. [76] explored omnidirectional observation and proposed a solution based on robotic companion device. FlyVIZ [5] also used a 360-degree video and remapped the image to the user's field of view. Similar techniques based on distortion were also used by Liang et al. in their two systems [48, 49].Beyond these approaches, Miyaki and Rekimoto [54] analysed laser-depth scanning for mapping one's surroundings and Mateevitsi et al. [52] explored bridging the spatial sensing using multiple channels, evaluating the potential of full-body designs. All the works which investigated a broadened field of view mentioned above reported positive results and the fact that users appreciated an increased awareness of their surrounding. A commonly reported problem was a steep learning curve. In contrast to previous work, we aim to design a lightweight perception of the space surrounding the user. We strive to support the user in maintaining physical distance, while minimizing the amount of additional information they receive.

Another strain of work explored extending users' awareness of things around them through alternative vision modes. Abdelrahman et al. [1] built an HMD-based system which enabled users to switch between normal, depth and thermal vision. They found that alternative vision modes enabled users to notice different details of their surroundings and led to increased awareness of space. Being aware of one's surrounding also implies knowing the position of one's body. Similarly, Grönvall et al. [28] and van den

Boogaard et al. [78] enabled users to perceive the strength of electromagnetic signals in their environment. Park and Lee [62] built a snowboard, which visualised the users position relative to the snow. Their works showed that additional information about relative position increased awareness of the environment. Our work is inspired by these examples. In line with the aforementioned studies, we extracted additional properties of the environment to offer more awareness to the user.

As our work studies the ways to help users safely move in public space, research which investigated interaction while walking is of particular interest. There were a number of systems, which investigated pedestrian navigation. Pfeiffer et al. [63] employed Electrical Muscle Stimulation (EMS) to divert users' walking direction, showing that users can be effectively aided in navigating in complex spaces. A number of papers contributed to understanding the requirements for systems for pedestrians. An in-situ study of PocketNavigator [64] showed that tactile feedback was an effective output method while walking. However, Montuwy et al. [55] stressed that certain forms of visual reference were also appreciated by users. Finally, Dobbelstein et al. [20] emphasised the need for spontaneity when designing for walking. The insights from these works impacted the design decisions in our work by charting the alternatives and constraints in the design of Gapeau.

Important lessons on designing for enhanced spatial awareness may also be learnt from navigation and obstacle-avoidance systems for people with visual impairments. Kayukawa et al. [38] proposed a suitcase using pre-emptive sound notifications to alert both the user and nearby pedestrians about the potential risk of collision. Their system employed an RGB camera to detect and predict the walking path of other pedestrians. A related approach was presented by Zeng et al. [83], who augmented a white cane with an obstacle avoidance system based on 3D time-of-flight camera. Solutions for visually-impaired people also concerned various feedback modalities to convey information on users surroundings, such as haptic [25, 61] and thermal [56] stimuli or abstract sonification [3, 38, 66]. While the design goals of Gapeau significantly differ from these systems, they informed our considerations on human recognition and feedback design.

2.2 Augmenting Distance Perception

Providing users with enhanced distance perception was investigated outside of pandemic-related contexts. Carton and Dunne [15] built a glove that helps firefighters estimate distance to objects in low visibility conditions. Their study showed that users were able to detect obstacles at a distance through vibrotactile feedback. The principle of sensing the presence of others was also used in an accessibility context. More precisely, Halperin et al. [31] designed a system for people with vision impairments that determines the distance to people in the proximity of a user using WiFi signals. Their device enabled users to effectively determine if others were in their close proximity. This theme was further explored by Buchs et al. [14] who proposed non-visual distance sensing integrated into a white cane. On another note, Niforatos et al. [57] build a skiing helmet which detected skiers behind the user, thus increasing their awareness of other people. Kim and Dey [40] explored application of augmented reality and haptic stimuli to increase distance awareness of automobile drivers, while CueSense [34] encouraged social interactions through proximity-based matchmaking. These systems showed that ubiquitous sensing of distance to other people in a wearable form is feasible, yet at the cost of increased cognitive load and limited only to specific environments. In contrast, our work investigates the use of distance-sensing devices in everyday situations regardless of the user's surroundings, offering a generic approach to distance sensing, suitable for use in social contexts.

The pandemic outbreak led to an urgent need for physically distancing from others and met with a rapid response from the research community. Within the HCI field, Wiberg [80] stressed the need to avoid using the term *social distancing*. A key task for interactive systems is to help users maintain physical distance while mitigating the negative social consequences of doing so.

Detecting whether or not two people are within a safe distance from each other is a technical challenge. Cristani et al. [17] showed that computer vision techniques can effectively estimate safe distance zones from video data. Goel et al. [26] verified that this was possible using campus security cameras. Malik [50] used ultrasound as a distance sensing modality and Bian et al. [10] proposed a system that enabled users to sense how close others were using magnetic sensing. They demonstrated that magnetic sensing was a suitable modality for sensing the physical distance to others. Ensuring that individuals maintain the required distance was also tackled using wireless communication between personal mobile devices. Arun et al. [6] and Gupta et al. [29] explored using Bluetooth signal exchange to assess distance between users. Tripathy et al. [77] used similar approach to create a wearable contact tracer, while Rusli et al. [72] equipped their app with geolocation units. These works show that sensing the distance to others is feasible and sensing technologies are not a barrier to widespread use of systems that support physical distancing. However, sensing distance between users employing personal devices is likely to pose significant risks concerning security and privacy violations [24]. Moreover, the social consequences of long-run usage of such systems are yet to be studied.

The design goal of Gapeau is to foster maintaining the physical distance proactively (in contrast to contact-tracing solutions), thus providing the user with agency. To explore this issue, our work focuses not on the implementation aspects of a physical distancing system, but on how it should communicate with the user and its social consequences.

The remainder of this paper describes the design process, implementation and evaluation of Gapeau. First, we report on our design process which involved an experimental vignette with video prototypes. We then provide the details of the implementation of the device. Next, we report on how we validated the functionalities of Gapeau. We evaluated our approach both in an experiment and during the actual pandemic in a qualitative field study. We first report on the quantitative results of the experiment and then report qualitative results from both studies.

3 DESIGN

Here, we describe the details of how we conceptualised and built Gapeau. Our main goal was to build a wearable device that would facilitate physical distancing and offer an increased perception of the people surrounding the user. Gapeau is a wearable device in the form of a hat. We decided to use a hat as it offered a type of object that a user would take when going outside. We considered alternative form factors such as umbrellas, belts, face masks or dedicated garments. Our choice of a hat was a pragmatic one: hats are universal garments with easily adjustable sizing. Thus, Gapeau can be easily shared between users, eliminating the need for producing versions of the system in different sizes. Further, locating the sensing device on a user's head offers relative stability to the sensors, contributing to increased sensing cohesion [33]. Finally, past work, e.g. [22, 49] showed the effectiveness of head-mounted sensing to extend distance perception, and we endeavoured to build on these insights.

Having decided on housing Gapeau in a hat, we were faced with key questions: (1) To whom should the system provide feedback, its wearer or also the people surrounding them? and (2) what feedback form should Gapeau use to make maintaining physical distance most effective?

3.1 Pre-study: Feedback Survey

To explore the two questions outlined in the previous section (target user group, feedback form), we conducted an online survey to investigate possible design alternatives for Gapeau.

3.1.1 Participants. We used Amazon Mechanical Turk to recruit $n = 51$ participants for the study. Participants were required to have at least 1000 completed tasks with an acceptance rate of at least 95%. The participants were aged 21–63 years, $M = 36.59$, $SD = 10.07$ and resided primarily in the US, Canada, United Kingdom and the European Union. Thirty-five participants identified as male and 16 as female. The participants received USD 1 for completing the survey which lasted on average $M = 12min\ 11s$, $SD = 4min\ 43s$. The compensation was determined based on Qualtrics duration estimates and calculated at a rate specified by the first author's institution.

3.1.2 Survey Content. The survey used an experimental vignette approach [2]. We asked users to imagine they were the person pictured in a series of video prototypes, see Figure 2 for an example. The operation of the device was intentionally pictured using some degree of abstraction, as the survey aimed to probe participants' perception of particular modalities, with limited prompt for speculations on possible implementation details. We conducted an experimental vignette study (i.e. a study where we ask participants to see the world through the eyes of a hypothetical person in a specific scenario), because it offers the means to balance the benefits of experimental research with high internal validity and the advantages of applied research with high external validity [2]. This method is very similar to tailored scenarios [16]. Experimental vignette studies have been used in a variety of research contexts and it has been shown that they deliver results comparable to 'real-life behaviour', e.g. [21, 30].

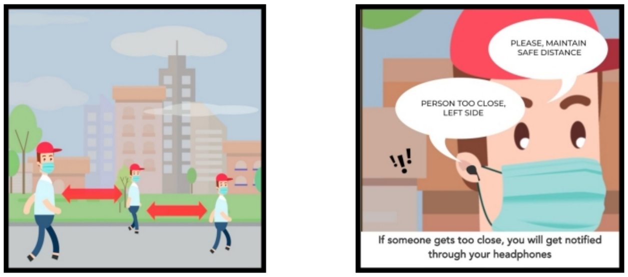

Figure 2: Excerpts for the videos used in the online experimental vignette, showing distance sensing (left) and auditory user feedback (right).

Responses were not counted if the total response time was lower than the total video running time. The survey consisted of three parts. In part one, we investigated how the users would like to control feedback provided by Gapeau: we compared automatic triggering, on-demand activation or receiving a notification about the need to use Gapeau. The second part investigated design alternatives for communicating to others that they were to close to the user. The third part of the survey examined different feedback form for communicating the proximity of other people to the user.

For each of the design alternatives, we measured perceived usability with the UMUX [23]. We also measured perceived acceptability using items suggested by Profita et al. [67]. We used eight items out of thirteen from their work as the remaining five query the participants about the qualities of the users. These were not applicable to an experimental vignette. Further, selective use of the items is methodologically possible as Profita et al. did not establish inter-factor correlations for their method and the results are analysed on a per-item basis. We also asked users to choose their preferred modality. To limit participant fatigue, we presented only 9 conditions to each participant. We used Qualtrics XM system to implement the survey. The survey, the results and the video vignettes are available as auxiliary material. Below, we present the results most relevant to our design decisions.

3.1.3 Results. We conducted one-way ANOVAs of align rank transformed (ART, [81]) data to determine which ways of controlling Gapeau were perceived as most usable and most acceptable. We found no significant results, $p > .05$. However, 48% of the participants chose automatic activation as their preferred method of controlling the device, as seen in Figure 3. Consequently, we decided that Gapeau would be operational when worn.

Next, we investigated how users would provide distance feedback to others in their personal space. We compared spoken audio feedback, abstract audio feedback (beeping) and feedback through a gust of wind. Again, one-way ART ANOVAs found no significant differences in terms of perceived usability or acceptability (Figure 4). We did not observe a clear preference between the possible feedback forms. Consequently, we decided to consider all three in the later stages of the design process.

Finally, we examined how users would prefer to receive feedback about someone approaching them. We considered a number of modalities based on related work: Augmented Reality (AR, [22]), a T-shirt Display (T-shirt, [53]), Audio feedback using a speaker (Speaker, [44]) and headphones (Headphones, [47]), Vibrotactile output (Vibration, [4]), Visual feedback at the edge of the field of vision (Edge, [41]) and heat-based feedback (Heat, [36]). Similarly to the previous parts of the survey we ran a one way ART ANOVA

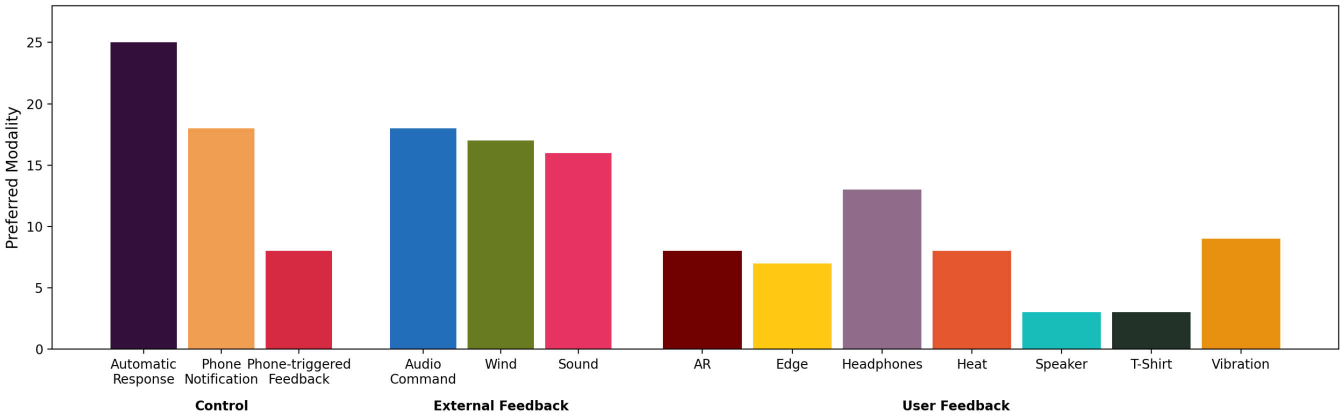

Figure 3: A summary of the key insights from our experimental vignette study. Users preferred a device that would activate automatically. There was no consensus on how to communicate feedback to others. The chart shows how many times each modality/version was rated as preferred in the survey

Table 1: Acceptability ratings for the different alternatives of how enhanced distance sensing could be communicated to the user using Profita et al.'s [67] metrics. We conducted one-way ART ANOVAs [81] to compare acceptance scores. Based on the results, we decided to not implement the AR, Heat and T-Shirt alternatives.

			AR	Edge	Headphones	Heat	Speaker	T-Shirt	Vibration
	$F_{6,116}$	p	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)
Awkward	4.140	$< .001$	5.00 (1.76)	4.15 (2.18)	3.00 (2.00)	5.09 (1.53)	4.77 (1.88)	5.52 (1.47)	3.82 (2.04)
Normal	7.367	$< .001$	3.40 (1.74)	4.30 (1.98)	5.27 (1.49)	3.52 (1.56)	3.95 (1.73)	3.04 (1.92)	5.14 (1.42)
Appropriate	5.269	$< .001$	4.00 (1.55)	4.90 (1.62)	5.14 (1.61)	3.61 (1.53)	4.00 (1.41)	4.00 (1.73)	5.23 (1.51)
Rude	2.884	$< .05$	3.38 (1.66)	3.65 (2.16)	2.86 (1.91)	3.35 (1.72)	4.00 (1.69)	4.17 (1.77)	3.14 (1.88)
Uncomfortable	4.380	$< .001$	3.86 (2.01)	3.95 (1.73)	3.41 (2.09)	5.52 (1.38)	4.73 (1.75)	5.04 (1.55)	3.73 (2.19)
Distracting	4.886	$< .001$	4.52 (1.86)	4.60 (1.82)	2.82 (1.89)	4.78 (1.44)	5.00 (1.57)	5.09 (1.59)	3.59 (2.04)
Useful	6.073	$< .001$	3.71 (1.59)	4.60 (1.82)	5.14 (1.61)	3.52 (1.88)	3.55 (1.63)	3.43 (1.90)	4.95 (1.62)
Unnecessary	4.278	$< .001$	4.86 (1.62)	4.00 (2.05)	3.82 (2.15)	5.39 (1.59)	4.41 (2.02)	5.52 (1.44)	3.55 (2.02)

to examine the effect of feedback modality on perceived usability. We obtained a significant effect, $F_{6,116} = 4.84$, $p < .001$. Post-hoc testing using Tukey HSD revealed that the AR modality was perceived as significantly less usable than the Edge feedback ($p < .05$) and the headphones ($p < .01$). Further, headphone feedback performed significantly better than the t-shirt display, $p < .001$. In terms of acceptability, one-way ART ANOVAs revealed significant differences. We summarise the analysis in Table 1. Overall, the AR solution and the T-shirt displays lacked acceptability, while the headphone-based and vibrotactile feedback were perceived as most acceptable. Based on the results, we decided that headphone, vibration and visual modalities would be implemented so that we could study them further.

4 IMPLEMENTATION

Based on the initial insights gathered in the survey, we implemented a functional prototype of Gapeau. In this section, we describe the technical specifications of the device and the sensing method which Gapeau uses to detect nearby people.

4.1 The Gapeau hat

We used an industrial-grade bump cap (a light hard hat) as the housing for Gapeau, as shown in Figure 5. The cap provided a firm frame to which we could attach sensors and electronics while still offering a reduced weight. We distributed six DFRobot URM09 analog ultrasound distance sensors[1] along the edge of the hat. The sensors were mounted in 3D-printed casing and affixed to the hat to protect them from the elements. Each of the sensors has a viewing angle of 60 degrees and a range of 520 cm. This way, the entire 360 deg space around the user was covered by distance sensors and the device could map all surfaces in the proximity of the users and calculate the distance to those surfaces.

In order to distinguish which of the detected surfaces were humans, we mounted two Sparkfun Grid-EYE AMG8833[2] infrared grid sensors on top of the hat. The technical specifications of the sensor offer human detection in the range of $7m$. Using a thermal sensor not only offered reliable human detection, but also allowed for fast processing and omitting collecting potentially sensitive data. The 8x8 pixel numerical matrix representation provided by

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[1] https://www.dfrobot.com/product-1862

[2] https://www.sparkfun.com/products/14607

the sensor could be processed using low-power electronics. The measurement resolution was also low enough to omit capturing any specific features that could have identified particular individuals. The data processing was based on comparing values in the resulting matrix against pre-calibrated thresholds. Gapeau does not store the measurement data after processing. Two of the sensors were mounted on 3D printed motor horn attached to a servomotor[3]. This way, the thermal sensors can be rotated to detect humans around the user. The processing unit was based on an Arduino Mega ATmega2560 microcontroller[4] coupled with an Adafruit PCA9685 motor driver[5] to operate the servomotor. The system was powered with consumer-grade powerbank of 5V operating voltage. System's power consumption is mostly affected by the rotation of the horn, while our observations show that the system can be used for over 3 hours using a 2500mAh powerbank. The prototype of Gapeau is presented in figure 6.

4.2 Feedback implementation

The design decisions concerning the choice of modalities were driven by the survey results. Despite the fact that feedback using a gust of wind performed well in the survey, we determined that a flow of air that could be perceivable from a distance higher than 2m would require extensive equipment and electrical power (large, high-power fans). As we wanted for Gapeau to remain a wearable device, we eventually decided not to implement that feedback form. Another argument against air-flow feedback was incompatibility with pandemic safety limitations (as the air flow can potentially boost virus spread). Consequently, we build three versions of Gapeau, shown in Figure 7: with visual, audio and vibrotactile feedback.

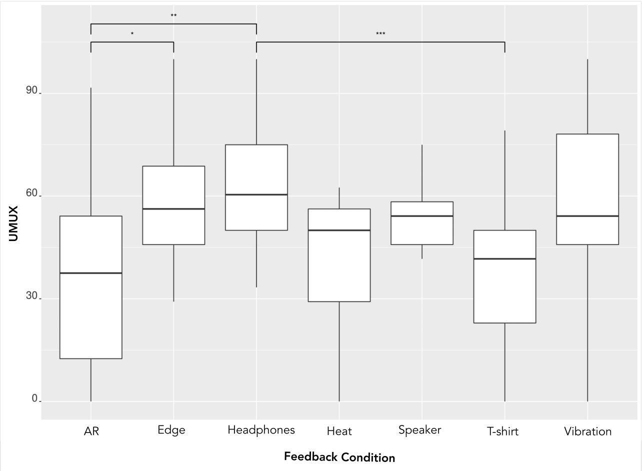

Figure 4: Perceived usability measured with UMUX scores for possible feedback modalities for Gapeau in our experimental vignette study. Audio feedback using headphones was perceived as most usable. Note that given the large sample and the ART-based analysis, the graph is used only for illustration purposes.

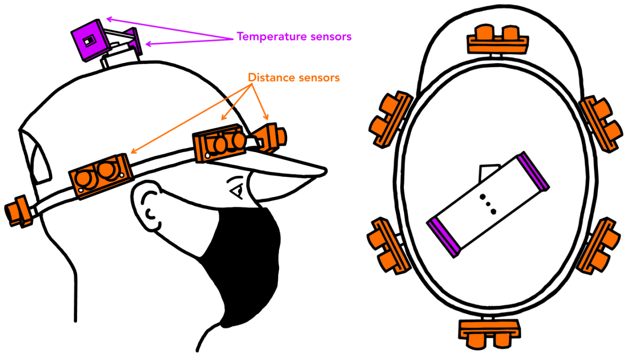

Figure 5: The sensors used to detect approaching humans in Gapeau: side view (left) and top view (right). When the ultrasonic distance sensors detect an approaching object, the temperature sensor is rotated to assess if the object is a human.

Figure 6: The prototype of Gapeau: the sensing hat (left) is connected to a control unit (bottom right), which is worn in a belt-case (top right) on the user's back.

The directional mapping pattern used for all feedback designs followed the scheme proposed by Schaak et al. [73], adjusted to match Gapeau's resolution. The devices used for visual and vibrotactile feedback are pictured in Figure 8.

Visual Feedback. We implemented visual feedback directly on the hat to minimise the need for additional equipment. We attached an Adafruit NeoPixel Jewel LED Matrix[6] to the underside of the visor of the cap, at 6cm from the rim of the hat. Our approach to implementing the visual feedback device followed the guidelines provided by Gröhn et al. [27]. Locating the matrix at the egde of the wearer's field of vision was inspired by Kiss et al. [41], who showed this approach is suitable for directional cues. The circular matrix had six LEDs and thus each LED corresponded with each distance sensor on the cap. If a human was detected by Gapeau, the LED would shine for 1s with increasing intensity as distance was reduced.

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[3] https://hitecrcd.com/products/servos/analog/micromini/hs-45hb/product
[4] https://store.arduino.cc/arduino-mega-2560-rev3
[5] https://www.adafruit.com/product/815
[6] https://www.adafruit.com/product/2226

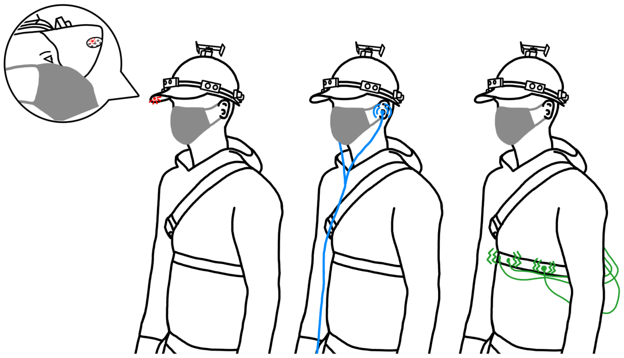

Figure 7: The three feedback options, which we implemented for Gapeau—visual, audio and vibrotactile (left to right).

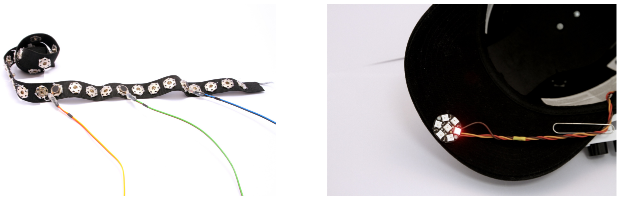

Figure 8: Our implementation of feedback in Gapeau. Belt with vibromotors (left) and an LED matrix on the visor of the hat (right). Feedback was mapped to the the distribution of the distance sensors on the hat.

Audio Feedback. The audio feedback design was inspired by considerations by Marquardt et al. [51] on signaling proximity in virtual environments. We used cabled headphones and an Android smartphone to implement audio feedback. The phone was connected to the Arduino which controlled Gapeau with a serial cable. We recorded voice commands for Gapeau with a 3D effect. The system communicated the direction from which a person was approaching the user with an illusion of the sound coming from that direction. The directional cues were: “Front”, “Front Right”, “Front Left”, “Back Right”, “Back Left”, “Back”.

Vibrotactile Feedback. We implemented the vibrotactile feedback system concerning the design guidelines formulated by Karuei et al. [37] and using the implementation strategy of Woźniak et al. [82]. Users could receive information about distance to others using vibrotactile feedback provided by an elastic chest-worn strap with motors. We built an adjustable strap with 36 slots, to which 6 Pololu 1638 piezoelectric vibration motors[7] were attached, mapping the corresponding directions on the wearer's torso (Figure 9. The belt wrapped around the user and vibrated to emulate an experience of 360 deg vibration. Thus, the vibration was perceived at different areas of the torso depending on which distance sensor registered an approaching person. This location was chosen due to the torso's directional stability relative to the walking direction [33]. Moreover, moderate sensitivity of this area toward vibrotactile stimuli allows for clear signalization, while not inducing irritation if signals need to be temporarily ignored by the user [37].

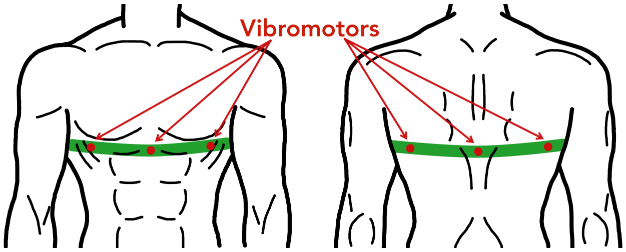

Figure 9: Position of the vibromotors on the user's chest when using Gapeau with vibrotactile feedback. Six motors correspond to six distance sensors on the hat. Vibration was perceived on the following regions of the torso based on the sensors: front—on the breastbone; front right/left—true rib regions; back right/left—on the latissimus dorsi; back—lower thoracic segment of the spine.

4.3 Physical distancing detection

Gapeau detects humans in the proximity of the user by sequentially triggering the distance sensors. The sensors are triggered with a $20ms$ resolution and values are averaged in a sliding window of three measurements. When an object closer than $2.5m$ to the user is detected, the servomotor rotates one of the thermal sensors to cover the field of view of the distance sensor, which detected the object. Temperature measurement and human recognition is then performed on a 64 pixel grid. The sensor requires calibration to the ambient temperature, which is done each time the system is started. The total latency of the system is low (worst case scenario for a trigger-to-feedback interval was estimated at $700ms$), which is comparable to natural visual-motor reaction time [35]. The short interval coupled with analysis based on iterative measurements results in limiting the impact of tilt and natural motion of the head while walking [33], which echoes previous findings on head-worn systems [22, 48]. On the other hand, if the proximity was preserved only within a period that did not enable the system to perform the complete measurement, its duration falls way below the threshold for potentially contagious encounters [7].

5 VALIDATION

Before allowing users to wear Gapeau, we wanted to verify if the sensing provided by our system was robust enough to effectively help in physical distancing. To that end, we conducted a series of validation studies: a sensing range test, a robustness test and an accuracy test.

5.1 Sensing Range Test

To test if the system effectively covered the entire space around the user, we conducted a sensing range test. The device was placed on a tripod at $h = 170cm$ above the floor. We marked a circle with a radius of $r = 2m$ on the ground and divided it into 12 circular sectors of $\alpha = 30$ deg each, see Figure 10. The individual sectors were centred on the positions between the two sensors

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[7] https://www.pololu.com/product/1638

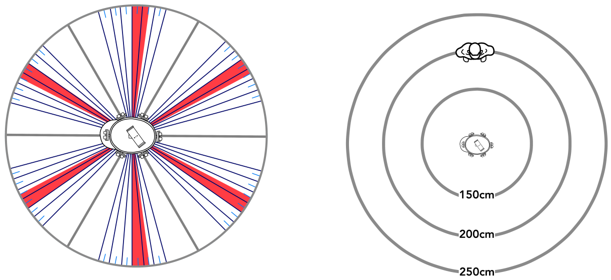

Figure 10: The validation of Gapeau. Measurement sectors and angular blind spots from the sensing range test (left) and the experimental apparatus for the robustness and accuracy tests.

as potential sources of error. We then marked 12 spots on each of the sectors (every 2.5 deg). We then placed a $w = 20cm \times l = 20cm \times h = 160cm$ wooden square cuboid at each of the positions (144 measurements total) and logged the sensor readings, verifying if any of the sensors registered the correct $d = 2m$ value. We then defined the *worst-case blind spot* of the device as the angular distance between the last positing where the cuboid was registered by one sensor and the first position in which the cuboid was registered by the next sensor. We found that the blind spot was $d = 7.5$ deg for all the sensor pairs. This implies that the maximum width, corrected for distance measurement errors of our testing rig, of an object that may be undetected by Gapeau was $w_{max} = 200cm \times sin(7.5\,deg/2) \times 2 = 26.16cm \pm 8.23cm$. Consequently, a person whose body width is lower than $w = 34.39cm$ could approach a user of Gapeau undetected. This, however, is true of a very small number of people [71].

5.2 Robustness test

Next, we tested how effective Gapeau was at distinguishing between object at different temperature and identifying humans. Like in the sensor range test, we placed Gapeau on a tripod at $h = 170cm$. We then marked three circles around the device at $r = [1.5, 2, 2.5]m$. We then placed 90 randomly spaced points on the circles, ensuring that there were 15 points per a sensor's field of view. We used three types of stimulus: the square cuboid used in the sensing range test, a male researcher $h = 174cm$ tall, and a hot water bottle filled with microwaved wheat. These examples simulated colder than human, human temperature, and hotter than human objects, respectively. The robustness test involved moving one of the object to one of the points on the rings in a random order. Overall, we performed 3 (circles) × 3 (objects) × 90 (points on circles) = 810 trials. We recognized a measurement to be correct, if the hat accurately distinguished a non-human object or the researcher, which was communicated by system log and visual feedback. Table 2 and Figure 11 show the results of the test. We found that the performance of Gapeau was satisfactory for a research prototype.

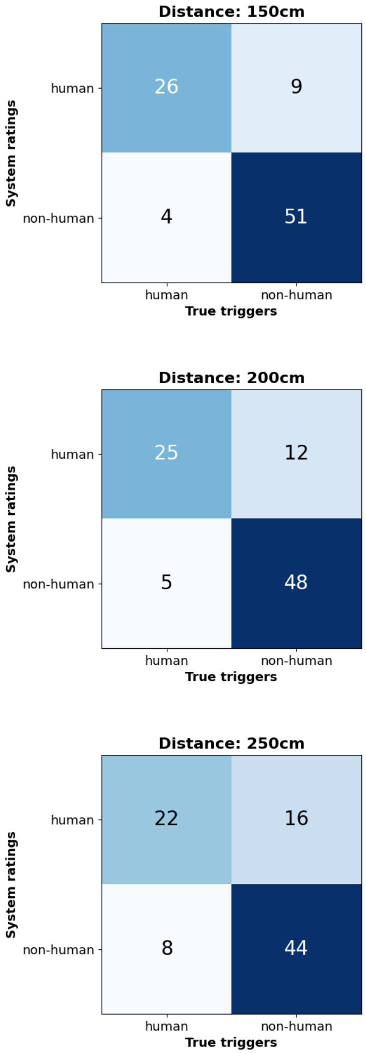

Figure 11: Confusion matrices illustrating the results of the robustness test at different distances to the user.

5.3 Accuracy test

Finally, we tested if Gapeau effectively detected people around the user regardless of the physical appearance of the individuals approaching the device. To that end, we conducted a test where we evaluated if the device correctly sensed the presence of three diverse researchers. We used the same setting as in the robustness test. There were three experimental subjects: a researcher who was $h = 183cm$ tall, a researcher who was $h = 150cm$ tall and a researcher on a wheelchair with a seated height of $h = 136cm$. The researcher would approach the device at one of the points in random order. We would then log whether the system registered a human and the measured distance. We completed 3 (circles) × 3 (researchers) × 90 (points on circles) = 810 trials. We considered a trial successful if the system read the correct distance ±5cm and correctly recognized whether the object as human. Table 2 shows error rates measured in the test. The error rates observed are low irrespective of test subject's physical appearance. Therefore, the device is capable to recognize a large majority of adult subjects [71]. While we recognize

Table 2: Results of the accuracy and robustness test. Note that, in Gapeau's case, recall is the key metric as high recall implies a lower number of undetected dangerous encounters.

Distance	Accuracy Test	Robustness Test	
	Error Rate	Precision	Recall
$150cm$	0.11	0.743	0.867
$200cm$	0.16	0.676	0.833
$250cm$	0.22	0.579	0.733

that postures of children under 8 y.o. [19] can fall beyond this validation, we consider encounters with unsupervised children beyond the analysed use case. Therefore, we considered the values acceptable for a research prototype, particularly as the error rate decreased with decreasing distance.

6 EXPERIMENTAL EVALUATION

The next step in our inquiry was evaluating whether Gapeau enabled users to (1) perceive distance better and (2) if it successfully facilitated physical distancing. Further, we wanted to determine (3) what feedback modalities were optimal for communicating the distance to others when walking. To that end, we conducted a controlled experiment in which the users wore Gapeau in a simulated environment.

6.1 Participants

We recruited $n = 28$ participants, 18 male 10 female aged $M = 25.11$, $SD = 8.85$. We recruited participants using university mailing lists and snowball sampling. The study was conducted in a period when the university was partially open and no participants travelled to campus specifically for the purpose of the study. We provided an online shopping voucher for the equivalent of USD 11 as remuneration for participating in the study. The user study was pre-approved and conducted according to the procedures of the first author's institution.

6.2 Apparatus

The study took place in gymnasium on campus. The gymnasium was equipped with forced ventilation facilities conforming to the requirements of the local health authorities. The movement area where the participants wore Gapeau was a $15m \times 25m$ rectangle. We put markers on the floor to guide the movement of experimenters and the participants. Additionally, the participant was guided by a custom-built pacing robot[8], see Figure 13. Since we anticipated that participants' walking speed would increase across trials, as one learns the route to be followed, the pacing robot enabled us to reduce the impact of the walking pace differences on the comparison of consecutive conditions. Gapeau measures the distance around the user in fixed intervals, therefore reducing the completion time would result in fewer measurements taken through the passage, favouring the earlier trials. We recorded all activity in the gymnasium with a video camera.

Participants were asked to wear face masks and a protective cap between their heads and Gapeau throughout the experiment. All equipment was disinfected and the room ventilated after participants left the gymnasium.

6.3 Task

Participants were asked to walk a predetermined route at a slow but steady pace, following the pacing robot at a constant distance. While walking, the participants were to maintain awareness of their surroundings and ensure that no one crossed into their $2m$ safety zone. At the same time, two experimenters were moving in the space in a predetermined pattern. Whenever a participant perceived that someone was too close to them, they would raise their hand. During each trial, the participant encountered nine events. These events were situations of possible proximity to one of the walking experimenters. There were two kinds of events:

- A static event: the participants would pass through a space in proximity of a standing researcher
- A dynamic event: the participants would find themselves in proximity of a moving researcher

For each of the event types, the experimenter would either maintain safe distance or deliberately fail to do so. The 'unsafe distance' in the study was set between $1.5m$ and $2m$, while the local safety standard at the time of experiment was $1.5m$. Thus, the participants and experimenters have never violated local physical distancing regulations. 'Safe distances' were set between $2.0m$ and $3.0m$. For dynamic events, the experimenter would begin walking when the participant crossed a marked trigger line on the floor. The event patterns were designed in a way that allowed experimenters to re-position themselves between events outside of the field of view of the participants. Figure 12 shows the layout of the route and the movement of the experimenters in an example task. There were four routes, each with nine events. The route itself, as well as the events on it were designed to appear different to the participants. In each condition, the participant would follow the same route but experience a different order and location of events, creating an impression of randomness. As a result, the distance travelled on each route was the same, i.e. $d = 103.1m$.

6.4 Conditions and Measures

In the experiment, we evaluated Gapeau in four conditions, No Feedback (NF), Audio Feedback (Audio), Visual Feedback (Vis) and Vibration Feedback (Vib). The conditions represented our alternative designs for Gapeau and a baseline condition, i.e. completing the task without an enhanced sense of distance.

We measured the following dependent variables:

Error Rate (ER). We counted the number of times when the participant incorrectly assessed the distance to the experimenter and did not react correctly to the proximity. For each participants, we calculated the number of total errors, the number of false positives (i.e. indicating that an experimenter was too close, while they were

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[8] constructed using Makeblock Ultimate creative kit www.makeblock.com/steam-kits/mbot-ultimate

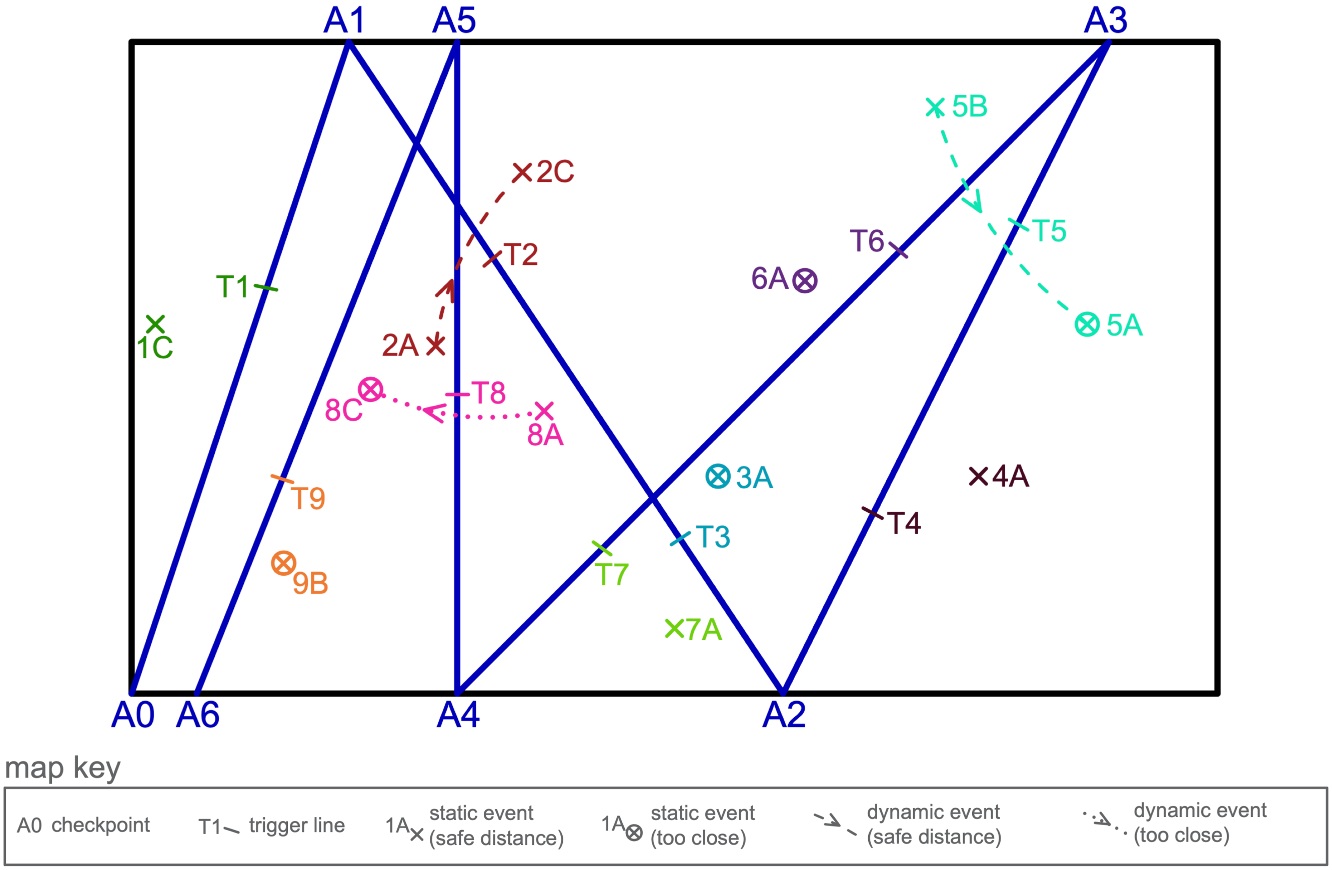

Figure 12: Layout of the route and the movement of the experimenters in an example task. Symbols mark the types of events to be enacted by the walking experimenters. The numbering reflects the order in which the particular events were triggered. The map key explains the mapping of event types onto symbols. A total of 4 different patterns were prepared to create an impression of randomness.

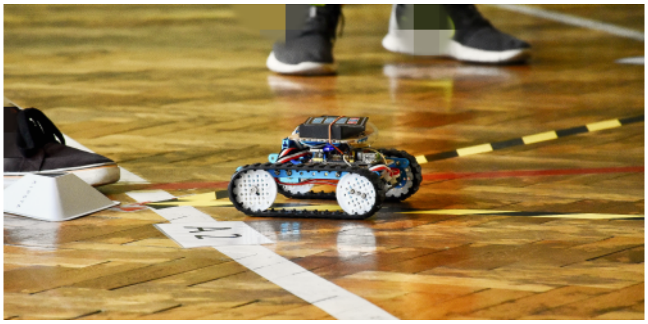

Figure 13: Custom-built pacing robot deployed during the experiment session.

in fact further than 2*m* away) and false negatives (i.e. the user not raising their hand despite the 2*m* perimeter being crossed).

Perceived usability (SUS). We used the System Usability Scale (SUS) [12] to assess the perceived usability of the different versions of Gapeau. We did not administer the SUS in the NF condition as no system was present in that case.

Cognitive workload. We assessed the perceived cognitive workload, which the participants experienced while competing the task using the NASA Task-Load Index [32].

We also conducted a debriefing interview in which we asked the users about their impressions of the system, potential contexts in which they would use Gapeau and social consequences of a technology-enhanced sense of distance.

6.5 Procedure

The experiment was scheduled in a way that participants did not meet each other. A face mask and a protective plastic cap were placed in front of the entrance to the gymnasium. We asked participants to put them on before starting the procedure. Next, we explained the purpose of the experiment and asked the participant to fill in an informed consent form with a disinfected pen. The participant was then allocated an initial condition and a route to follow. Conditions and routes were order-balanced using Latin

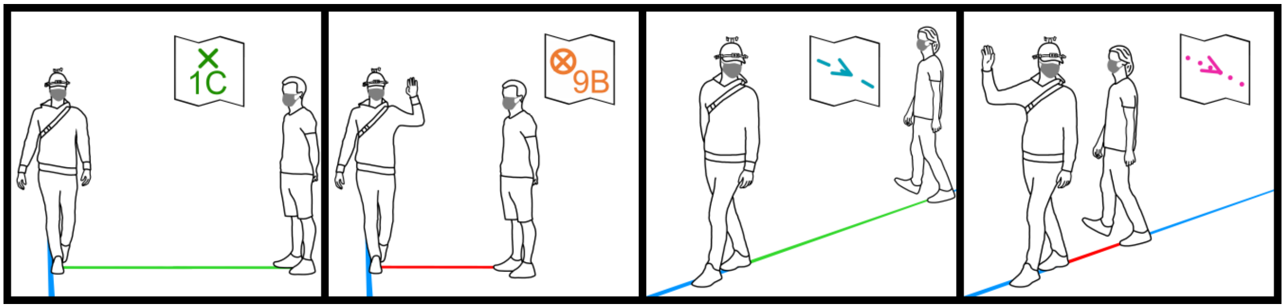

Figure 14: Different types of events used in the experiment: static event with safe distance preserved, static event with safe distance violated, dynamic event with safe distance preserved, static event with safe distance violated. Symbols in map-shaped boxes show symbols used on the layout shown in figure 12.

squares. If the condition involved using Gapeau, we asked the user to try the feedback, moving as they desired until they reported they could perceive differences in distance to people. Then, the participants started the task. The pacing robot began to move. Two experimenters enacted the required events, while one experimenter was monitoring and counting errors. After each condition, the participant completed a NASA TLX questionnaire and an SUS questionnaire for conditions with Gapeau. This order of events was then repeated for all four conditions. Finally, the participant was invited to an adjacent room furnished for a safe interview, where we conducted the debriefing. The closing interview was recorded using a voice recorder.

6.6 Results

Here, we present the quantitative results of our experimental study.

6.6.1 Error Rates. We conducted one-way ANOVAs to investigate the effect of the conditions in our study on total error rates, false positives and false negatives. We found significant results for total errors and false negatives. We then conducted post-hoc tests with Tukey HSD. Table 3 and Figure 15 show the results of the analysis.

6.6.2 Usability. Next, we examined the effect of the feedback modality used to interact with Gapeau on SUS scores. To that end, we conducted a one-way ANOVA on align-rank transformed [81] data. There was a significant effect, $F_{2,54} = 7.03$, $p < .01$. Post-hoc test showed that the Vis condition was perceived as significantly less usable than the Audio and Vib conditions, both at $p < .01$. Figure 16 illustrates the results.

6.6.3 Cognitive workload. Finally, we conducted a one-way ANOVA to investigate the effect of the version of Gapeau used in the task total NASA TLX score. We found no significant effect, $F_{3,81} = 1.37$, $p = .26$. We then analysed the individual dimensions of the NASA TLX with one-way ANOVAs and found that there was a significant effect on Physical Demand, $F_{3,81} = 2.85$, $p < .05$. Post-hoc analysis with Tukey HSD revealed that there were no significant pairs of conditions. The full results of the NASA TLX are presented in Figure 17.

7 IN-THE-WILD EVALUATION

Having evaluated the effectiveness and usability of Gapeau, we wanted to explore how it could be used in a real-life concept and investigate the social acceptance of a system for better physical distancing. In order to do so, we needed to find an effective and safe way to gather users' opinions on Gapeau when in the field. Having considered different approaches to probing system's acceptabilit [42], we decided to conduct a field study [13] where one researcher used Gapeau in places where problems with physical distancing might occurr. As the perceptions of the importance of physical distancing could have varied across the period of the pandemic, we conducted the study in two parts, at different phases of the pandemic (referred as Series 1 and Series 2). This approach allowed us to probe whether the perceptions of our system are strongly affected by the current narrative on COVID-19 in the area of the study.

7.1 Feedback for passers-by

We utilized audio feedback to inform other pedestrians that they violated the safe distance to the researcher, following the results of our survey-based design study. We used two different warning designs to investigate the differences in understanding and obedience. We incorporated the abstract metaphor proposed by Kayukawa et al [38], providing a loud beeping sound whenever the safe perimeter was disturbed. The alternative design was based on work by Kukka et al. [44], employing voice command to warn the nearby pedestrians. Each time an individual was sensed too close to the researcher, a voice command was played. Both designs employed broadcasting the message for people surrounding the wearer and were empirically explored throughout the field study. The feedback was implemented using an Android smartphone (same as used for the experimental study) and a Bluetooth speaker, attached to the wearer's body.

7.2 Procedure

We conducted the deployment of Gapeau in teams of two researchers. One researcher would wear the device and use it in a public space, while the other researcher was in charge of conducting a structured observation and short interviews with the passers-by [11]. We conducted the study in a number of locations where problems with

Table 3: Errors recorded in our experiment. Condition pairs with significant differences in post-hoc test are marked with * and †. All marked pairs are significant at the $p < .05$ level.

			NF		Audio		Vis		Vib	
	$F_{3,81}$	p	M	SD	M	SD	M	SD	M	SD
Total errors	3.26	$< .05$	$0.29^{*\dagger}$	0.45	0.19^{*}	0.39	0.21	0.41	$0.19^{\dagger}$	0.40
False positives	1.07	.36	0.07	0.26	0.06	0.24	0.04	0.20	0.04	0.20
False negatives	2.60	$< .05$	0.22^{*}	0.42	$0.13*$	0.33	0.17	0.37	0.16	0.37

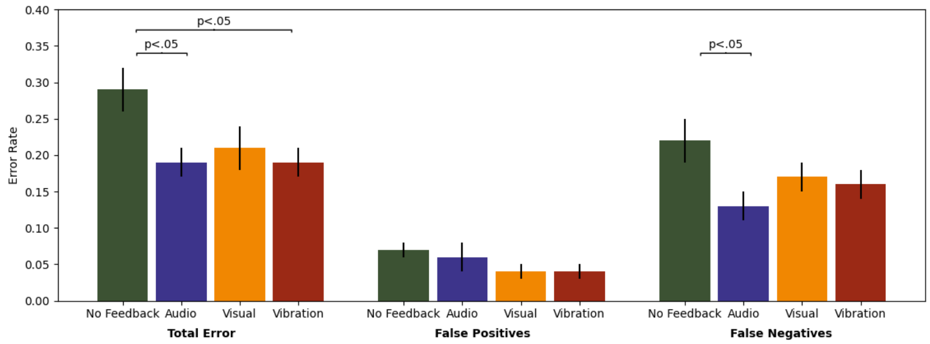

Figure 15: Errors in detecting approaching experimenters in our study. A false positive is wrongly identifying a safe situation as dangerous. A false negative entailed not detecting that the experimenter crossed the safe perimeter.

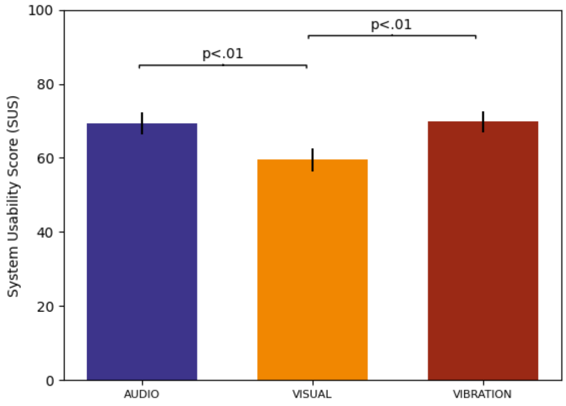

Figure 16: Perceived usability assessment in terms of SUS scores for the three feedback conditions in our study. Visual feedback was perceived as significantly less usable than the other two versions of Gapeau.

physical distancing were reported by local media. For this study, Gapeau used two versions of audio feedback: voice command and abstract (beeping). We conducted four sessions for a total duration of $t = 7h$ in Series 1 and 5 sessions for the total duration of $t = 8h$ during Series 2. Table 4 shows an overview of the locations and feedback modalities used.

Table 4: Locations visited during the in-situ study. The durations of using each feedback modality are marked for respective locations.

Location	Series 1		Series 2	
	Abstract	*Voice Command*	*Abstract*	*Voice command*
Busy street	15min	45min	25min	45min
Park	80min	90min	60min	90min
University campus	30min	40min	30min	40min
Shopping centre	30min	30min	20min	40min
Residential area	20min	40min	25min	40min

In the study, one of the researchers would walk in a possibly congested place. The device would provide audio feedback according to the proximity of other people. Whenever the device elicited a reaction, the observing researcher would query the pedestrian if they would like to participate in an anonymous 2-minute interview to share their reactions and opinions concerning the system. The interview addressed the following questions:

- What is the purpose of this device?
- Did you understand the command provided by this system?
- Would you obey the command provided by this system?

Researchers encouraged the participants to share their views on using such a system in public, and queried them about contexts in which they would consider using the device themselves. Throughout the study, the observing researcher would take notes of relevant events. We noted whenever a passer-by visibly noticed the device. Spontaneous reactions were documented with timestamps. Thus, the collected data consisted of recordings of impromptu interviews and the contents of the researcher's notebook. Figure 19 depicts the deployed experimental setup. Both researchers wore face masks throughout the experiment.

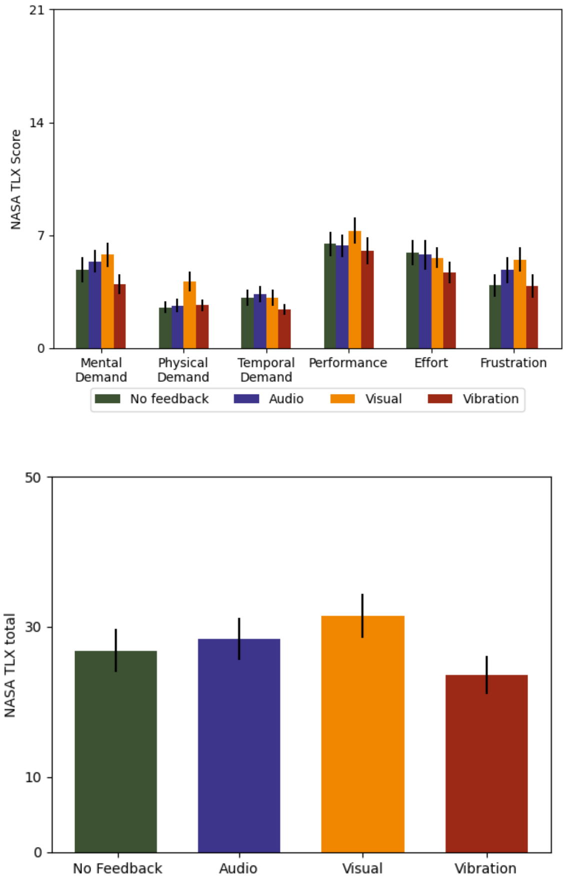

Figure 17: NASA TLX mean subscales scores (top) and mean total score (bottom) collected in our experiment for the experimental conditions. Error bars show standard error.

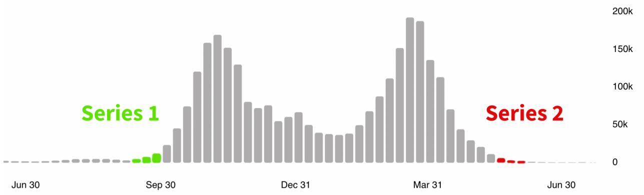

Figure 18: The development of the pandemic in the region of the study. The bars represent the weekly number of new infections recorded in the area, where our study was conducted [60]. The weeks in which the study was conducted are marked in colour.

We conducted two series of observations, at different phases of the pandemic with different measures being legally binding - the first series of observations was conducted when the 1st strike of the pandemic was anticipated and consecutive restrictions were introduced on a weekly basis (21026 infections diagnosed in the month of the study), while the second series was conducted 10 months later, during the cooldown period (2620 infections diagnosed in the month of the study). Figure 18 shows the dynamics of the disease spread within the region of the study.

During the 1st series, we observed and took notes of 336 passers-by and promptly interviewed 58 of them. In the 2nd series, we noted our observations on 362 passers-by and interviewed 48 of them. Throughout the study, we observed a total number of 698 pedestrians and briefly talked to 106 of them.

7.3 Analysis

Interview recordings, both from the field study and the debriefing interview after the experiment, were transcribed verbatim. Together with the researcher's observation notes, they formed our qualitative data corpus. We first coded the answers to the three structured questions of the in-the-wild study impromptu interview to obtain an initial quantitative assessment. In line with Blandford et al. [11] we applied the pragmatic approach to thematic analysis for our qualitative analysis. One researcher open coded 20% of the material and proposed an initial coding tree for the data. The initial coding tree was discussed in an iterative session with three researchers using multiple examples from the data. The rest of the corpus was divided between three authors. After coding the full data set, we used affinity diagramming to create themes, which represented recurring topics in the dataset.

Figure 19: During the in-the-wild study researchers visited different congested places, where problems with maintaining physical distance were frequently reported. Impromptu interviews were conducted to gather spontaneous feedback.

7.4 Results

Figure 20 shows the answers to the three interview questions in our field study. We observed that almost half of the pedestrians encountered in Series 1 were able to correctly guess the purpose of Gapeau. The majority of the passers-by understood the audio command produced by the system, and more than 60% declared that they would behave according to the instructions provided by the device. We observed that respondents in Series 2 identified the correct purpose of Gapeau less frequently, while being similarly eager to respect the commands. We attribute this observation to an overall decrease in media coverage on COVID-19 over the study period, so the pedestrians were no longer expecting disease-related actions in the streets. We also noted a slight increase of "I would not obey" answers, which were often accompanied by an opinion that physical distancing is no longer necessary.

Next, we report on the four themes which we created based on the qualitative data.

7.4.1 *Social importance*.

This theme describes how participants in both studies perceived Gapeau through the lens of a community effort in fighting the pandemic. While many passer-bys were surprised by the device's appearance, they would quickly reflect that the purpose of Gapeau was relevant to the current situation. The feedback provided by the device was seen as a necessity:

> *"This is a thing that's necessary, there's no reason to be upset!"*

Further, using Gapeau was perceived as an expression of consideration for others. Participants commented that wearing the device increased one's safety and the safety of others. One participant described the potential use of our device as a reasonable approach to solving the physical distancing problem:

> *"I think I would use it. Everyone's supposed to have some common sense. You should control yourself. And that's a means of controlling yourself."*

One of the participants in Series 2 mentioned that such systems might be especially beneficial during the cooldown periods.

> *This can be a really nice thing to use right now. People have this euphoria, infection rates are low, places re-open. Now it's the time to remind people to keep their discipline.*

However, some participants expressed that while they understand the reasons to use the device, the long-term social effects of popularizing such systems might be harmful. We observed more people expressed similar views in Series 2 during the cooldown period.

> *I think this is bad for us overall. People are already distant, families collapse, strangers do not trust each other. What's the point in staying healthy, if you end up sitting alone at your flat?*

7.4.2 *Focus on others*.

When discussing the potential use of Gapeau, fourteen passers-by in Series 1 did not imagine themselves using our device, but rather suggested that other people use it. Many assumed that their sense of distance was sufficient to maintain safe separation and additional aid was not needed. As a consequence, participants were surprised if Gapeau detected that they were too close to the researcher. This is illustrated by the following dialogue between to pedestrians:

> *A: "I wouldn't wear this, I know how far is two meters."*
> *B: "But we would've walked closer to this guy had it not been for the voice..."*

These views were echoed by some participants interviewed almost a year later, who also considered that such devices are no longer useful.

> *"It could have been useful when many people got ill day to day, but I don't think it's needed now."*

However, 18 passers-by expressed opposite views, emphasizing that negligence in preserving the distance can easily lead to worsening the overall situation.

> *"It is necessary to remind people about the distance, especially now, when the restrictions are lifted. If we don't control ourselves, the 3rd strike will get here sooner than we expect"*

Twenty-two participants stated that while they are far from interested in using such a system, they would obey the commands provided. One of them emphasized the role of respecting each other's rights.

> *"I think this system exaggerates the problem, but of course I would keep my distance when told. One needs to respect others' will, even if I see it as paranoid."*

Participants were also eager to report behaviours which they perceived as negative. Gapeau was sensed as a possible way to prevent such behaviours or avoid places where lack of physical distancing occurred. One participant suggested that Gapeau could be used to implement a certain form of social order:

> *"This would be useful, because people can't stand in a queue these days. This would tell them how."*

7.4.3 *Context of use*.

Finally, thirty-four passers-by shared possible usage scenarios for Gapeau. The device was primarily associated with potential professional use. Participants commented that it was particularly useful for professions where work was performed among people outdoors. One participant declared an explicit will to use Gapeau at work:

> *"This could be a work tool. I would wear this to work. You would need to hide the cables, but I would definitely take it to work with me."*

Another recurring topic was using Gapeau in different life circumstances. Participants listed contexts where people were likely to be too close to each other and imagined using Gapeau. The form factor of a baseball cap reminded participants of situations in which one would wear headgear. The seasons were also a factor:

> *"People wear hats in the winter. And they get closer together because it's cold. This is a winter thing."*

Other participants mentioned that specific use cases might reveal more successful than outdoor use. Participants mentioned that using Gapeau in stores, shopping centres, and other crowded indoor areas could solve problems, which often lead to conflict.

> *"Some people just crawl on your back when standing in line. Tell them not to, and they start to quarrel. I would use it to avoid such situations.*

7.4.4 *Applications beyond pandemic*.

Both during the post-experiment interviews and the in-the-wild study, participants elicited various ideas on how similar systems could be employed beyond the pandemic context, and what features would be desired. Participants suggested that such a system could be employed as a personal security tool, e.g for women walking alone at night.

> *I walk through the park at night, and it feels somewhat scary. It would be nice to get warned if someone was following you.*

Four participants mentioned that such systems could easily help people with chronic diseases, who are especially sensitive to infections. Other participants suggested that such systems might be suitable for the visually impaired.

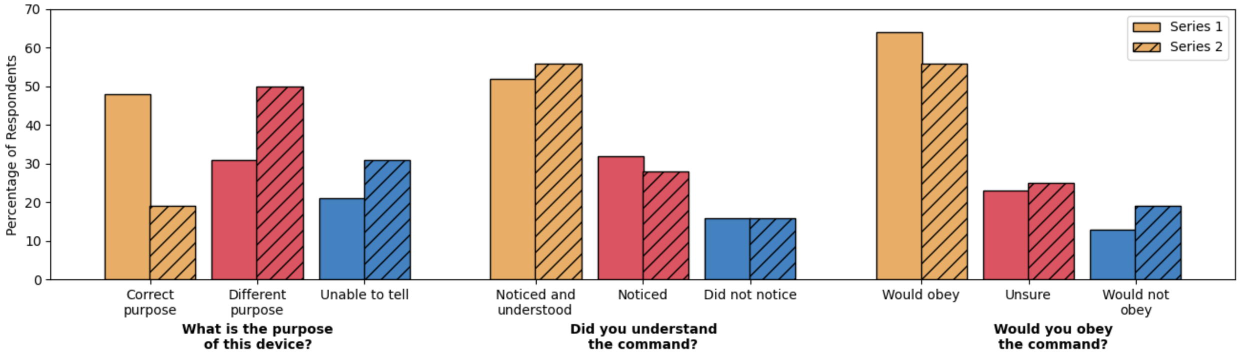

Figure 20: Answers to the three questions, which we asked during our in-the-wild study. The graph shows percentages based on answers from $n = 58$ participants in Series 1 and $n = 48$ participants in Series 2.

> *In my office, there is a guy who had his liver transplanted. He keeps his personal distance at all times, but it feels impolite to ask your colleagues to back off. This thing could help him a lot.*

One participant envisioned a similar system equipped with a smoke sensor could be used to avoid passive smoking and detecting violations of no-smoking policies.

However, some participants emphasized that in order to reach satisfactory usability as a garment, the aesthetic aspects need to be improved.

> *The times are special, so e.g. doctors wear weird suits, but it needs to look nice for me to consider using it. Maybe a straw hat or a visor would be better....*

During the post-experiment interviews, researchers gathered suggestions to make the system more lightweight and introduce sensor redundancy to substitute moving elements. Moreover, while the overall reception of hat-mounted device was positive, some participants noted that this could be a limitation in certain cultural and/or religious contexts.

8 DISCUSSION

In this section, we reflect on the findings of our study and contribute insights for systems that augment the sense of distance.

8.1 Gapeau Effectively Augmented the Sense of Distance

Our experimental study showed that the participants made significantly fewer mistakes in detecting whether or not someone was approaching them in their close proximity when using Gapeau as indicated by results in Table 3 and on Figure 15. This was primarily achieved by reducing the number of times at which the participant wrongly assumed that they were within a safe distance. A reduced error rate did not come at the cost of increased cognitive load, as suggested by the NASA TLX results. This means that an augmented sense of distance effectively helps users in physical distancing. While most research on augmented sense systems explored novel interaction techniques for enhancing human capabilities, our work shows that, in the context of a pandemic, augmented sensing systems can effectively help to follow safety measures. Compared with our validation results, we can observe that the interface part of the device is the key to improved performance. It is the interpretation of Gapeau's feedback that was most likely the primary cause of error. Consequently, our work echoes past findings from other explorations of augmented sensing systems, which indicated that feedback design is the key limiting factor in extending the human sensory range, e.g. [41]. We advise that such systems offer customization options to match users' preferences in different social and environmental settings. Using both audio and vibrotactile cues brought improved performance, while the participants mentioned different factors that would guide their choice between the two, that are related to their lifestyles and work environment. Further improvement of the feedback design is likely to make the system ready to become an everyday companion. Moreover, we recognized that the aesthetics of the device is crucial to ensure its positive perception as a piece of garment. These observations show that such devices present significant potential to become an everyday companion, once delivered in sufficiently appealing and usable form. However, as the side effect of regular usage of Gapeau, users could start delegating their distance awareness solely to the device.

8.2 Visual Feedback Was Least Effective and Usable in Conveying Distance Information

The results of our study showed that visual feedback did not significantly reduce the number of errors compared to no feedback. These differences can be explained by the fact that the visual sense is often highly engaged while walking, monitoring the environment and ensuring that the user does not walk into obstacles. Consequently, haptic and audio feedback was less distracting and allowed the users to focus on the task. However, we cannot exclude that the design of the visual feedback could be improved to offer better performance. This would, in turn, require an alternative form factor for the device which would be less portable.

8.3 Using Gapeau Was Perceived as Acceptable in Certain Contexts

Qualitative feedback from debriefing interviews and our in-situ study showed that users found that the functionalities provided by

Gapeau were socially important. The majority of the participants declared an intention to use Gapeau and follow its instructions. These observations show that perceptions of social acceptability are altered in a situation of a global crisis. Researchers standing on the street wearing what appeared to be a propeller hat did not elicit surprise or laughter, but often provoked a discussion about physical distancing. Some respondents raised questions concerning the long-term consequences of rigorous approach to physical distancing, highlighting their potential effects on social relations. Participants were concerned with the social context of potentially using the device and its appropriateness. Interestingly, many passers-by claimed reluctance to use Gapeau themselves, while suggesting that other people should use the system, as they do not maintain the safe distance. This assessment though might be caused by false belief of one's own ability to accurately assess the distance (the Dunning-Kruger effect [43]), coupled with an honest opinion that physical distancing is necessary. Moreover, the observations mentioned above seem to remain unchanged along with different stages of the pandemic development. Having probed pedestrians' opinions during the cooldown period, we observed that even those who no longer consider it necessary to maintain distance to strangers are willing to respect others' preference to do so. This finding shows that the social embedding of technologies and the values which they carry are of particular importance if the design goal of the artefact is social good. We recognized that participants are considerate both of the immediate results and long-term effects of using such systems.

8.4 Enhanced Distance Perception is Considered Useful Beyond the Pandemic Context

While our investigations were focused on the pandemic context, we recognized a number of potential scenarios where similar systems may prove beneficial. Respondents of our in-the-wild study emphasized that Gapeau could be considered as a work tool for people working in outdoor environments, performing activities that are potentially harmful for the passers-by, e.g. ground works, spraying, greenery maintenance. Other participants suggested that systems similar to Gapeau could be used in indoor scenarios, wherever the risk of collision with objects or people are considered (e.g. due to obstructed view, using soundproofing gear etc.). In fact, such collisions are among the most frequent contact-modes of in-work injuries [65]. Maintaining distance between people and other objects is often a part of the regular safety protocol (eg. in chemical, food or manufacturing industry), and could be considered to complement novel interactive systems for industrial process supervision [58, 69]. Similar systems could also benefit workers interacting with autonomous machines [70] or aid rescue forces working in conditions of limited vision [39, 79].

Our studies showed that amplified distance perception could be also employed in various everyday scenarios. Interviewees suggested that a more discreet version of the system could be used as a personal security tool for pedestrians. Moreover, we encountered suggestions that the distance assessment could be coupled with other sensing capabilities, e.g. to avoid passive smoking or radiation. Accurate distance perception is also considered important in sports (eg. skiing [57]), where it is often challenged with other perception-impairing factors [45]. The ability to precisely assess distance to others is also crucial for various assistive systems for the visually impaired [38].

8.5 Limitations

In the process of creating and evaluating Gapeau, we needed to take multiple decisions. Here, we reflect on some of them and consider alternative solutions. First, we recognise that Gapeau's sensing hardware and algorithm could be improved. We decided to build the system as a reaction to the COVID-19 pandemic and understanding its use in context was our priority. However, in the future, we plan to improve the sensor system by introducing redundancy for improved coverage. Moreover, more advanced processing methods would likely make the system more robust across various climates and environmental conditions. Second, we chose to conduct a qualitative field study to investigate the social context of Gapeau. While a more structured evaluation, such as considering different audiences as suggested by Rico et al. [68] would have been preferred, we recognised that the pandemic situation would affect the perception of our system. Thus, we opted for increased ecological validity, which necessitated a trade-off in terms of how structured our data could be. Moreover, we recognize that the location of our study (EU country) does impact the overall discourse over pandemic restrictions and affects the social acceptability, which could be different for other areas. Future studies could potentially examine how reflection on such technologies affect perception and behaviour towards safety restrictions [8, 9]. Finally, we note that our experiment used a distance higher than the safe distance as a simulation of an unsafe distance. While this was necessitated by legal and ethical considerations, we cannot fully exclude that the users' perception and thus the results of our study could be altered if our study would involve other people actually getting closer than $1.5m$ to the participant.

9 CONCLUSION

In this paper, we reported on the design, implementation and evaluation of Gapeau, a hat-mounted sensing device with ultrasound and thermal sensing system for helping users in physical distancing. We demonstrated that our research prototype effectively enhanced the sense of distance to others, therefore contributing to social safety. The evaluation of the proposed approach was conducted both in controlled experiment and during the exploratory study conducted in the wild during the COVID-19 pandemic. Our studies showed that wearable sensors are an appropriate approach to fostering spatial awareness, and that the audio and vibration feedback modalities are suitable to convey information on distance to other people. Gapeau effectively reduced the number of errors in estimating whether someone was too close to the participants. Users found that Gapeau is potentially socially important and suitable for work contexts. Moreover, participants envisioned a number of potential usage scenarios for similar systems. Therefore, there is a broad class of further research directions related to wearable systems for proximity sensing augmentation to be pursued in future inquiries. We found that systems designed to serve a purpose of social good meet with increased acceptability. We hope that our work contributes to an understanding of how augmented sensing systems can help us in maintaining safety. We also hope that the utility of Gapeau will be limited due to physical distancing requirements being lifted soon.

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