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A Multimodal Alarm System for Risk Management in a Clinical Lab

Federica Cena, University of Torino, Torino, Italy
Ilaria Lombardi, University of Torino, Torino, Italy
Agata Marta Soccini, University of Torino, Torino, Italy
Federico Sarzotti, University of Torino, Torino, Italy
Alessandra Re, University of Torino, Torino, Italy
Marco Trizio, University of Torino, Torino, Italy
Margherita Micheletti Cremasco, University of Torino, Torino, Italy

ABSTRACT

In this article, the authors aim at finding a way to effectively communicate situations of risk related to work safety, by catching workers' attention without interrupting their main task. They designed a multimodal alarm solution specifically conceived for a biomedical lab, where workers might be intoxicated due to the possible leak of reagents or to excessive exposure to potentially toxic substances. The authors propose a novel multimodal alarm system which makes use of different sensory modalities, touch and vision. In particular, it exploits wearable technologies to improve the effectiveness of the alarm in the context. In details, it offers 1) tactile alarm to catch user attention, 2) different alarm modalities for collective and personal risks, 3) visual cue to provide immediate diagnostic information on the risk source, and more detailed information on the risk nature. In this article, the authors describe a pilot test in the real context of use to inform the design of the system. The results are promising for the development of the solution.

KEYWORDS

Alarm Systems, Human-Alarm Interaction, Usability Field Study, Wearable Technology

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1. INTRODUCTION

An alarm works in a very simple way: it attracts attention and asks for human intervention. From a cognitive point of view, alarm effectiveness in capturing attention is influenced by physical salience, "the degree to which a stimulus is likely to attract attention based on its low-level properties and independently of the mental state of the observer" (Awh, Belopolsky, & Theeuwes, 2012). It strictly depends on the sensory modality that is activated.

The most salient and widely used alarm modality is the auditory one (Edworthy & Hellier, 2006). It is used in many high-workload safety-critical environments, such as during surgery (Edworthy & Hellier, 2006). Over the last thirty years, their use has become even more widespread also in other contexts because of a greater attention to safety (Edworthy & Hellier, 2006; Shah et al., 2015; Sousa et al., 2016). Auditory alarms showed many criticalities: they could be confusing, obtrusive and uninformative (Edworthy, 1994; Schmidt & Baysinger, 1986; Meredith & Edworthy, 1995). Instead of being a mechanism for improving the safety of the worker, this kind of alarms often increases workload, and produces a hostile work environment due to high rates of false, annoying, and inopportune alarms (Xiao & Seagull, 1999).

Given the limitation of auditory alarms, different alarm modalities have been used. In particular the tactile modality that showed to be especially effective when cognitive load is split on several sensory channels, like in driving collision avoidance tasks (Chun et al., 2012; Meng & Spence, 2015). Tactile alarms seem to maintain the efficiency and omni-directionality of the auditory stimulus, granting an adequate level of salience even if they are not suitable for collective risk (Wickens & McCarley, 2007).

In general, it has been proven that the design of an alarm system should be customized to the specific condition of use, in order to improve the human-alarm interaction, analyzing the ways alarms are integrated into the working places in a systemic perspective (Amaldi et al., 2007, Haas & Van Erp, 2014; Van Erp, Toet, & Janssen, 2015). The goal of the present work was to provide an alarm system that was effective in the specific working environment of a toxicology lab of a major hospital in Torino, Italy, in the context of an IOT-based safety project (Antonini, Boella, Calafiore et al., 2016). In this environment, workers might be intoxicated by harmful reagents leaked from their containers, or might be over exposed to potentially toxic substances. Existing sensors detect data related to the level of toxicity of the environment, and go off once the threshold is overcame. Thus, in order to better know the context where to situate the alarms, the authors started with a participatory activity analysis to highlight risks and discomfort experienced by the operators in current working practices (Trizio, Occelli & Re, 2017). The analysis highlighted the specificities of the lab working conditions: (1) the workers might be doing critical activities that should not be interrupted if not strictly necessary; (2) they are potentially exposed to collective but also to personal risks, their performance often diverges from the expected procedures. Specifically, the non-compliance with organizational policies and procedures might cause personal risks that can be under-estimated even by the experienced operators.

Moreover, the workers must have both hands free, therefore cannot manipulate a phone or other devices. Finally, the study evidenced a lack of a customized management of emergency situations, with no differentiation of the treatment of different typologies of risks, firstly personal or collective risks. As auditory stimuli are currently mainly used for all kinds of risks, it emerges the need of a different aid for managing alarms, more sophisticated and adapted to the specific conditions of the lab, capable to:

- catch the user attention in an immediate way, without interrupting the main task (goal 1)
- make workers distinguish between collective and personal risks, without annoying workers that are not personally involved (goal 2)
- increase workers' awareness about risks (goal 3).

To reach such goals, the authors propose a novel multimodal alarm system which makes use of different sensory modalities, i.e. touch and vision, and that is integrated in the existing one but with advanced functionalities, i.e. able to provide:

- tactile alarm by means of wearable devices to catch user attention (goal 1)
- different alarm modalities for collective and personal risks (goal 2)
- visual cue to provide immediate diagnostic information on the risk source, and more detailed textual information on the risk nature for later fruition (goal 3).

In the paper, we describe a preliminary pilot test in the real context of use of the solution. We designed it for the real workers of the lab, thus considering their anthropometric measures and their habits, in order to find the best solution for them. The results are promising for a further development of the solution.

The paper is structured as follows. Section 2 presents the background and related work, while section 3 describes the specific context for which the alarm solution needs to be designed. Section 4 presents the alarm solution designed for the context, while Section 5 and 6 presents respectively the usability study and the results. Section 7 concludes the paper.

2. BACKGROUND AND RELATED WORK

Wearable technologies are accessories, such as watches, bracelets, etc., that incorporate advanced electronics, while smart fabrics are materials that consist of a set of conductive fibers capable of detecting environmental stimuli and interact, via Bluetooth or wireless, with a computer or a smartphone.

One of the major fields of application of wearable technology is healthcare. Several systems based on wearable wireless sensors have been developed to measure physiological parameters such as heart rate, temperature, and blood pressure (Lukowicz, Kirstein, & Tröster, 2004). In the assistive technology context, wearable technology is used to monitor elderly people, especially their general health status or eventual falls.

These solutions are also currently used to improve workers' safety, mainly in situations where operators risk their lives and need constant monitoring of their wellbeing, where the subjects are often drivers, firemen and armed forces. One example is the SmartCap[1], a device that exploits electroencephalography to provide real time measurements of the fatigue of vehicle drivers or operators of heavy equipment; remote operators will be alerted via both audio and visual alarms; Optalert's glasses[2] measure the frequency of the operator's blinks to identify the earliest signs of drowsiness and provide real-time information to the driver and the supervisor.

Such existing systems, in all domains, aim at detecting dangerous conditions and provide alarms to third parties, while in the new system the target user is an active subject at work. The system aims at being not only an alarm, but also an information system, with the goal of improving awareness about inadequate working conditions and the potential risks. In this sense, the solution is more similar to the Quantified Self (Li, Dey, & Forlizzi, 2010), where wearable technologies are adopted by users to gather data about different aspects of their lives (steps, sleep, heart rate, etc.). One last difference is that the system presented in this paper provides users with information about the environment and not bodily functions.

The Table 1 summarizes the proposed system's features (rows) with respect to solutions in different fields (columns).

For what specifically concerns the human-alarm interaction modality, as mentioned in the introduction, auditory is the most frequently used typology of alarm (Edworthy & Hellier, 2006, Shah et al., 2015; Sousa et al., 2016), but it presents several limitations, especially for what concerns cognitive workload (Schmidt & Baysinger, 1986; Edworthy, 1994; Meredith & Edworthy, 1995).

Moreover, the uncontrolled proliferation of alarming devices creates a sort of cacophony that increases the risk of alarm desensitization and omission of appropriate reactions. This phenomenon of apathetic responses is known as alarm fatigue (Johnson et al, 2017, Xiao & Seagull, 1999), it often appears as a human adaptation to a significant amount of false positive alarms, and can lead to dangerous and even life risking circumstances. It is worth to mention that previous studies propose design guidelines to prevent the appearance of alarm fatigue in medical staff (Cvach, 2012), but again while they communicate a danger related to a third party, in this case patients, the current work is about sensing the workers themselves.

The system here discussed should be able to discern two kinds of alarm: collective and personal ones. While the former could be effectively conveyed with auditory alarms, the latter needs to be communicated only to the target worker, both to respect her/his privacy and to avoid annoying other workers. Herring and Hallbeck's (2010) study on alarm design came to the conclusion that the best type of alarm system for a wearable neutron detector, a case which is very similar to ours, is "a multi-modal visual-tactile alert system, with the primary alert being tactile, to notify the user in an efficient, non-startling, non-irritating way". Taking the move from this study, we opted for a wearable device with a tactile modality component (vibration) and a visual one (light).

Table 1. Features of the proposed system with respect to different fields

Features	Assistive Technologies	Workers Safety	Quantified Self	Multimodal Alarm System
User	passive user (patient)	active user (worker)	active user	active user (worker)
Typology of alarm	personal	collective - personal	personal	personal - collective
Target (who receives the communication)	third parties	user - third parties	user	user
Information	about users	about users and environment	about user	about environment
Goal	emergency management	emergency management	information system	information system for risk management
Context	daily life	work	daily life	work

3. CASE STUDY: A CLINICAL LABORATORY

In this section, the specific context where the solution needed to be positioned is presented. It is the toxicology lab of a major hospital in Torino, Italy (Figure 1).

The 12 workers at the Lab perform analyses for the control of pollution levels in the environment, as well as for the monitoring of individual exposures to metals, solvents, pesticides and other toxic substances. The activity is structured in four different sectors (letters in Figure 1):

- Chemical-Biological Analysis: Such as blood, urine and other biological samples (A)
- Chemical-Environmental Analysis: Sampling and analysis of environmental chemical pollutants (B)
- Metal Analysis: With both biological and environmental samples (C)
- Fiber and Dust Analysis: I.e. asbestos and crystalline silica analysis (D)

Figure 1. Toxicology lab map

Three kinds of risks can occur at the Toxicology Lab (sorted by frequency of occurrence):

- Chemical Risk: Inhalation or skin contact or due to leaks of methanol or acetonitrile from overfilled tanks
- Biohazard: Contamination from blood or other body fluids
- Climatic Risk: Noise, temperature, humidity, lighting, aeration

Moreover, the distinction is between:

- Collective Risks: Involve the whole working space, and thus all the people who work there, and can be caused by microclimate changes as well as general presence of toxic substances in the workplace
- Personal Risks: Involve a single person in a specific area of the lab, a combination of where the worker is and what toxic substances are in the specific spot where the person is. The personal overexposure could be due to a peak value or to the persistence of a toxic substance over time

Such risks do not require immediate response or intervention. The aim of this work was to design an alarm system that is integrated in the current procedure, it does not replace it. Thus, in the case of classic danger situations, traditional auditory alarm is activated.

4. A PROPOSAL FOR A MULTIMODAL ALARM SOLUTION

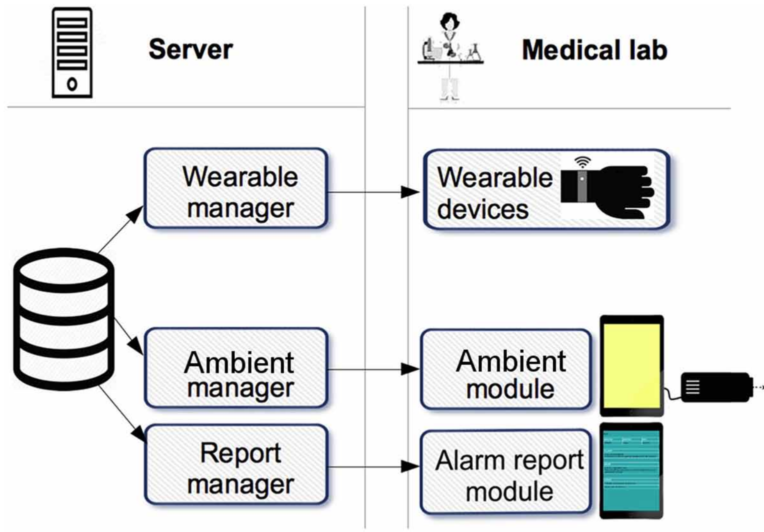
In this working environment, the goal was to design an alarm solution able to:

1. catch users' attention in an immediate way
2. distinguish between collective and personal risks
3. increase worker's risk awareness

To reach these goals, the authors propose to:

1. convey the alarm by the vibration of some wearable devices. The authors considered auditory alarm as too intrusive and unfitting for situations, since it urges for immediate response (Pirhonen & Tuuri, 2010) and might need to be set to a high level to overcome the existing noise
2. implement two different types of alarm: a collective alarm in case of environmental risks, and an individual alarm in case of personal risks. In both cases, the alarms consist of a vibration, but in case of a collective alarm, the stimuli are also visual: a light appears on the wearable devices while an environmental system base on projectors lights the source of danger (e.g. a leaking container). Again, no auditory

Figure 2. Architecture of the prototype



alarms are used, also for a matter of privacy of the people involved in the individual risk

3. provide visual diagnostic information about the source of the risk in an immediate way by giving visual lights coming from the environmental system. Moreover, further information related to the kind of risk is conveyed with a daily report, provided by a mobile app

In order to test our idea in the context, the authors developed a first prototype, composed of 1) a wearable solution, 2) an environmental solution and 3) a report system (Figure 2).

4.1. The Wearable Solution

The authors designed and developed three prototypes of wearable devices: a wristband (W), an armband (A) and a necklace (N) (Figure 4) in order to test which is the most acceptable for users in the specific context. While a wristband is the most common kind of wearable device, it could hinder the activities performed in the laboratory. This problem exists in the case of the necklace as well, that in addition is not easily visible either. The armband, on the contrary, is arranged in a position where no other accessories are usually placed, but it does not touch the skin, and that can prevent the detection of the vibration. Also it is not completely visible for the user, but it has the advantage that it does not obstruct workers' task.

The devices' purpose is to inform users about situations of risk which anyway do not require immediate response or intervention. In case of risk (either collective or personal), a warning signal in the form of a tactile vibration is emitted to catch the attention without forcing the workers to interrupt their task or look away immediately. In case of collective risk, the wearable also emits a visual signal (a white LED) that the users look at once they can divert the sight from their work.

Figure 3 shows how the interaction between the user and the system flows.
Implementation details. The three prototype devices are composed of:

- A Wi-Fi module (Wi-Fi module ESP8266-01)
- A led (a Lilypad white LED)
- A Vibe board (a Lilypad Vibe board)
- A Switch (Lilypad switch)

The Lilypad component is connected to the ESP8266 (Figure 5, Figure 6). The circuit is charged by a rechargeable LIPO 3.7 V - 4.400 mAh battery or by an USB power bank.

During the test, the battery was arranged into the workers' white coat pocket, hence the connecting wires were properly shaped: longer for the wristband and shorter for the armband and the necklace. Moreover, the devices were resizable to fit each

Figure 3. Interaction flow

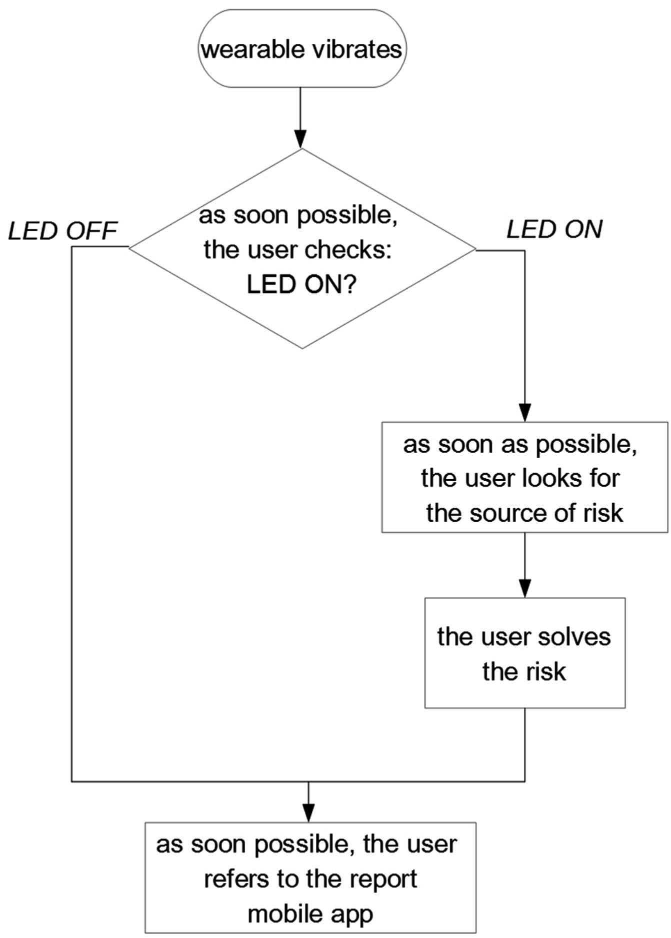


Figure 4. Wristband (a), Armband (b), Necklace (c)

Figure 5. Wearable device scheme

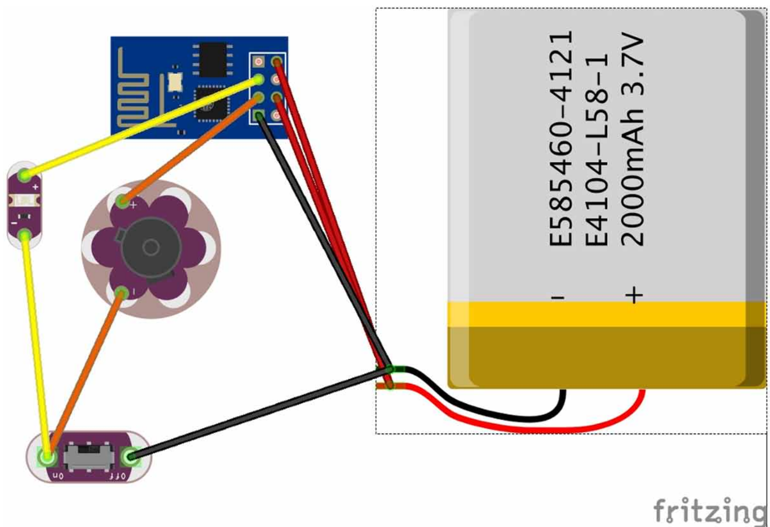
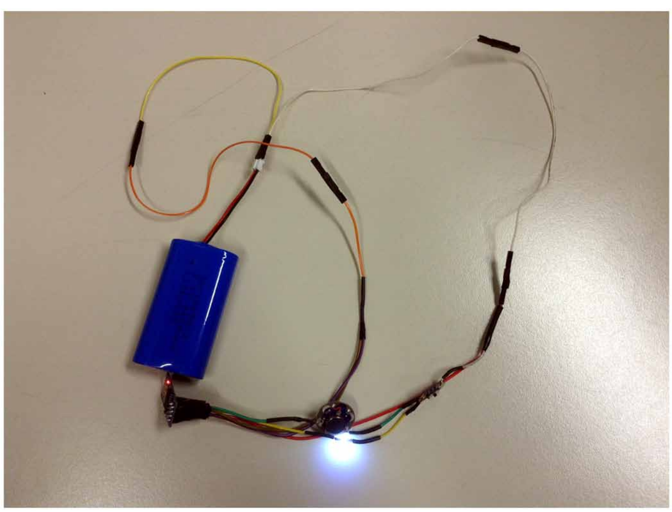


Figure 6. Wearable device electronics



user's physical characteristics and were positioned in a way that the LED was visible to the worker (Figure 4).

4.2. The Environmental System

The environmental system is an array of stations, spread around the laboratory, all connected to a central server that sends information to the stations regarding collective environmental risks. Every station includes a portable projector, thanks to which the system provides visual stimuli. The stations are compact and barely visible to the workers.

The system retrieves from some sensors the exact position of the source of the dangerous event in the lab, and, through the use of lights, provide some information to the users. Specific colors are projected on the physical objects in the lab that are the location of the source of the danger. Yellow and red lights were used during the experiment, to show the users where the source of the risk was.

It is designed as the prototype of a system capable of mapping the whole lab. For the sake of the experiment, though, the authors did not need to develop the whole system, but only implemented two stations close to the most probable sources of risk.

Implementation details. In every station of the Environmental System, a portable projector is directly connected to a mini iPad through the lighting port. Via the mirroring function, every station projects the contents of the screen of the iPad (Figure 7).

The system app is running on the iPad and is managed by a PHP customized server. The environmental station receives from the server a colored background screen for the iPad that is shown by the projector in which the color represents the current status of the alarm. In a default status, no risks are detected: the server sends to the stations a black background. The projector visualizes a black image and thus it does not emit any light, which simulates the OFF state of the projector. In case a collective risk appears, the server sends a colored background to the station that monitors the specific source of the risk. In that case, the connected projector is turned ON and it projects over the source of the risk the colored background of the iPad.

4.3. The Report Module

Users can take advantage of an online report (Figure 8), which offers information such as the daily log of the alarms, data regarding the current and past risks, date and time of the alarms, type (in terms of personal or collective), name and quantity of the dangerous substance. The report can be accessed using the Alarm report module of the iOS app.

5. USABILITY STUDY

Given the complexity and variability of the work system, the authors opted for a field study to assess the prototype in the real working conditions (Rogers, 2011). Given the

Figure 7. iPad screen

small group of workers, they followed a within-subject design, asking operators to wear the three devices (one at a time, in different order) while performing their activities.

The usability evaluation had two goals: diagnosis (Was the wearable device compatible with the activities carried out by the operators? Was the app offering all the information they needed?) and comparison (Which of the three alternative wearable device was the best?). The final goal is to have insight for the development of eventual final solutions.

5.1. Participants

The aim of this work is not to find a standard design for an average user, but to design the devices on the specific users involved in the specific environment. Among the 12 lab workers, 8 participants were involved, 3 female and 5 male, distributed on the 4 indoor activity sectors. Table 2 summarizes the participants' demographic characteristics by gender and age, anthropometric aspects like height, weight, wrist and neck circumferences, and their work sectors. Anthropometric measurements were relieved to take in account both the sample's variability and the adjustability degree of the devices in the different placements. Measurements were collected following anthropometric international standard (ISO/TR 7250-1, 2010; Peebles & Norris, 1998).

Comparing participants' anthropometric characteristics with national and international database (ISO/TR 7250-2, 2010) the sample was rather representative of variability: about height Italian males variability from 5th to 95th percentiles, while females were all over 50th to more than 95th percentiles; about weight males were over 5th to more than 95th while females all lower than 50th percentile. Differently, wrist and neck circumferences have rather small measurements comparing with national and international database and there were not 95th European and USA percentiles participants' values.

Figure 8. The online report

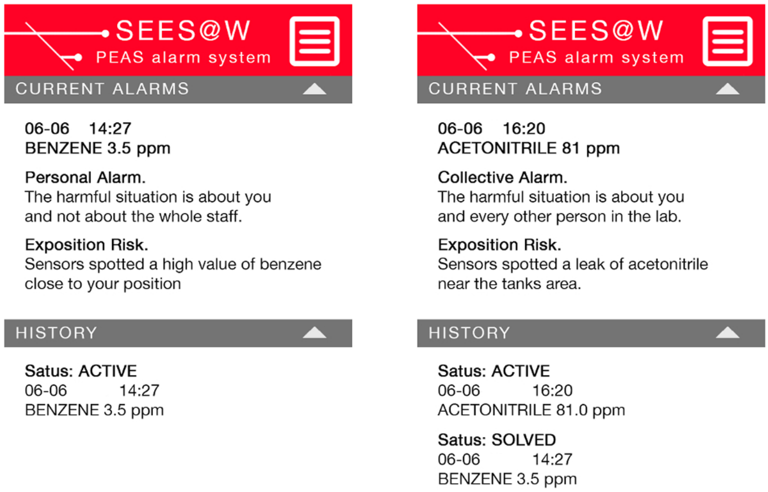


Table 2. Participants features

Participants' Codes	P1	P2	P3	P4	P5	P6	P7	P8
Gender	M	M	F	M	M	F	F	M
Age	49	50	59	54	55	59	24	25
Height (cm)	178	184	174	185	160	174	160	179
Weight (kg)	104	113	62	72	66	61	40	67
Wrist circumference (cm)	18.5	18.4	16	17	15.2	15.5	13	17
Neck circumference (cm)	42	44.2	34	38	35	36.4	27	34
Indoor working sector	B	A	D	C	A	D	B	C

5.2. Evaluation Scenarios

The authors defined three scenarios for the test:

1. Personal exposure to acutely toxic chemicals. The sensors detect the presence of benzene in the area in which the operator works. The wearable is activated through vibration. Looking at the wearable, the worker does not see the light signal. They realize that it is a personal warning and leave the work place to go to the tablet to check on the app the causes of the alarm. Outside the workplace, the app highlights exposure to benzene. The situation is serious, the person has to intervene in accordance with the emergency procedures. When the alarm stops, the operator goes back to work.
2. Collective exposure to acutely toxic chemicals. The sensors placed in close proximity to the tanks for chemical disposal detect acetonitrile in the environment, and the alarm system sets on. At the same time the wearable activates vibration

Table 3. Experimented alarms

Alarm	Information	Technologies
Collective	The sensors in the lab near bins disposal detect acetonitrile	• wearable (vibration + light) • environmental system • app
Personal	A high level of benzene has been detected in the air, near the person	• wearable (vibration) • app
	The person remained too long in a lab area where the sensors detect a critical level of ethanol.	• wearable (vibration) • app

and a LED light. The workers feel the vibration and, looking at their own or others' wearable, see the light and understand that it is an environmental alarm. Looking around, they search for the source of risk and see that the projector connected to the iPad is lighting the tanks with a specific color: thanks to the clue, the user detects the tank overflow. People are expected to empty the disposal tanks following the safety procedures. The consultation of the app is not required in this case, unless the workers decide to look for further information. When the value of toxic chemicals in the air falls back to normal values, the alarm stops and operators get back to work.

3. Personal cumulative exposure to toxic chemicals. A worker feels the vibration from the wearable and then knows that there is an alarm currently underway. Looking at the wearable, (s)he does not see the light signal, then the warning is personal and (s)he leaves the location to gather further information querying the app on the tablet placed outside the workplace. The app reports that the person has remained too long in a lab area where there is a critical amount of ethanol. The person intervenes to reduce the ethanol level. When the reagent's toxic value in the air decreases, the alarm stops and the work restarts regularly.

Table 3 resumes the alarms experimented for each scenario.

5.3. Procedure

During the test, to avoid any interferences, the researchers remained outside the laboratory. The workers knew that a process had been activated in the laboratory to assess and monitor chemical risks. Different device sequences were tested (wristband, necklace, armband / armband, wristband, necklace / necklace, armband, wristband) randomly on the eight participants. Each participant tested the three scenarios in the same order: a personal acute exposure, a collective alarm (air dispersion), and a cumulative personal exposure. One single worker at a time was wearing one device.

When the alarm started, the operator was asked to go and look at the app or to the lighted zone, taking the necessary procedures to return to normal. As a final step, at the end of the experience each operator was asked to fill out a questionnaire.

Table 4. The usability framework

	Effectiveness	Efficiency	Satisfaction
User	Is the system perceived as helpful and in line with needs/expectations? 3 items	Is the system easy to use and the procedure easy to remember? 3 items	The system is intuitive and easy to use. At some point I forgot I was wearing the device Overall, I am satisfied with the use of the device. I think that the device is too complicated to use. I would recommend the system to my colleagues. At times I felt tension because of the device. The device looks aesthetically pleasant.
Task	Does the system prove effective in all the performed tasks? 1 item	Is the device uncomfortable in some of the tasks? 1 item	
Equipment	Does the system prove effective when operators interact with the equipment in different tasks? 2 items	Is the device interfering with some activities or equipment? 2 items	
Environment	Does the system prove effective in often changing environmental conditions? 2 items	Is the device uncomfortable in given environmental conditions? 1 item	

5.4. The Questionnaire

The authors chose to realize a questionnaire specifically focused on the situation to be evaluated, to support diagnosis for improvement and comparison for the choice of the most effective prototype. Following the general indications given by the international standard (ISO 9241-11:1998 (ISO, 1998), they created a framework where the columns include the three dimensions of usability evaluation (effectiveness, efficiency, and satisfaction), while the rows present the components of the context of use (user, task, equipment, environment). In the Table 4, the authors provide the macro-categories they used as a matrix to formulate the items for each section.

Comparing the most known usability questionnaires (SUS, Brooke, 1996; QUIS, in Shneiderman and Norman, 1992; USE, Lund, 2001; IsoMetrics Usability Inventory, Gediga, Hamborg, and Düntsch, 1999; SUMI, Mansor, Kasirun, Yahya, and Arshad, 2012), the authors selected the items that are consistent with the specific system to be

Figure 9. Item example

1) If I had the device, I would use it regularly:

- **Wristband**

	1	2	3	4	5	
strongly disagree	○	○	○	○	○	strongly agree

- **Necklace**

	1	2	3	4	5	
strongly disagree	○	○	○	○	○	strongly agree

- **Armband**

	1	2	3	4	5	
strongly disagree	○	○	○	○	○	strongly agree

tested. Some items had to be rephrased, some others were ad hoc created. The final version of the questionnaire provides 25 statements with 5 response options ranging from "strongly disagree" to "strongly agree".

Following the three usability dimensions, we also provided three items (one for each dimension) to evaluate the interaction with the Environmental System.

When necessary, in the same statement the 5-point Likert scale is repeated for each device, in order to collect comparable data. One example is given in Figure 9.

In the questionnaire, the authors used all positive statements, asking operators to rate their level of disagreement or agreement, according to Sauro and Lewis (2011).

Finally, four open questions asked the operators to list the most positive and negative aspects of their experience and to give suggestions for improvements.

A conclusive item concerned the importance attributed to the system for safety purposes, with a 4-point scale from "great importance" to "worthless", to obtain a more polarized answer on the device usefulness excluding the neutral option.

6. RESULTS

Firstly, the authors present a report on some observation data they were capable to collect as the glass wall of the lab allowed to record workers' reaction to the alarm. Secondly the subjective quantified data resulting from the final questionnaire, filled just after consulting the app.

6.1. Observation Data

The authors collected performance data regarding the time interval between the activation of the alarm and the interruption of the task; the amount of time necessary to localize the source of risk (just in case of collective alarm); the quality of the interaction with the tablet.

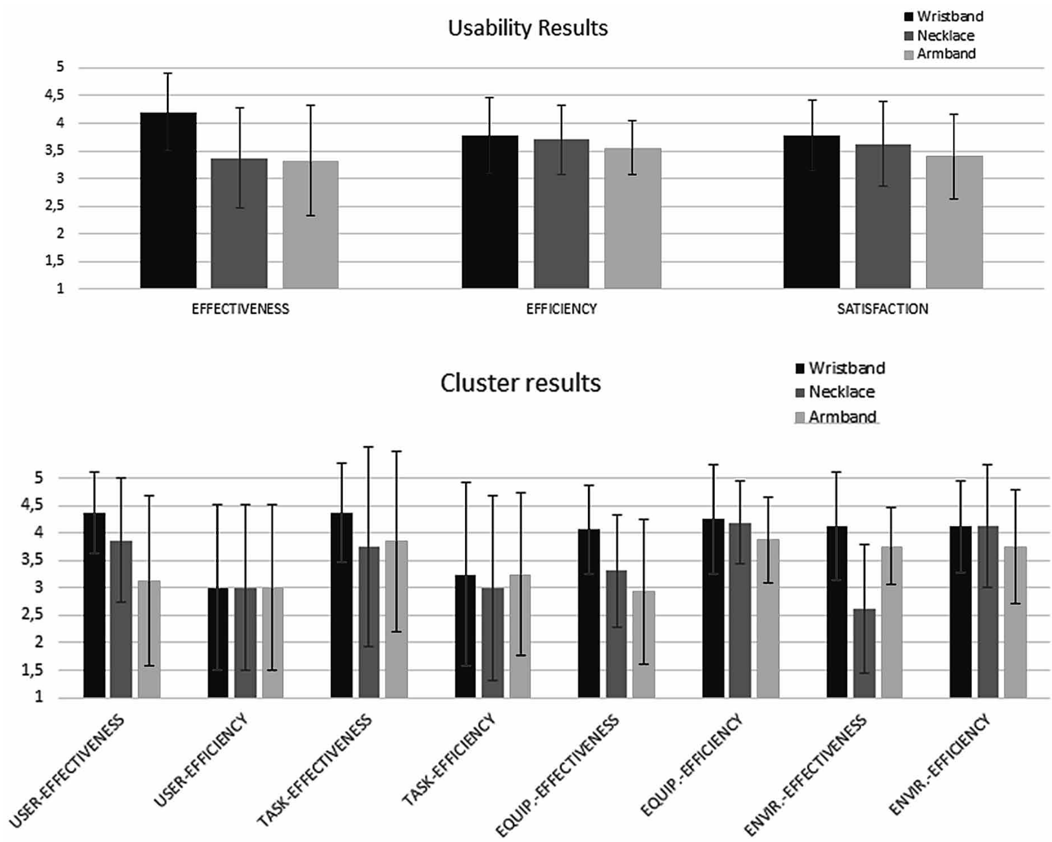
All the operators responded to the alarm in a time between 2 and 17 seconds, depending on the activity they were performing when the alarm went off. Only one did not respond to the vibration and asked to stop the alarm in order to complete the task. As for the Environmental System, all the operators quickly located the source of the risk.

All the operators interacted without errors with the tablet provided outside the laboratory and had no problems in understanding what was going on. After the consultation, they said they had obtained all the information needed to effectively manage the alarm condition. One tester spontaneously asked to download the app on his smartphone and was immediately imitated by two others.

6.2. Questionnaire

The authors carried out a descriptive analysis both for diagnosis and comparison purposes.

Figure 10. Usability Dimensions and Clusters Results (The Error Bars Refer to Standard Deviation)



6.3. Diagnosis

The evaluation of the system is positive, with regard to both relevance for safety (4-point scale, 0-3, M = 2.50, SD = 0.53) and usability, with higher values for "wristband". The system is rated to provide adequate information (M = 4.38; SD = 0.51), to be easy to use (M = 4.57; SD = 0.53), intuitive (M = 4.63; SD = 0.91) and simple (M = 4.75; SD = 0.46). Only the aesthetics reports negative scores (wristband M = 2.38 SD = 1.40; necklace M = 2.50 SD = 1.51; armband M = 2.25 SD = 2.25), probably due to the prototype state of devices. The evaluation of comfort of use shows variability (wristband M = 3.25 SD = 1.66; necklace M = 3.00 SD = 1.69; armband M = 3.25 SD = 1.48) suggesting that the compatibility between the product and some tasks needs further attention. Furthermore, the answers on the correct perception of the functional state of the system show average means in the different conditions, with some negative evaluations (M = 3.00; SD = 1.51). In the final open-ended questions on the positive and critical aspects of the system, two participants reported some problems related to the use of the armband device, highlighting difficulties in perceiving the vibration. One of the two users suggested also to increase led light intensity, vibration and range of action of the wearable system. It was also advised to connect the wearable system to other personal mobile devices. No other critical aspects of the devices, nor need of additional information on the alarm report were indicated.

The analysis of perceived usability of the environmental system is positive as well. Both the questions on effectiveness (M = 4.63; SD = 0.74) and efficiency (M = 4.38; SD = 0.74) indicate how the adopted solution simplifies the individuation of the source of the collective exposure and results in a faster alarm response time, without interfering with usual tasks. Satisfaction also shows positive evaluations (M = 4.13; SD = 0.99). Two participants suggested to add to the actual environmental system specific information on the exposure's cause through the projection of the reagent name or chemical symbol.

6.4. Comparison of the Wearable Devices

Results of the study comparing the three devices are reported in Figure 10. The wristband received the most positive evaluation by all the participants and in all the usability dimensions.

As the authors analyze each cluster in detail, some additional indications emerge. In "user-effectiveness" significant mean differences between the conditions were found in the answers to the item "If I had the device I would use it regularly", where the condition "armband" shows the lowest scores also with negative statements.

No statistically significant differences emerge in the analysis of the interaction with the tasks. The means generally indicate positive values, higher for the wristband condition (M = 3.88; SD = 1.12). Nevertheless, in all conditions the wearable device can cause discomfort performing some tasks.

Armband resulted preferred both for males and females, whether or not they had watch, bracelets or elastic on the wrist. Only one subject (female) judged necklace as favourite and the best one in efficacy. Another female and one male with jewelry-necklace, at the end of the questionnaire, expressed their preference for the neck device but, evaluating the physical interaction quality and the signal perception level, anyway attributed better values to wristband condition.

Talking about the device's adjustability and adaptability to anthropometric variability, the wrist choice seems to be preferable because the inter-individual variability is more limited compared to the others (Peebles & Norris, 1998).

The white coat proves to be a potentially critical aspect of the equipment as it can reduce the alarm perception, in particular in the necklace and in the armband condition. Only in the wristband condition the mean value is positive, even if with two negative evaluations.

The evaluation of the interaction with the environment shows in general positive scores with a constant preference for the wristband device. In relation to the LED light visibility, only the necklace condition proves to be ineffective (M = 2.63; SD = 1.18) with a statistically significant difference with the wristband (M = 4.13; SD 0.99) and the armband scores (M = 3.75; SD = 0.70).

The analysis of satisfaction didn't show statistically significant differences between the three conditions, rather a tendency to perceive wristband as the most satisfying with very positive scores (M = 4.50; SD = 0.75), higher than necklace (M = 4.00; SD = 0.92) and the armband (M = 3.75; SD = 1.16), still globally satisfying.

Also, in the answers to the item "At some point I forgot I was wearing the device" the wristband condition reports the highest scores. The item reports medium values with high variability, highlighting a still critical aspect that confirms the previous considerations on the prototypical state of the products.

7. CONCLUSION

In this paper, the authors propose a novel multimodal solution to communicate in effective way situations of risk in biomedical labs. Given the specific features of this context, they propose to integrate existing general-purpose auditory alarm system with a combination of other modalities, i.e., wearable devices combined with a projection-based environmental system and a mobile application. The main novelty of this contribution with respect of the state of the art is the particular combination of such multimodal alarms to provide different types of alarm in case of personal or collective risk.

The paper describes a preliminary usability test of the prototype to have some insight for the full development of the system.

According to the test, most of the time the solution was perceived as discreet. The usability testing and the questionnaire results give a positive evaluation of the alarm system, as well as suggestions for improvement. The system proved to offer a clear, unobtrusive and useful information (Stanton, 1994) on the different risks potentially present in the work environment, increasing operators' awareness and a rapid and punctual diagnosis through the environmental system or the app solutions. The tests did not reveal any failure in response to the alarm: with one exception, all the participants interrupted their tasks and followed the procedures. This immediate reaction seems to confirm that the physical salience of the alarm was reached (Wickens & McCarley, 2007), not only because of the employment of different sensory channels but also because of its consistency with the activities performed in the lab.

Limitations of the work are related to the artificial nature of the experiment, due to the objective impossibility to recreate a real risk condition in the hospital lab. Of course, dangerous situations were just simulated, and this could be a bias in the way people reacted to the alarms. Moreover, the prototype is only a simulation for the test and our prototype is not integrated in the complete system at this stage.

In conclusion, some future work could be to redesign the devices according to the testers' suggestions, with a special attention to aesthetics. Since the wristband prototype received the most positive evaluation by all the participants, the authors chose this configuration to be adopted in the system. They plan to investigate more in detail this solution and the integration of the prototype in a smart watch with the possibility to convey all the three types of alarm analyzed: vibration, acoustic signal and visual stimuli. Moreover, people could better accept that kind of device. The authors also plan to investigate how changes on vibration pulse duration and inter-pulse interval affect the perceived urgency and annoyance. They also consider to re-design the environmental system bringing attention to key spots that might have different meanings. Moreover, the authors plan to perform other tests to measure the cognitive load in managing the multimodal alarm.

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ENDNOTES

1 http://smartcaptech.com/
2 http://www.optalert.com/drowsiness-detection-glasses

Federica Cena is a researcher at the Department of Computer Science at the University of Torino (Italy). She is a member of the Intelligent User Interfaces group. She received her PhD in 2007 in the area of semantic web for distributed user-adaptive applications. She is working on user modeling, personalization and ubiquitous computing, Web 2.0 and Semantic Web for user modeling and adaptation. In the last years, she is mainly devoted to studying the implications of Internet of Things for user modeling and personalisation. She has served as a program committee member of several international conferences and workshops. She has organized several international workshops on user modeling.

Ilaria Lombardi received a master's degree, magna cum laude, in Computer Science at the University of Torino and, after a fifteen-year experience first as a programmer and later as a project manager in different private companies, a Ph.D. in Computer Science in 2011. She currently is a research fellow at the University of Torino. Her research interests include the study, design, prototyping, implementation and evaluation of smart objects and adaptive systems. Moreover, she collaborates with the ICxT laboratory at the University of Torino on projects that foster innovation in SMEs applying new technologies such as Internet of Things.

Agata Marta Soccini is a PhD Student in Computer Science at University of Torino (Italy), and a research fellow at the National Institute of Informatics in Tokyo (Japan), her main research field being Virtual Reality. In Torino, she is a member of the EIDOS research group, mainly exploring computer vision in virtual reality, while in Tokyo, as a member of Inamura lab, she is focusing on embodiment, immersion and cognitive factors in virtual reality, and the application of these technologies in medical fields. She has served as a reviewer and a program committee member in several major international conferences on virtual reality, computer graphics, and digital arts.

Federico Sarzotti received his PhD in Computer Science in 2017 at University of Torino in the area of Internet of Things and Human Computer Interaction. He received two M.D. in Computer Engineering from the Polytechnic of Torino and the Polytechnic of Milano. After several years as IT senior auditor in the automotive field, he is a Computer Science teacher in a High School in Torino. His research interests include the Internet of Things field, artificial intelligence, HCI and data analysis and visualization.

Alessandra Re, Professor of Work and Organizational Psychology at the Department of Psychology, University of Torino from 1998 to 2015, was Head of the Doctoral School in Human Sciences of the University of Torino from 2006 to 2010. As Vice-President, then President of the Italian Ergonomics Society (1998-2004), she has contributed to the growing of ergonomics as both an interdisciplinary academic research field and a profession that became established with the organisation of the first Italian Vocational Master's Programmes in the field. Her main research interests and collaborations focus on Organizational Psychology and Ergonomics, specifically on the ergonomic analysis of work activity, with attention to health and safety issues and to the organizational improvement.

Marco Trizio, Ph.D. in Applied Psychology and Ergonomics. User Experience Researcher. Main research interests: User-Centered Design, usability and user experience; applied cognitive psychology; human-computer interaction; ergonomics. Principal projects: - Cognitive evaluation of an electronic charts display (ECDIS) in maritime domain: Evaluation of the influences of the technological changes in the ship deck on situation awareness and on anticipatory processes; usability tests of the interface; user requirements identification. - User centred design, usability and UX applied to mobile apps: Research and development of autonomous driving interaction guidelines - Mobile Application Development course of the Politecnico di Torino and the Joint Open Lab of Telecom Italia, in training engineers and psychologists to UCD themes, and in developing the design processes of several mobile apps. - Analysis and design of human-machine interfaces; - Analysis of alarm wearable devices; - Websites usability tests and definition of design guidelines (in different contexts); - Risk assessment.

Margherita Micheletti Cremasco, Researcher in Physical Anthropology at Dipartment of Life Sciences and Systems Biology at University of Torino (MIUR SSD-BIO08) from December 2008 and Member of the Executive Council of Innovation Interdipartimental Center " ICxT "(ICT e Innovazione per Società e Territorio) - University of Torino. Teaching on: Physical Ergonomics, Anthropometry and Anthropology Research activity focuses on: -anthropometric and biomechanical surveys on Italian populations, synchronic and diachronic variability, the secular trend of stature, the incidence of overweight/obesity in relation with life style, sports, habits about technology use, and health implications at different ages. -human interaction with life environment and technological artefacts particularly about elderly (elderly-home Interaction, HCI in old age, human-machine interaction during ageing) -ergonomic analysis of work activities in various contexts, manufacturing systems, industrial and agricultural companies, integrating different evaluation methods to assess biomechanical workload, with attention to health, safety and comfort.