Carl von Ossietzky
Universität
Oldenburg

Fakultät II – Informatik, Wirtschafts- und Rechtswissenschaften
Department für Informatik

Multimodal Alarm Distribution System for Intensive Care Units

Dissertation zur Erlangung des Grades einer
Doktorin der Ingenieurswissenschaften (Dr.-Ing.)

vorgelegt von

M.Sc. Vanessa Cobus

Erstgutachterin / Zweitgutachter:

Prof. Dr. Susanne Boll
Prof. Dr. Markus Löchtefeld

Tag der Disputation: 30.03.2020

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Oldenburg, den 18.12.2019

Vanessa Cobus

Zusammenfassung

Mit der zunehmenden Entwicklung von Biosensorik und den damit verbundenen Möglichkeiten der Patientenüberwachung steigt auch die Anzahl akustischer und visueller Alarme auf Intensivstationen (ITS). Diese Alarme (in etwa 250 pro Patient am Tag) sind für jede Person auf der Intensivstation hörbar und somit störend für Patienten sowie Personal. Jeder Alarm muss von der zuständigen Pflegekraft bezüglich der Ursache sowie Dringlichkeit analysiert und bewertet werden, was 1) eine hohe kognitive Belastung und 2) das potentielle Risiko für Alarm Fatigue, eine Desensibilisierung sowie verlangsamte Reaktionszeit auf Alarme, darstellt. Die Mehrheit der wissenschaftlichen Ansätze mit der Absicht, Alarm Fatigue zu reduzieren, befasst sich mit Verringerung der Anzahl von Alarmen, wie z.B. durch verbesserte Algorithmen, intelligente Alarm Delays, sowie Änderungen im allgemeinen Arbeitsablauf und der Alarmpolitik. Hiermit konnten bereits signifikante Verbesserungen erzielt werden, jedoch sind die verbleibenden Alarme nach wie vor allgegenwärtig hörbar. In dieser Dissertation wird untersucht, wie Patientenalarme designt werden sollten um Pflegekräfte persönlich und unaufdringlich zu alarmieren und dementsprechend die Geräuschbelastung auf Intensivstationen zu reduzieren. In partizipativen Designstudien wurden Alarmmuster für ein Head-mounted Display entworfen und geeignete Modalitäten innerhalb von Laborstudien mit Intensivpfleger/innen evaluiert, um so ein multimodales Alarmdesign für am Körper getragene Patientenmonitorsysteme abzuleiten. Die Ergebnisse zeigten, dass für eine Kurzzeitnutzung die persönliche Alarmierung im Vergleich zum State of the Art von den Pflegekräften bevorzugt wurde. Anhand der Ergebnisse konnte ein multimodales Alarmmuster abgeleitet werden, welches in einer Google Glass integriert wurde. Zur Bestätigung von Alarmen wurden erste berührungslose Interaktionsdesigns entworfen, die in einer Pilotstudie evaluiert wurden. Für anknüpfende Forschungsarbeiten bietet diese Arbeit Designrichtlinien zur Gestaltung körpergetragener Alarmsysteme.

Abstract

With the increasing development of biosensor technology and the associated possibilities of patient monitoring, the number of acoustic and visual alarms in intensive care units (ICU) is increasing as well. These alarms (about 250 per patient every day) are audible for every person in the intensive care unit and thus disturb both patients and staff. Each alarm must be analyzed and evaluated by the caregiver in charge of the cause and urgency of the alarm, which is 1) a high cognitive load and 2) the potential risk of alarm fatigue, desensitization and slower response time to alarms. The majority of scientific approaches aimed at reducing alarm fatigue focus on reducing the number of alarms. E.g., such as improved algorithms, intelligent alarm delays, and changes in overall workflow and alarm policy. Significant improvements have already been achieved, but the remaining alarms are still audible everywhere. This dissertation examines how patient alarms should be designed to alert nurses personally and unobtrusively, thus reducing noise exposure in intensive care units. In participative design studies, alarm patterns for a head-mounted display were designed and appropriate modalities within laboratory studies with ICUs were evaluated to derive a multimodal alarm design for bodyworn patient monitor systems. The results showed that for short-term use, personal alarms were often preferred by nurses compared to state alarms. Based on the results, a multimodal alarm pattern could be derived, which was integrated into a Google Glass. To confirm alarms, first touchless interaction designs were implemented, which were evaluated in a pilot study. For subsequent research, this thesis provides design guidelines for body-worn alarm systems.

Acknowledgments

At this point, I want to thank different people who supported me during my time as a PhD student. First of all, I want to thank my supervisors Susanne Boll and Wilko Heuten for guiding me back into the right direction. Their critical but most of all inspiring feedback helped me shaping the person I am today[1]. I appreciate the freedom you gave me during the whole time and I am thankful to be part of the coolest team ever!

Further, I want to thank my committee members Markus Löchtefeld, Andreas Hein, and Frerk Müller-von Aschwege who enabled me to conduct my defense virtually (despite the current circumstances). Markus, I hope, we can soon have a real life toast in Oldenburg.

Many thanks go to the AlarmRedux Research Group, especially Dirk Hüske-Kraus, Rainer Röhrig, and Mark Wilken for their help and feedback, but also to the teams of the Uniklinikum Gießen Marburg and Klinikum Oldenburg, who spent their valuable time to serve as participants in my studies. Without you, this work would not have been possible.

Thanks as well to the best colleagues I could imagine: The PIZ-Team with Tobias Krahn, Christian Kowalski, and Pascal Gliesche and the whole INS-Team, especially Tim Stratmann, Uwe Grünefeld, Heiko Müller, Shadan Sadeghian Borojeni, Jutta Fortmann, Andrii Matviienko, Lars Prädel, Abdallah El Ali, Swamy Ananthanarayan, and Torben Wallbaum. Furthermore, I am thankful for having been able to supervise these excellent students who supported me a lot: Clarissa Sielemann, Bastian Erhardt, Hannah Meyer, Thomas Neemann, Steffen Busse, Rabea Müller, and Tobias Lunte.

For their help, but also emotional support, I want to thank my closest friends Sebastian Weiß, Erika Root, Stefan Oehmcke, Alex Erlemann, Gerrit Apeler, Dirk Pippich, Julia Dutt, and Katinka Hoppe.

Finally, I want to thank my whole family, starting with my sister at heart, Jasmin Remmers, and my cute little Sophie. Of course, I would also like to thank the Seifenclan including Ulrike, Rolf, Janna, and Morten, but most of all my partner in crime and best friend Henrik Seifert (and Arti). Thanks for enduring my moods and supporting me during the stressed times.

And last but not least, I want to thank my parents Conrad and Christel Cobus, as well as my sister Cosima Cobus who unconditionally loved and supported me, even though it might have been hard sometimes. I would not be where I am today without you.

[1] Sometimes one just need a small kick in the b***.

Contents

"And there is no quiet there, nor silence."

Edgar Allan Poe, Silence (1837)

1 Introduction

Intensive care units (ICU) are special hospital departments that cater patients who either recover from major surgical procedures, or suffer from severe and even potentially life-threatening illnesses or injuries. Persons in such a critical condition, who may also rely on respiratory, cardiac or other life support, require an uninterrupted monitoring. Therefore, ICUs are equipped with highly sophisticated technical systems and devices for patient monitoring. These medical devices issue visual and acoustic alarms, each of which has an individual sound, with the pitch and frequency of the sounds increasing with the priority of the alarm.

Figure 1.1: Technical devices trigger more than 300 alarms per patient every day. [RHK12, SFA19]

Research has shown that the number of alarms can rise to up to 350 per patient a day [RHK12]. Since most ICUs foster a ubiquitously audible alarm distribution, each of these alarms sounds from a central working and monitoring station and, depending on the local alarm policy within the hospital, also from the patient‘s room – audible for every person in the ICU but difficult for the source to be identified [Blo08]. An alarm can be triggered by various reasons, e.g., if a threshold exceeds a predefined value, but also if a sensor was accidentally was displaced. Therefore, each alarm needs to be evaluated individually by the responsible nurse. The majority of the issued alarms, however, require no intervention from the other nurses and distract them from their current task. In addition to the unnecessarily increased cognitive workload, the high number of alarms results in desensitization and lower response time of healthcare professionals. This condition is called alarm fatigue [RHK12]. Alarm fatigue may have severe consequences not only for the patients but also for the healthcare professionals. Staff involved in a negative

patient event (e.g., due to a missed alarm) can suffer from trauma called "second victim syndrome," when the person who feels responsible for the failure suffers from guilt and depression, perhaps even occupational disability [Gri14].

Possible reasons for the high number of alarms and thus, the resulting alarm fatigue are, e.g., the use of default values for alarm thresholds. Default values can cause many unnecessary alarms by signaling that a vital data point exceeds the threshold but does not pose a threat for the patient). Other reasons may include inadequate use of electrodes or sensors, which can cause false alarms by e.g., falling off or disconnecting [WHKK+17]. Using smart alarm-delay algorithms, daily electrode changes, or alarm management education already shows positive effects in reducing the number of unnecessary alarms [WCB+18]. The remaining unnecessary alarms, however, are still audible for every person in the ICU, distracting both patients and nurses.

Though it also showed significant improvements for the nursing staff, only very few research investigated the personal distribution of alarms as alternative to the ubiquitous distribution [CFDS14]. A body-worn device, for example, can allow just the responsible nurse to receive the alarm. This would reduce the number of acoustic alarms for each nurse. Moreover, we assume that audible alarms can also be conveyed reliably via silent modalities. Previous work in several domains has shown success using visual or tactile alerts [AVSC06, CPL+06, LS10, MRC+15]. However, the focus is rarely on nurses who are exposed to the alarm load for the entire shift[CFDS14, KGS+19]. Specific design guidelines for wearable, multimodal alarm distribution systems are needed, to reduce the alarm load for both, healthcare professionals and patients.

In our work, we aim to fill this gap. In cooperation with nurses, we investigate the suitability of light, vibration, and unobtrusive sound for critical care alarms using a wearable alarm system (WAS) in the form of a head-mounted display (HMD). We designed noiseless alarms and evaluated them including the WAS with the target group in a simulated ICU setting. The results of this thesis contribute to the question how alarm systems should be designed for safety critical environments in which the user is exposed to physical, cognitive and precision demanding loads.

1.1 Challenges

In the previous section, we described an acute alarm problem that affects each person staying on an ICU. The loud alarms are disturbing due to their ubiquity, which can affect the recovery process of patients. however, the majority of them are justifiable and it can be life-critical if they are not noticed. For this reason, it is necessary to find an alternative that allows the alarms to be kept away from patients but still reach nurses at all times. One approach to implement this is to bring the alarms directly to the nurses via body-worn (wearable) systems. In

general, developing a wearable system that is accepted by the user, so that s/he is willing to wear it voluntarily is challenging. A well designed usability and user experience plays a prominent role, but also and especially the comfort factor is important for wearable computers. However, an ICU provides further challenging requirements that needs to be considered. One prominent example is that nurses are not allowed to wear any jewelry (or devices) on their lower arms or in a region which may affect the safety of themselves or their patient during care.

This means that common design recommendations for wearable systems [GKS+98] cannot be adopted as they are, but need to be extended. Therefore, we have to work in close cooperation with the actual users, nurses. This provides the overarching challenge, since there is a recent nursing shortage that makes them a rare and expensive resource [BRP+11, LCW17].

In the following, we describe three key challenges which need to be addressed to develop an alarm system for nurses in ICU.

Integrability into the Nursing Workflow

The tasks of a nurse are highly demanding in several ways. To be integrable into the nursing workflow, during the whole process of development and evaluation, the concrete task loads of a nurse must be taken into account. This includes also the comfort factor. Since nurses need to be frequently available for changes in the patients' health status, the comfort of a wearable system needs to be assured. The challenge is, to comply those factors without breaking the strict safety and hygienic regularities.

Information Representation

The role of an alarm system is to notify nurses about potentially life threatening changes in the health status of their patient or technical defects of the sensors. For such safety critical information, it is important to present it fast and easily identifiable and unambiguously interpretable [TO07]. The design of the information representation must be appropriate to the respective urgency it shall represent. Finally, the information needs to be perceivable but not too distracting from critical tasks nor for patients or colleagues. All these factors must also comply with 1.1.

Interaction Design

Another challenge is to design a suitable interaction method for the user with the system. Therefore, it needs to be explored which inputs are actually needed, first. To comply with nursing tasks, the interaction with the system should happen touch-free. This does also avoid a risk of cross-contermination due to germs on the hands. Also for the interaction design, 1.1 must be considered, especially the

execution of the input during physical demanding (e.g., mobilization) or social (e.g., conversation with relatives) tasks.

1.2 Research Questions and Contribution

The described challenges led us to three key research questions, we explored within this thesis.

RQ1 What constitutes the design space for wearable alarm systems for critical care?

RQ2 How must noiseless alarms be designed to alert with different levels of urgency?

RQ3 Which interaction method for alarm systems is suitable for nursing tasks in ICU?

In the following, we describe these questions in detail and summarize our contribution to research.

1.2.1 RQ1: What constitutes the design space for wearable alarm systems for critical care

To develop a system which is worn by nurses throughout the whole shift, we need to explore and define the design space for wearable alarm systems. Therefore, requirements must be derived, which combine safety and hygienic regularities with the nurses concrete needs and demands, but which are are also compatible with nursing tasks.

Therefore, we did a literature analysis, first. To explore deviations from the literature, we did a shadowing session for a whole early shift on an aesthetic ICU. Additionally, we did semi-structured context interviews with ICU nurses of different experience, to answer open questions that arouse during the shadowing session. The results of these analysis, helped us shaping first ideas for a new approach to distribute alarms. To concretize our ideas, we conducted expert group discussions with different stake holders from different ICUs.

There are several ways to forward alarms via a wearable device to the responsible nurse, but some not each modality nor each body location is suitable to be integrable into the nursing workflow. Based on the results of our analysis, we shaped the design space for wearable alarm systems.

We found that body parts permitted according to safety guidelines are not consequently also suitable body parts for the attachment of a WAS. As a contribution, we gave a rating for body positions as guidelines for future investigations. Moreover, we justify suitable modalities to represent personal alarms.

1.2.2 RQ2: How must noiseless alarms be designed to alert with different levels of urgency

To reduce the acoustic alarm load on ICUs, we aim to design alarms are not audible for surrounding people (colleagues, patients, relatives). Therefore, different modalities are feasible. Based on our requirements, and thus, the defined design space, we focused on the audible, tactile and visual channel. In several user studies, we designed and evaluated noiseless alarms under nursing task conditions.

For the audible channel, the alarm patterns were already predefined and well established. Therefore, we needed to investigate a medium to replace the the obtrusive method. We found, that bone-conduction speakers are a suitable alternative for ubiquitous alarm distribution.

For the tactile and visual channel, alarm patterns needed to be designed to convey three different levels of urgency. Highly important was that the patterns needed to be clearly identifiable, easily distinguishable, well perceivable without being too distracting. All factors must apply during nursing specific loads. We found suitable peripheral light and vibration patterns that were implemented in a head-mounted display.

In an evaluation with the target group, our noiseless alarms were found to be more suitable than the state of the art. Based on the error rate, reaction time, qualitative feedback, as well as the perceived suitability, comfort and usability rating, we could derive a multimodal alarm design that consists of an audible-visual pattern for critical alarms and only visual patterns for non-critical, or technical alarms. The vibration patterns turned out to be not suitable to be conveyed to the head. However, our prior study showed that they perform well on the upper arms.

We validated the suitability of peripheral light and audible alarms in a further study, in which we integrated them into AR-glasses. As a proof of concept, we evaluated the readability of textual information, displayed on a near-eye display, in combination with our noiseless alarm design. From the results we could conclude that light alarms have an influence on the readability of the display, however, the readability was still well. Moreover, the prototype has shown a high comfort during nursing specific loads, which let us assume that it might be also wearable in a longer term.

Overall, we contribute with a noiseless alarm design, which alerts unobtrusively via audible and peripheral visual alarms. This design is compatible with near-eye displays to show alarm relevant information, e.g., the relevant patient, and the alarm causes.
Moreover, we provide vibrotactile ICU alarms, which not might be suitable for head-worn devices, but perform well on the upper arms and might be suitable for other body parts.

1.2.3 RQ3: Which interaction methods for alarm systems are suitable for nursing tasks in ICU

Another issue we addressed in this thesis is the interaction with the alarms. Commonly, nurses acknowledge alarms via a touch input on the patient monitor. This provides the risk of cross contermination. The risk of an infection is even higher, when the touch input takes place close to the face. For this reason, a touchless interaction method for the alarm system needs to be designed. Touchless interactions were already designed and explored for different domains. However, the nursing workflow provides several constraints which are not addressed, yet.

Therefore, we started our investigations with a literature research, followed by a brainstorming session with user experience experts. We collected multiple touchless interaction variants, and their pros and cons in regard to the executability during typical nursing tasks. Afterwards, we conducted a semi-structured interview with nurses to focus on one specific input, first. In a first study, we evaluated the feasibility of head, shoulder and foot gestures to acknowledge an alarm during physically demanding tasks. Our results indicate that feet interactions are a promising approach to follow for a touchfree alarm acknowledgement.

1.3 Scientific Approach

Especially for safety critical systems it is important to address the users' concrete needs and requirements to develop a system with a high usability to be accepted, and used voluntarily. Therefore, the human-centered design process (HCD) is defined in ISO standard 9241-210 [Int19]. This standard describes an iterative design approach which involves the user in each part of the development. Based on fundamental context and requirements analysis for the planned interactive system, first design solutions are implemented and finally evaluated with the target group. An overview of the process can be seen in Fig. 1.2.

Analogously, there is an international standard for application of usability engineering to medical devices, defined in IEC 62366 [Com15].

There are two main differences between those standards.
1. ISO 9241 provides very concrete design guidelines for interactive systems which are demanded in IEC 62366.
2. However, in contrast to ISO 9241, IEC 62366 considers the aspect of risk management or the safety of users and patients.

Since we are doing fundamental research in which we aim to investigate research questions along research prototypes, we focus on the design and usability of a wearable alarm distribution system and follow the HCD. This does also mean, we will not evaluate our findings in the field to ensure the safety of the patients. However, for future states of development, following the IEC 62366 should be considered.

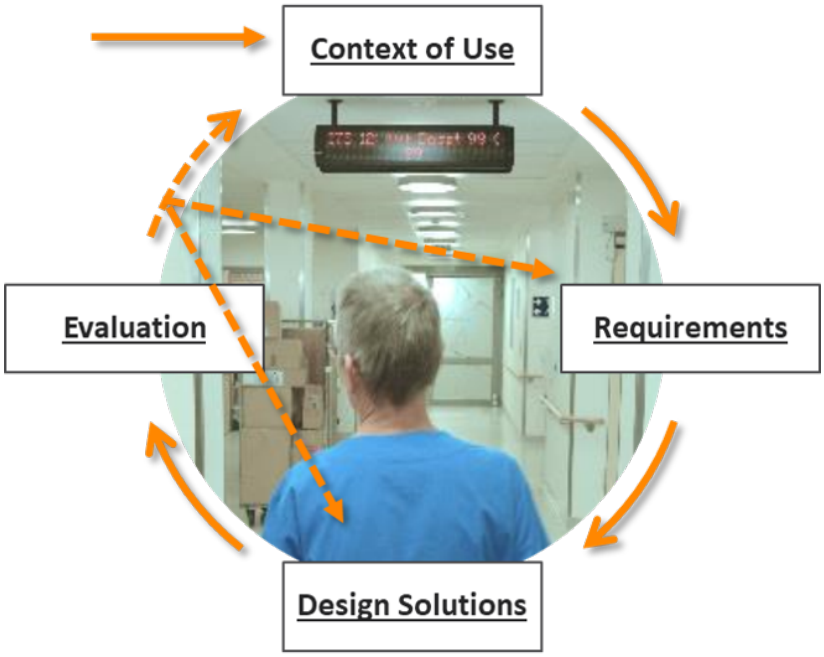

Figure 1.2: The Human-Centered Design Process [Int19]. [Cob19]

There are several methods to include the user within the different stages of the development. In the following, we describe those methods, we used within the different steps of the HCD [SC17].

1.3.1 Analyzing the Context of Use and Requirements

The context of use describes the conditions, in which the system will be used. This includes the actual users, their tasks and tools which are also used, and their social, but also technical and physical environment. Closely related to this are the user requirements, some of which arise from the context.

There is lot of literature for nursing training which let us explore this context superficially. However, each ICU has its own policy regarding alarm, nursing, and team management. This also applies to dealing with special situations, which need to be identified.

Therefore, we have carried out ethnographic studies in order to include such processes in our planning.

1.3.2 Brainstorming

A brainstorming session [Raw17] is a method, to create new and unusual ideas within a group of participants. Therefore, a the participants will be confronted with the problem and shall create ideas to solve this problem. A brainstorming session starts with the motto "Quantity breeds quality", this means, possibly many ideas should be collected, combined and improved. In the final state, these ideas should be sorted and rated. We used this method to find new interaction methods for wearable alarm systems.

1.3.2.1 Shadowing

Shadowing is a technique that is widely implemented in user research. The idea is to accompany the user and observes how they act in the field, or in later states of development, how they use they product or service within their natural environment.

The benefit from shadowing is, that e.g., unplanned events can be observed and thus, also deviations from standards in nursing processes that should be considered for the design process.

There are several ways to collect data from a shadowing. The best and most efficient method is to implement sensors, cameras, or microphones. In our case, we had to stay with the analogous way and write down our notes via pen and paper.

1.3.2.2 Semi-Structured Interviews

We conducted semi-structures interviews with ICU-nurses and physicians to explore their concrete needs. This is an interview, which is supported by guiding questions. Such a conversation allows information to be obtained on previously defined partial questions and offers a certain amount of freedom. This makes it possible that aspects, which the interviewer may not have considered so far, can be addressed by the experts during the interview [Weß].

1.3.2.3 Expert Discussions/Focus Groups

Another method we used in our initial analysis phase, were expert discussions. Expert discussions, or also focus groups are guided but open discussions with mainly six to twelve participants which are conducted mainly in early states of development. It serves to create first ideas, or concepts, or gather requirements for a planned system.

1.3.3 Create Design Solutions

In this phase, concrete concepts for the final system will be created which can then be evaluated by the user.

1.3.3.1 Prototyping

Developing high functional products is expensive. Therefore, the first ideas and concepts should be implemented in non-, or later, in semi-functional prototypes. They help to evaluate the concepts and ideas with the target group.

Prototypes can be build in several fidelities, depending on the state of development. They should be easy to build, to fix, and to improve.

In our research, we used lower fidelity semi-functional prototypes to design and evaluate our alarm designs, and touch-free interaction concepts. Moreover, we created a high fidelity prototype to evaluate the integrability of these alarms with a near-eye display.

In our research, however, we will not go beyond the status of the prototype as they serve to answer fundamental research questions and a product also requires the lengthy process of certification for medical devices.

1.3.3.2 Participatory Design

Another method we used in our design process, was the participatory design. In participatory design, the designers and users work together to develop a concrete idea, or concept.

The advantage is, that the user's unbiased point of view, and experience are brought directly into the design.

1.3.4 Evaluation

Our concepts were evaluated with participants outside the target group, in early states, where no expertise was needed, and finally, with the actual users. Therefore, we conducted several comparative within-subject studies, in which a participant had to perform tasks which mimic the task loads of a nurse as a prime task. Meanwhile, we presented our design solutions on our prototypes, s/he had to evaluate. This procedure helped us, to improve our ideas and bring the findings to an evaluation with the target group.

To answer our research questions, qualitative and quantitative data were collected.

1.3.4.1 Quantitative Data

Safety-critical systems are characterized by the fact that a failure or an error in their use leads to loss of life, significant property damage or damage to the environment [Kni02].

Therefore, in our studies, we focused on measuring the error rate and the reaction time as quantitative data. This helped to compare the quality of our concepts against the state of the art. Additionally, we used standardized questionnaires, e.g., the System Usability Scale (SUS) [Bro96] to measure the usability of an interactive system, the Comfort Rating Scale (CRS) [KB05], which serves to develop the comfort of wearable computers, and the Raw TLX [HCG+11], to measure the cognitive and physical task load.

1.3.4.2 Qualitative Data

Since quantitatively good results does not ensure that a system is user friendly, we also collected qualitative data. Therefore, we used the thinking aloud protocol [Jää10], which means, that the participants were asked to speak their thoughts out loud during the whole study. Since the quantity and quality of the results depends on the participants character and willingness to communicate, we also conducted semi-structured interviews at the end of the study, to find out possible improvements.

1.4 Thesis Outline

This thesis consists of overall nine chapters. The structure is visualized in Fig. 1.3. The first two chapters cover the introduction to the problem and relevant background information for the research presented in this thesis. Chapter 3 to 8 describe the user studies we have conducted to answer our research questions. In the last chapter, we discuss our findings and contributions to the research questions, and provide suggestions for future research.

In the first chapter, we introduced the research topic and the problem that we have addressed in this thesis. Subsequently, we gave a description of the challenges, the topic provides and our research questions and contributions towards these challenges. Finally, we presented our scientific approach and name methods we used to answer the research questions.

Chapter 2 gives a detailed overview of the necessary background information of this research. We start with a general explanation of ICUs, specific regularities and nursing workflows, followed by the description of patient monitoring systems and their alarms. We continue with the psychological perception of alarms and effects of distractions through patient alarms. Finally, we provided related work that addresses the alarm problem on ICUs and point out the gap we address.

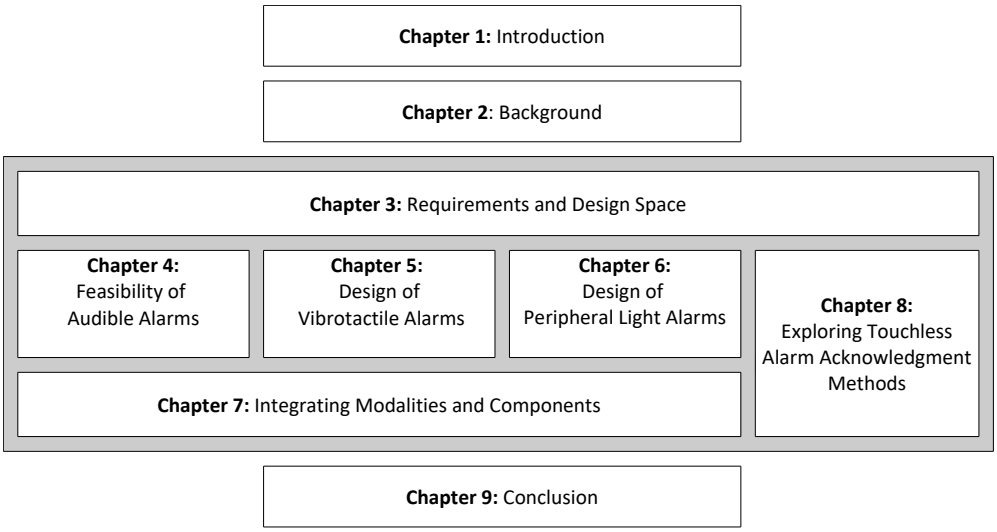

Figure 1.3: Outline of the thesis: Chapter 1 and 2 cover the introduction and background, Chapters 3 to 8 present the studies conducted to answer the research questions RQ1 - RQ3. Chapter 9 provides the discussion of the results and contribution, and highlight potentials for future work.

Chapter 3 covers the user requirements and design space for wearable alarm systems. First, we summarize our shadowing session in a ICU, followed by expert discussions to concretize first ideas. Afterwards, we sum up the derived requirements for a wearable alarm system. We then, end up with the definition of our design space for multimodal, wearable alarm systems (RQ1).

Chapter 4 focuses on auditory alarms. First, we present relevant background information about auditory perception. Afterwards, we describe a lab study to explore the feasibility of audible alarms during nursing tasks to address RQ2. Our presented findings indicate that audible alarms conveyed via bone-conduction speakers can compete with speakers, the common way of alarm transmission.

In Chapter 5, we describe the design and evaluation of vibrotactile alarms to address RQ1 and RQ2. We start this chapter with the description of the tactile perception, followed by related work that helped us shaping our alarm patterns. The study itself consisted of two parts. Based on the results of the first study, we could find two suitable sets of vibration patterns that represent three levels of urgency. These patterns were evaluated in a second study with nursed during physically demanding tasks. This study has shown performing a primary task had a strong influence on the perceivability, and thus, the distinguishability of the alarms. However, the design with an increasing number of vibrations for increasing priority has performed with a low error rate and reaction time. We suggest these patterns to represent vibrotactile alarms on WAS.

In Chapter 6, we present the design and evaluation of peripheral light alarms to address RQ2. This chapter begins with the explanation of visual perception and related work that had shown success in representing information with peripheral light. From a first study, in which we presented light patterns from prior work [MCM+15] on a HMD under physically and cognitively demanding task conditions, we learned that light patterns needed to be redesigned to represent three different, well distinguishable urgency levels. Therefore, we did a second, participatory design study in which we found five light patterns for each urgency level. We evaluated the light patterns in a third study, during precision demanding tasks. From the results, we could derive an alarm design, we suggest to represent peripheral light alarms.

In Chapter 7, we describe the process of deriving a multimodal alarm design and its integration into a Google Glass Enterprise Edition (RQ1, RQ2). We conducted a competitive study with nurses under cognitively, physically and precision demanding tasks. Our results indicated that noiseless alarms conveyed via a head-mounted display performed better than speakers regarding suitability and feasibility, annoyance level, error rate, response time. Based on the qualitative feedback, we derived a multimodal alarm design for HMDs, which was implemented on a Google Glass. The choice of hardware was based on expert interviews. In a further study, we found that peripheral light alarms influence the readability of a near-eye-display. However, the readability of the display, and the alarms' identifiability and distraction, were still rated as good. Finally, our prototype was rated as comfortable, thus we assume that such a system might be also wearable in a longer term.

Chapter 8 focuses on touchfree interaction methods for the medical context (RQ1,RQ3). The chapter starts with related work that address this topic. From a brainstorming with user experience experts, we derived a list of interaction methods to interact with patient alarms. We provide pros and cons with focus on the compatibility with nursing tasks. Based on an expert interview, we implemented a gesture based alarm acknowledgment to evaluate the suitability of head, shoulders and feet as input methods during physically demanding tasks. Our findings indicate that feet show potential to be investigated in the depth.

We conclude this thesis in Chapter 9, where we highlight our key contributions to answer our research questions RQ1 - RQ3, point out important limitations and give suggestions for future work in the field of multimodal alarms in safety critical environments.

1.5 Publications

Excerpts of this work have been published in peer-reviewed scientific conferences and journals. In the following we list all core publications, ordered by their

publication date in descending order. Additionally, we provide references to these publications at the beginning of the respective chapters.

- Cobus, Vanessa ; Busse, Steffen ; Heuten, Wilko: Glass++ Evaluating Multimodal Alarms on Google Glass. In: *Mensch & Computer*, GI / ACM, 2019, S. 795–799
- Cobus, Vanessa ; Busse, Steffen ; Heuten, Wilko: Integration of multimodal alarms into Google Glass: demo. In: *PerDis*, ACM, 2019, S. 36:1–36:2
- Cobus, Vanessa ; Heuten, Wilko: To Beep or Not to Beep? Evaluating Modalities for Multimodal ICU Alarms. In: *Multimodal Technologies and Interaction* 3 (2019), Nr. 1. `http://dx.doi.org/10.3390/mti3010015`. – DOI 10.3390/mti3010015. – ISSN 2414–4088
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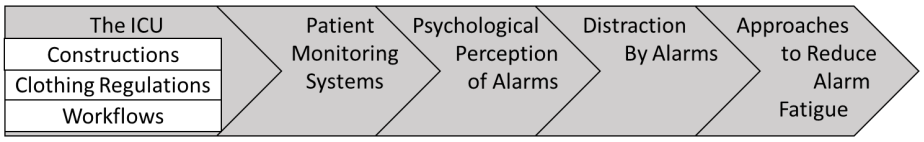
2 Background

In the following, we outline the background of this thesis, including the basic knowledge of an intensive care unit including the construction of ICUs, clothing regulations, and nursing workflows, followed by the special feature of ICUs, the continuously patient monitoring, and finally causes and effects patient alarm alarms as well as approaches to reduce the alarm load.



2.1 The Intensive Care Unit

2.1.1 Construction of Intensive Care Units

Different than in usual hospital wards, patients with severe and life threatening illnesses and injuries who are often in an unstable condition are treated in special hospital departments called monitoring units. In Germany, they are divided into "Inter Mediate Care" unit (IMC) and Intensive Care Unit (ICU). Patients in IMCs have no more need for complex intensive care, but are are still subject to monitoring. Their condition requires care on a level between a normal ward and an ICU. Therefore, the IMC is commonly located close to the ICU and the nursing staff work closely cooperatively. ICUs, on the other hand, offer patients the maximum possible medical and nursing care. For that reason, there is a central monitoring station and working place in the center of the ward, from where nurses should always have a view of the patient (e.g. through a window in the patient's room). Additionally to the monitoring, this place serves for nursing documentation and other organizational tasks. A sterile room where consumables, medication, blood and blood products, and care materials can be stored, as well as a non-sterile room with fecal and hygiene sinks for fecal and waste collection systems should also be in the immediate vicinity of the patient rooms.

Furthermore, an intensive care unit should have the following rooms: An equipment room, a ward physician workstation with access to all patient data, a senior physician room, an office for ward management, a conference room with connection to the monitoring system, space for private belongings and a lockable cabinet for patients' valuables, a conference room for conversations with relatives, a staff lounge, a ward kitchen, and toilets for staff.

The patient rooms are either double or single bed rooms, whereas double bed rooms must have a privacy screen between the patients. The single patient rooms usually serves for infectious patients. Therefore, they must be equipped with a

sluice or an anteroom in which care materials and protective clothing are stored. Moreover, each patient room should have a workstation with integrated hygiene sink, disinfectant dispenser and waste bin. The size of a room should be at least $40m^2$ for double and $25m^2$ for single patient rooms (see Fig. 2.1).

Figure 2.1: Empty patient room. [Cob19]

The German interdisciplinary association for intensive and emergency medicine[1] (DIVI) [JKK+10] recommends 8 to 12 beds and therefore treatment places for an ICU to ensure appropriate patient treatment.

Each bed must be accessible from four sides and hydraulically adjustable. It is basically equipped with oxygen, compressed air, ventilation, and monitors.

These monitoring systems ensure a continuous observation of the patients health status and notify the staff with audible and visual alarms in case of changes.

Fig. 2.2 shows the overall structure of a typical ICU. Alarms that occur from a patients room are audible on the whole ICU. In general, nurses are assigned to patients that are locally close to each other so they can easily localize their patients' alarm. However, in some cases, this is not possible which may cause

[1] Translated from German: Deutsche Interdisziplinäre Vereinigung für Intensiv- und Notfallmedizin

longer distances to walk, and moreover, a higher load to identify and localize the alarm.

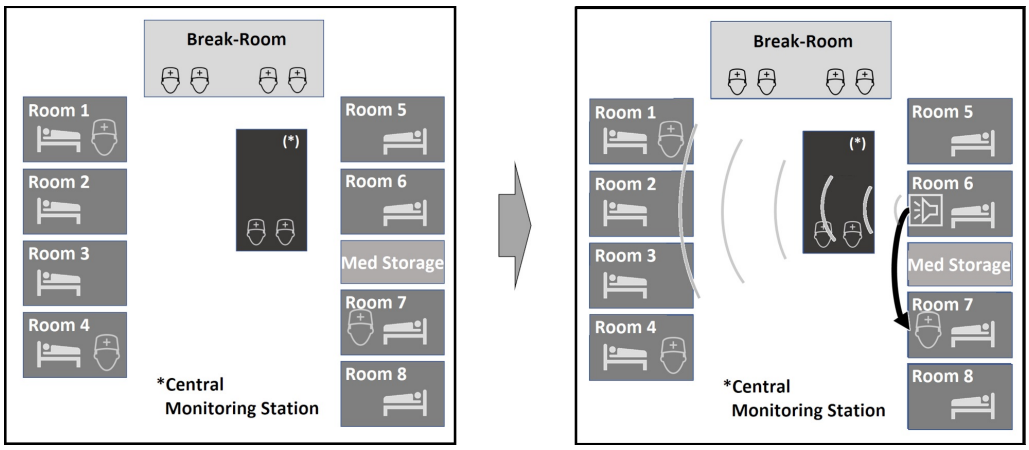


Figure 2.2: A typical ICU structure and its disadvantage.

The consequences of these alarms will be described in Sec. 2.2.

2.1.2 Clothing Regulations for Safety and Hygiene

The clothing worn by medical staff in German hospitals serves to protect nurses private clothing. Basically, it is a short-sleeved casack: a closed short-sleeved shirt with an overlapped V-neck, one breast pocket and two side pockets, as well as matching trousers which will be worn throughout the whole shift (see Fig. 2.3). Additionally, medical staff needs to wear thin and liquid-tight gloves to avoid getting in touch with body fluids, secretions and excreta. For i.a. ICUs, there is a specific color coded department restrictive clothing [KW08].

The work clothing has no specific protective function for the medical staff or the patient. Since nursing means a high physical load that requires walking and standing for long periods, the work shoes be comfortable, slip-resistant, but also disinfectable.

For quarantine rooms of patients with resistant germs, there is also protective clothing that serves to protect the work clothing from contamination. Commonly, this is disposable clothing which is disposed after leaving the quarantine room (ideally in a sluice) [BDG97]. In certain situations, the clothing should be changed immediately, e.g., during invasive procedures, for immunosuppressed patients, as part of standard hygiene, when staff are expected to come into contact with body fluids, secretions and excreta, or when a patient is isolated from contact with an epidemiologically relevant pathogen [KW08].

Figure 2.3: Work clothing of an ICU nurse. [Cob19]

The ICU-clothing has to be changed daily or immediately in case of contamination. It is cleaned by proven effective disinfectant washing procedures [Nus09].

The employer must provide a sufficient number of work and protective clothing. It must also be ensured that in areas with an increased risk of infection, which includes intensive care units, medical staff are not allowed to wear jewellery such as watches and wedding rings on their hands and forearms [BDG97].

This is an important factor for developing wearable systems for ICU.

2.1.3 Workflows in ICUs

People who work in ICU that are affected by the noisy environment are medical, nursing, and other staff which includes e.g., physical therapists, or cleaning personnel.

A physician with further training to intensive care physician needs to manage an ICU. S/he has to work full-time on the ward but is released from patient care due to his or her supervisory and management tasks. One more intensive care physician should be permanently present or available in the ICU per shift.

The length of stay in the intensive care unit per shift, and thus, the exposure through noises, as well as the patient contact is longer for nurses than for medical and other staff. Therefore, we focus on the nursing staff as target group. The nursing staff in the intensive care unit per shift essentially consists of one nurse with qualifications in anaesthesia and intensive therapy in a nursing management

position and nurses for patient care, of whom at least 30% should be further trained ICU nurses [Fre, LMW12]. For the treatment of patients in ICUs, wide-ranging knowledge and skills in the field of intensive care are required. The additional skills can be acquired through appropriate intensive care further training and courses of study.

Nurses' work in hospitals is divided into different shifts per day, early, day and night shift. Between the shifts, there is a general handover in which the staff informs the next shift about the status of the patients, particularities and upcoming treatments or interventions. Afterwards there is a detailed handover for each patient from nurse to nurse. Each shift starts officially with a routine check and includes meal preparations, preparation and application of medication, and documentation. Moreover, new patients are admitted or the transfer of patients is prepared.

The early shift stands out from the others insofar as, in addition to the morning blood collection, an extensive body care, dressing changes and patient mobilization are also carried out. These tasks are carried out in the other shifts only as required. Independent of the patient's health status, the nurse talks to the patient to calm him down, as soon as s/he enters the room. Moreover, s/he explains each step s/he makes while nursing.

In the overlapping time between the early and the day shift, the patient visit with the treating physician or interventions take place. [Kli16]

In addition to nursing care, the essential task in intensive care is the continuous all-embracing monitoring of the patient's condition in order to be able to immediately react to corresponding changes. Therefore, the vital parameters are closely monitored by nursing staff and patient monitors which are described Section 2.2.

2.2 Patient Monitoring Systems

To ensure an uninterrupted monitoring, multiple sensors are attached to a patient and connected to a patient monitoring system.

For each physiological parameter, upper and lower thresholds can be set (see Fig. 2.4), which are continuously displayed on the monitor in the standard display next to the numerical value of the parameter (see Fig. 2.5).

Figure 2.4: A nurse adjusting alarm thresholds. [Cob19]

These monitors display the following information for each patient:

Oxygen saturation (SaO_2): Peripheral SaO_2 and heart rate are measured using pulse oximeters.

Blood pressure (RR) and mean pressure: Both values are displayed on the monitor. The mean pressure gives information about the peripheral blood circulation.

Heart rate (HR): Derivation via electrocardiography (ECG) cable or pulse oximeter.

Temperature: Measuring probes can be anal, nasal or oral or are integrated into other systems (e.g. stomach probe).

Blood gases: Either peripheral (earlobe, finger) or arterial (arterial cannula). It provides regular values on blood pH, O_2 and CO_2concentration, SaO_2 electrolytes, blood sugar, lactate and others [Fre, JKK+10].

Fig. 2.5 shows a single patient view on the top and the multiple patient view on the bottom. In the multiple patient view, the healthcare professional can switch between the patients by tapping on the tabs.

If a threshold is exceeded or not reached, an alarm tone graded according to severity is usually triggered, based on IEC standard 60601-1-8. The pitch and frequency of the beeps increases with the priority of the alarm. This standard was

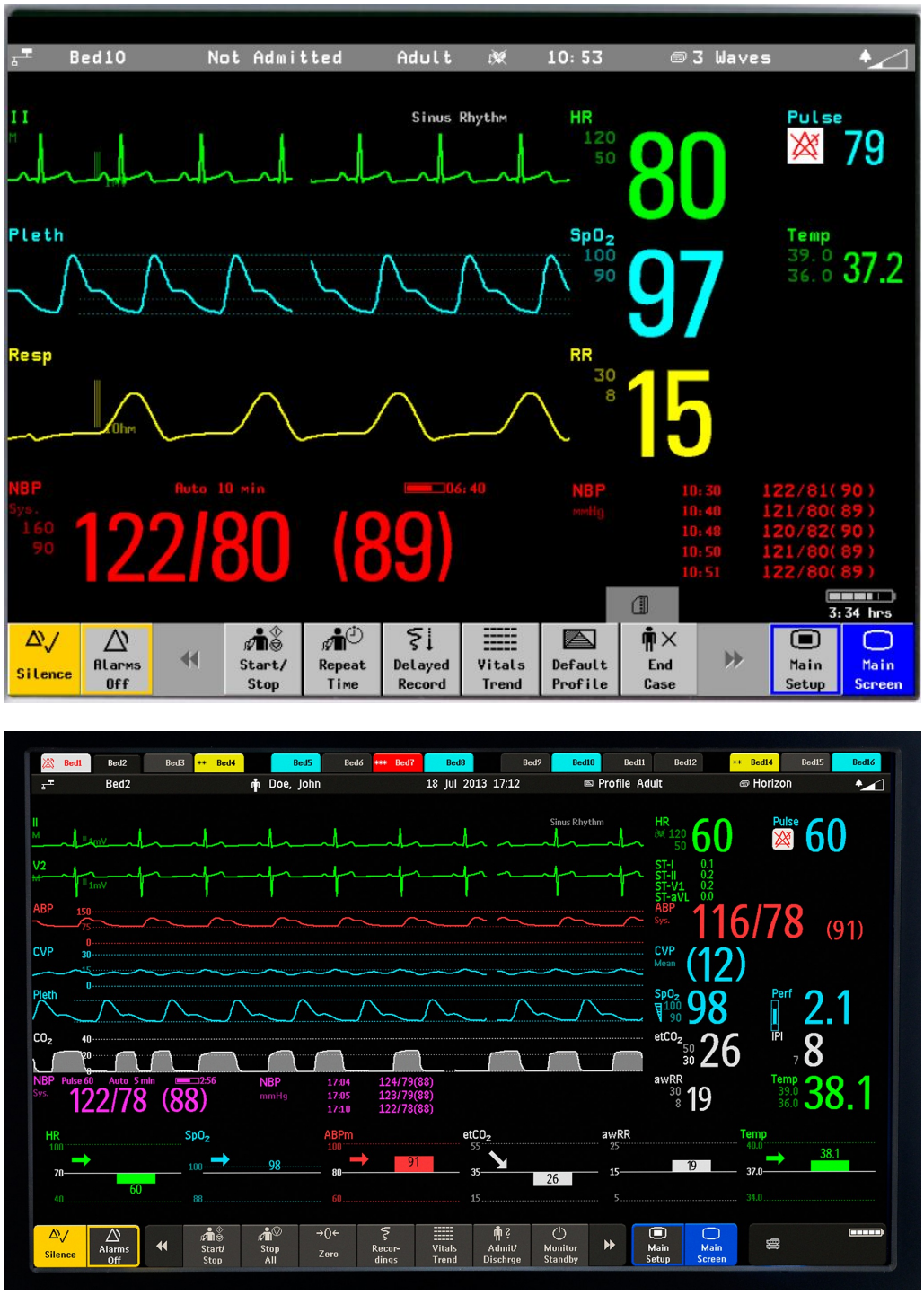


Figure 2.5: Patient monitor: Single vs. multiple patient view [Hea19, Phi19].

published in 2005 and ensures a unification for alarm sounds to reduce the risk of misinterpretation. In addition, a color-coded, graded alarm message appears on the screen and the numeric value that triggered the alarm flashes. A further signal are alarm lamps on the patient monitor, which signal a red or yellow alarm by flashing the corresponding colored alarm lamp.

These alarms are commonly divided into three categories:

Technical Alarm If a sensor is ripped off or cannot measure the data reliably, or if there is a malfunction of the device. The alarm source is commonly highlighted on the monitor display with a predefined color. In the case of a technical it is highlighted blue, so the technical alarm is also called "blue alarm".

Uncritical Alarm The uncritical, or "yellow alarms" are caused by exceeding a predefined threshold. This could be, e.g., lower blood pressure.

Critical Alarm A critical alarm indicates a potentially life threatening situation that requires immediate attention. The source is commonly highlighted red, so they are also called "red alarms".

If the patient monitor is connected to a central monitoring station via a network, the alarm is triggered at both the patient monitor and the information center. The alarm status of other patient monitors in a defined care group can also be displayed on each monitor within the care group [Phi16, GE 13, Dra13, Min10].

If more than one alarm is triggered at a time, all alarms will be displayed on the screen in an information area next to each other and sorted by priority. The alarm tone for the alarm with the highest priority also sounds.

To stop the noise, an alarm needs to be acknowledged and evaluated by the responsible nurse. In this case, the alarm message is ticked on the screen. Accordingly, s/he needs to decide, if and which interventions should take place. In each shift, nurses also have to acknowledge alarms from patients assigned to other colleagues. This needs to be communicated to the respective nurse. Additionally to the monitoring alarms, each device that is not connected to the monitoring system issues their own alarms.

2.3 Psychological Perception of Patient Alarms

An alarm system serves to quickly draw the attention of nursing staff to a technical problem or changes in the patient's condition. This section describes the human perception as well as methods to influence the perception and guide attention.

The human perception serves to inform us about our surrounding. Through five sensory channels (sight/vision, hearing/audition, touch/tactition, smell/olfaction, and taste/gustation), the body can absorb information, which is then processed and

interpreted. Meanwhile, interactive systems can communicate with all five sensory channels to guide the attention. In HCI, the mode of communication between an interactive system and one of the human senses is called "modality" [JS05].

Described by Michael Posner [Pos80] in 1980, the perception of a person can be influenced by endogenous and exogenous orientating, which means a guidance of the current focused attention. Endogenous orientating means the focused attention is allocated by the person's internal motivation and mood, e.g., goals, plans, expectations or emotions. The endogenous (intentional) orienting needs to be interpreted by the observer which means it directs the attention slowly and controlled but can also be ignored by the responsive person [Jon81]. E.g., the goal of a nurse is to care for their patient. If s/he is entering their patient's room to give a bed bath, and s/he would notice that the patient turned paler, she would also check (intentionally) his/her vital data.

In contrast, the exogenous orienting means the stimulus triggered allocation of attention by external events or changing environmental characteristics, such as unexpected interruptions or alarms.

However, exogenous factors can also influence behavior without gaining focused attention, e.g. if the signal is of low intensity or the focused attention is on the completion of a task. These factors are also referred to as preattentive reference, are perceived peripherally and are further trained by endogenous factors, e.g. a person can process the information faster and more accurately if he expects this information. The preattentive reference gains focused attention when, for example, the signal increases in strength or the competing task is completed. Finally, focused attention is used to monitor a system status or actions that affect the system status, and the output signals of the system status can lead back to exogenous or endogenous orientation. Penelope Sanderson [San06] visualized the control of attention through endogenous and exogenous orienting in a diagram (see Fig. 2.6).

An alarm device aims to quickly trigger the exogenous orienting process by alerting the user and the endogenous orienting process with alarm categories and additional, textual information which is needed to interpret and evaluate the alarm.

2.4 Distraction by Patient Alarms

Studies have shown that the number of alarms rises up to 350 per bed a day [RHK12].

The noise load is one reason that patients who stay in the ICU for longer time often suffer from post-traumatic stress syndrom. Moreover, the loud environment is known to increase the recovery time [KO12].

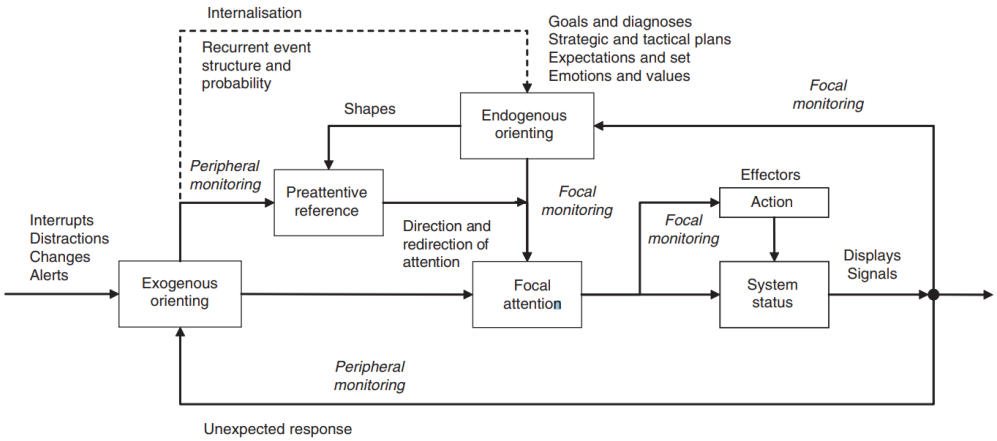


Figure 2.6: Guiding focused attention, model by Penelope Sanderson et al. [San06].

The majority of the issued alarms, however, require no intervention from the other nurses and distract them from their current task. In addition to the unnecessarily increased cognitive workload and interruptions, the high number of alarms lead to mistakes in the actual tasks.

A further consequence of the alarm load is a desensitization and lower response time of healthcare professionals. This condition is called alarm fatigue. This means, the medical staff, especially due to the high number of false alarms, no longer notices the alarms, registers them late or loses confidence in them and underestimates them [Cva12, RHK12]. The behavior to not pay attention to alarms which in the past proved to be false is called "Cry-Wolf effect" [Cva12].

Another cause of alarm fatigue is the difficulty for nurses in identifying the cause and severity of the alarm. As soon as an alarm is perceived as unimportant, there is a risk that it will simply be turned off, muted or ignored by medical staff. This leads to a potentially threatening situation for the patient. The US Food and Drug Administration, for example, reports 500 alarm deaths in intensive care units in the United States over a period of five years, and the number of uninvestigated cases is estimated even higher.

An associated risk factor is the second victim effect. Due to the aforementioned alarm fatigue, critical care nurses might miss an alarm which in the end leads to a critical, potentially fatal, situation for a patient. In addition to the tragedy for the patients themselves, this causes a severe second victim effect for the care takers [JT12].

Finally, it it points out that the high number of alarms and the resulting alarm fatigue has severe consequences for both, patients and healthcare professionals.

2.5 Approaches to Reduce Acoustic Alarms

With the intent to reduce alarm fatigue, many interventions have been evaluated so far [WCB+18]. These can be categorized into non-informatics and informatics approaches.

The non-informatics approaches focus on changes in the alarm- and ICU management policy. This includes the standardization of the use of patient monitors, e.g. with the introduction of alarm customization for each patient and alarm management education for the staff. But also simple solutions, e.g., daily electrode changes could improve the alarm situation and decrease the number of false alarms [BCBK+16, GC10, DDF+14].

The majority of the informatics approaches focused on the application of alarm suppression algorithms and alarm or notification delays. This approach could minimize, e.g., the number of alarms which were caused by oscillations of the vital data and normalize itself [ADSC17, KMN+15].

All of these interventions showed positive results in decreasing the number of alarms. However, the remaining alarms are still obtrusive and audible for every person in the ICU. As the nursing workflow includes moving frequently between patient rooms and other locations, an alternative promising approach is to forward alarms directly to responsible healthcare providers. One example system for this approach is a pager. The portable device notifies nurses and, especially, physicians about relevant changes in the health status of their patients with vibrotactile and audible cues. Maria M. Cvach et al. [CFDS14] developed a novel alarm escalation algorithm that distinguishes between a crisis and non-crisis condition of high priority alarms. If the first nurse does not react to a crisis alarm in a certain period of time, a second nurse will receive the alarm. Different from our alarm model, in the Cvach model the charge nurse will be notified if there is no reaction within 60 seconds. For a non-crisis alarm, the algorithm causes a delay before the first escalation step. That algorithm was implemented as a secondary alarm notification system on pagers and tested for six months on two surgical progressive care units. The approach significantly decreased the mean alarm frequency and duration on the participating ICUs and shows the importance of distributed alerts.

In 2014, Sandra Brander et al. developed a conceptual design of a mobile healthcare device to improve the information flow in hospitals by forwarding information to the responsible nurses [BSS14]. The device takes the form of a nurse watch with three buttons. One red button is supposed to trigger an emergency alarm, a yellow one to call for assistance, and a white one to mute or forward alarms. Similar to pagers, the system uses vibrotactile and audible cues to notify the user. Nurses from three hospitals were involved during the whole development process. This work shows requirements for a mobile healthcare device based on a user-centered approach. Although portable devices such as pagers or a nurse watch can improve the distribution of alarms in hospitals, they have the

disadvantage that they have to be put inside pockets. In stressful environments like ICUs this may result in hygienic issues and a thus provides the risk of a cross contermination. Moreover, as nursing tasks are often stressful and physically demanding, the vibrotactile signal may go undetected [CBM+87].

Avinash Konkani et al. [KOB12] name the following requirements for alarms: First, alarms should have clear characteristics; they should be easy to locate; they should differ from other alarms; they should be easy to learn and remember; they should not interfere with communication; and they should not be drowned out by other sounds. Finally, they see the need for the IEC standard to be modified. We want to address this by using more than just the acoustic channel to guide the nurses' attention.

A promising alternative to convey alarms is a head-mounted display (HMD). HMDs have shown success in continuously displaying information within the medical domain and subsequently raising the awareness of medical staff for their patients.

In 2015, Natalia Wrzesińska analyzed healthcare-related research which focussed on smart glasses [Wrz15]. This work points out that the majority of the current studies used Google Glass. One example is the work of Wolfgang Vorraber et al. [VVS+14], who did one of the first studies in this field. Via a Google Glass application, they monitored patient vital data during radiological interventions. Due to the reduction of head and neck movements toward the patient monitor, efficiency and awareness of the task could be improved. A more recent work that showed the potential of HMDs in healthcare was done by Pascale et al. [PSL+19]. They introduced Google Glass as a support to maintain nurses' awareness of their patients' health status without affecting their nursing task.

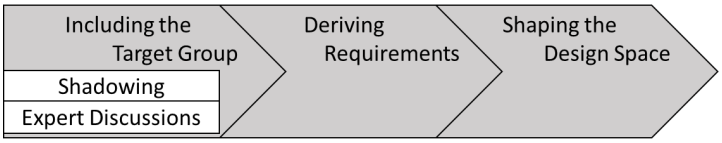
The mentioned works show that there is a high potential in using Google Glass to display patient information in healthcare, especially on ICUs. With a good readability and comfort, it is well integrable in the nursing workflow to improve nurses' awareness for their patients.

However, conveying alarms using HMDs is still unexplored. Literature shows still a gap of noiseless ICU alarms, we want to address.

In this thesis, we aimed to explore different modalities to convey patient alarms directly to the responsible nurse. For this reason, we developed a wearable alarm system. This may help to reduce 1) the general noise load on ICUs, and 2) the number of acoustic alarms, and thus, the risk for alarm fatigue.

3 Requirements, Alarm Distribution, and Design Space

To develop a system which supports ICU nurses, we needed to analyze the context of use, thus, the ICU, in depth. Therefore, we conducted an ethnographic study consisting mainly of two parts: a shadowing session in a surgical ICU with 13 beds and two group discussions with 4 and 3 healthcare professionals from different hospitals. Based on this, we derived requirements and shaped our detailed design space for a wearable alarm system.



Parts of this chapter were published in Cobus, Vanessa ; Boll, Suanne ; Heuten, Wilko: Requirements for a Wearable Alarm Distribution System in Intensive Care Units. In: *Zukunft der Pflege , Tagungsband der 1. Clusterkonferenz 2018 – Innovative Technologien für die Pflege*, oops, 2018 (ZdP '18). – ISBN 978–3–8142–2367–4, 185–189.

3.1 Shadowing on an ICU

In Chpt. 2, we described the formal regularities and workflows in ICUs. However, irregular situations may cause deviations from the standard processes so we worked in the morning shift on a local surgical ICU to explore differences from the literature. Therefore, we accompanied a nurse with 30 years of experience and supported her in caring tasks for her two patients.

3.1.1 Methodology and Preparation

As it was described in Sec. 1.3 of the first chapter, a shadowing session serves to accompany the target group or user and observe how they act in the field, or in later states of development, how they use they product or service within their natural environment [McD05]. This technique benefits from unplanned events that could be observed and thus, also deviations from standards in nursing processes that should be considered for the development of the WAS and planning further user studies. For this shadowing session, we visited a local surgical ICU with 13 beds. This required the permission of the head nurse. He was contacted before via e-mail in which we described our planned procedure in detail and afterwards we made an appointment. He advised to bring comfortable shoes and eat before

the shift, since the job is physically demanding and one has to walk and stand a lot.

A surgical ICU treats patients who came directly from a surgery until they will be relocated to a normal ward. This kind of ICU has the advantage that the patients with different conditions (stable, unstable, ventilated, conscious, unconscious, or in quarantine) will be treated, which means, several workflows can be observed. We were invited to observe the morning shift because it contains a variety of different activities and represents the diversity of tasks in nursing best (see Chapt. 2.

In a normal environment, shadowing sessions can be conducted using recording devices like cameras, microphones, or other sensors to gather data from the observed participants and analyze how they actually behave in their everyday life. Hospitals, especially ICUs are subject to strict safety and hygienic regularities, which makes it a time-consuming and laborious process to get a permission to bring self-developed sensors into the ward. The reason for this is that some devices may cause interferences with the infrastructure of the hospital which may result in the failure of a system.

Also video or audio recordings require the permission of a medical ethics board to assure the safety of the patient's health and privacy. This means, to implement a sensor device at the patient room doors which counts alarms and measures via NFC how often a nurse enters the respective room was not possible. Like suggested in the Guidelines for shadowing of Rebecca Gill et al. [GBD14], we used a hardback notebook and a well-writing pen to make a diary, to comply with the safety regularities and not cause any interference with technical devices. To not disturb the workflow, we were assigned to an experienced nurse who we accompanied through her morning shift who also invited us to perform all nursing tasks on our own.

Since the nursing tasks that were performed required in most cases both hands, notes were made just each hour in the break room and included the description of each task that was made and communications between the nurses. To avoid a cross-contamination, hands were disinfected before and after entering a room.

The ICU we observed was a project partner of the project "AlarmRedux"[1].

3.1.2 Procedure

We arrived 15 minutes before the shift started and were let into the locked ICU. The blue working clothes (see Fig. 2.3) were handed out and a rest room to dress was shown. After dressing, we were introduced to our the assigned nurse.

[1] AlarmRedux was a project funded by the BMBF (FKZ: 16SV7503) - `https://www.offis.de/en/offis/project/alarmredux.html`

The shift started at 06.00am with the general shift handover. This means the nurses of the prior shift reported the status of their supervised patients in the break room. Afterwards, the nurses divided up for the patients. Therefore, they chose (if possible) either patients they knew already, or patients whose beds were localized possibly close to each other. Generally it should be avoided to care for more than one patient who needs to be in an isolation room. The nurse we accompanied was assigned to two ventilated patients. One of them was in an isolation room due to a resistant germ. Next, there was a direct patient handover from the former responsible nurse who explained detailed information of the patient. At 07.00am, blood was taken, and the patient's vital data was documented. Then drugs were administered. The nursing documentation was repeated every hour. Afterwards, we started caring for the first patient. This includes washing, examining wires, tubes and the body, changing electrodes and mobilizing him. During the whole procedure, the nurse communicated every step to the patient. After the nursing documentation at 08:00am, we started caring for the second patient in the isolation room. Therefore, we had to put on rubber gloves, a mask and a protective gown. Each time we had to leave the isolation room, we had to put them off before. At 09:00am, we had a break. Nevertheless, our supervising nurse had to look for her patient twice during the break. At 09:30pm, there was a morning meeting with all nurses, the ward physician, a senior physician and two physiotherapists. In this meeting, the nurses reported the current status of their patients and conspicuousities which need to be treated. Moreover, the physician announced the pending treatments for the respective patient. After the 10:00am documentation, we prepared the medication for the patients. During this process, the nurse was interrupted three times, so she had to leave with a syringe in her hand, acknowledge an unnecessary alarm and could finish her task after around 5 minutes. At 11:30, we supported the ward nurse with nursing for a new patient. Around 12, the nurse and a treating doctor changed the connectors for the isolated patient. During that operation, another nurse cared for other patient. At 12:50pm the general shift handover started. The morning shift ended at 01.30pm with the direct patient handover.

3.1.3 Results

We analyzed the gathered data based on the procedure for qualitative content analysis of Philipp Mayring et al. [MF19]. Therefore, the notes from the diary were inductively coded. This means, we summarized the notes, and looked for specific categories that may help to derive requirements. We finally divided our findings into the categories "Tasks", "Alarms", and "Interaction".

Tasks

From the shadowing session, we could learn that nursing tasks are stressful and physically very demanding. A nurse has to care for around 2 to 3 patients during

their shift, which requires moving frequently between patient rooms and other locations coupled with physically demanding tasks (like mobilizing patients). After entering or leaving a patient room, the healthcare professionals disinfected their hands or put off protective clothes. Moreover, there is a high continuous cognitive load, since nursing includes calculating, reading and writing vital data.

Alarms

Besides the high alarm load, there are several other disruptive noises (i.a., other medical devices that are not connected to the monitoring system, telephones, clanking glass containers, conversations of other colleagues) which make an ICU a very loud environment. Since the ICU has an open-door-policy, each noise is also audible in the patient rooms, which should be considered for developing a system for this context.

The perceived alarms were mostly low priority alarms. Due to the yellow highlighting of the relevant vital parameter which caused the alarm on the patient monitoring display, they were called "yellow alarms". Analogously, technical alarms were called "blue alarms" and critical ones "red alarms".

Interaction

Regarding the alarm management policy, we could observe that most of the time, the first step was to acknowledge an alarm in the relevant patient room. However, the relevant alarm information could also be seen on the monitoring display in other patient rooms. In this case, to acknowledge an alarm the nurses had to interrupt their current task, go to the respective patient, acknowledge the alarm and after the appropriate action (e.g., change the alarm threshold) they could return to their former task. When asking about the "pause" or silencing alarms feature, a nurse replied that this function is not appreciated since it leads to forgetting about turning them on again. "Postponed is not abandoned.", she said. In some cases, nurses cannot react to an alarm. In that case, the nurse a) asks for support beforehand, or b) shouts out for support. This is another factor which can be optimized to make the ICU a quieter environment.

3.2 Expert Discussion with the Target Group

As a second step, we did two group discussions with 4 and 3 participants from two different hospitals (from different federal states) with different levels of experience. This helped us, to address the users needs in our requirements and find out, which factors are most important for the target group.

3.2.1 Methodology and Preparation

To analyze the requirements from the view of different stakeholders, we conducted two semi-structured expert discussion sessions, one in Lower Saxony, the other one in Hesse, where two cooperating ICUs were located.

Expert discussions benefit from getting input from different perspectives, so ideas can complete each other. Therefore, it is useful to invite different stakeholders. However, to avoid inhibitions and to enable a free discussion, participants from the same employer should not come from different work hierarchies [SC17].

For each session, we sent calls for participation to workers from cooperating ICUs. We decided to included every person who has to work with ICU alarms to get as much information from different perspectives as possible and invited 10 participants, 5 for each session. We prepared the following key questions that should guide the discussion without influencing the participants.

1. Who of the nurses in the ICU should get which alarms?
2. How should they be acknowledged or forwarded?
3. How would you like to be alerted?

These questions should lead to our requirements for a new alarm system.

3.2.2 Procedure

The first group consisted of two physicians, a charge nurse and a medical engineer from the same hospital in Hesse; the second group consisted of a charge nurse, a nursing instructor and a nurse from two different hospitals and an institute for nursing in Lower Saxony. We prepared sheets with the key questions that were taped on the tables (see Fig. 3.1) and printed some of our ideas that were not shown in the beginning. After a short introduction into the topic, the participants could write their own ideas on white sheets and tape them underneath each question. Afterwards the participants got the chance to discuss their ideas, vote for ideas, or change their answers. Finally, we presented our ideas as well, to let them be discussed. Overall, each session took about two hours.

3.2.3 Results

After summarizing the notes from the discussion, we deductively coded [MF19] them. Therefore, we derived the categories "Escalation", "Alarm design", and "Device", based on the shadowing session and the related work and have sorted the results of the expert discussion to this effect. This helped us, finding concrete requirements for the WAS.

Due to their awareness of the relevance of the issue, participants in both sessions were communicative and motivated from the beginning. However, firstly, nurses were concerned whether another technical device could fix the lack of nurses, which they mentioned as the root problem. All participants agreed that a patient's alarm should be forwarded to the responsible nurse, first. However, the physicians added that they also want to receive critical alarms for their patients. In both sessions, it was remarked to alert a second nurse from the appropriate care sector as a first escalation level. The remaining nurses will be alerted only as the last escalation level. All participants agreed that in case of critical alarms, the first escalation level will be skipped and the alarm should be directly forwarded to the whole shift. We asked in both sessions, in which situations a device should not alert the healthcare professional. One participant of the first group noted directly that alarms should alert the user in every situation. After a short discussion, the group concluded that there should be no alarms in specific rooms, as e.g., the break room. Moreover, alarms should be generally not audible for patients. The second group proposed that the device should enable the possibility to sign off from alarms. When we led the participants to the alarm categories, one participant of the first session proposed to forward technical alarms just to the nursing station. This led to the discussion that a missed technical alarm could hide a critical alarm, what makes it "as urgent as a yellow one". Consequently, the participants agreed to forward all alarm types "that refer somehow to patients". The technical alarms were also a discussion point in the second session. One participant mentioned that this frequent "beep" of the technical alarm is just a background noise which is acoustically not prominent. However, the participants of the second session agreed, that they consider the alarm division in three stages as useful. When we asked, how they should receive an alarm, the first answer of the first group was "a Smartphone". However, there were concerns of all participants that there should not be another phone in their pockets. After we asked them to go more into detail, one participant confessed that they are in general not aware "what is possible with the today's technology". Afterwards they agreed in some device which alerts preferably silent, e.g., vibrating or blinking. One participant stated: "Well, the noncritical alarms could blink somehow. Somewhere. But I have no idea how this should be possible". Alternatively, the alarm loudness should increase with the priority and alarms with a high priority should generally remain audible. The second group focused directly on vibration. In their opinion, the most important factor for a WAS was the size. Additionally to the general safety and hygienic regularities, the device should be as small as possible. For that reason they rejected their idea of a vibrotactile belt and came up with a personal mount (e.g., an armlet or leg band) on which the "technical parts" can be attached. Finally, it should withstand the frequent patient contact "with all associated factors" (e.g., contact with body fluids). Regarding the functionality of the system, the participants of both sessions agreed, that the device should not differ too much from the current monitoring system. Therefore, the wearer should be able to acknowledge an alarm with the device. Moreover, it should forward alarms after

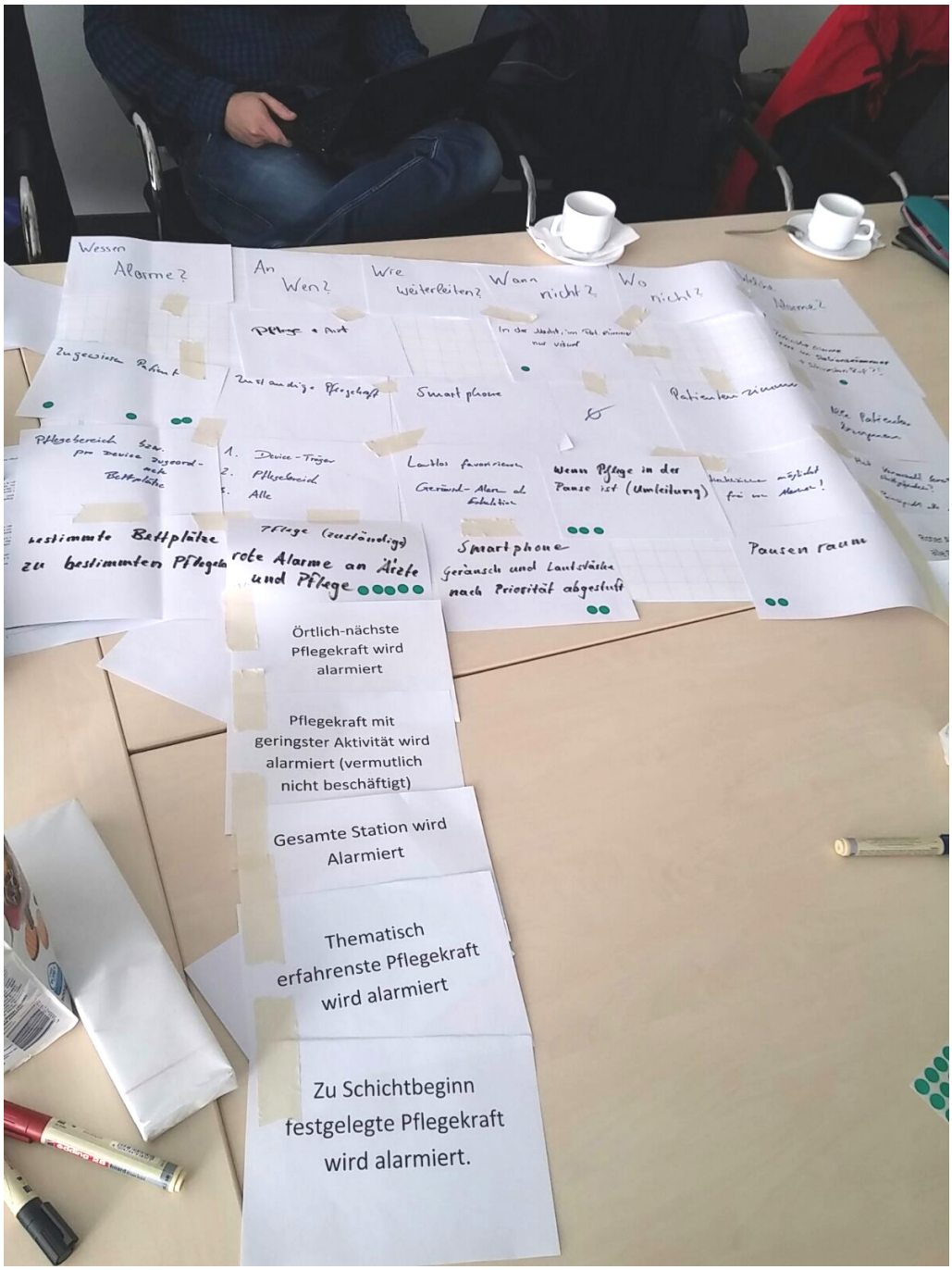


Figure 3.1: Results from an expert discussion [CBH18].

a certain time automatically. The second group proposed also an "emergency button", which acts like a red alarm and calls for help.

3.3 Discussion

Generally, in the beginning of both sessions, shadowing and expert discussion, nurses were not convinced by the idea of "yet another technical device", since they see the root problem in the lack of nurses. However, in course of the discussions, they were more and more enthusiastic of the idea of a WAS. This shows the importance to make our focus clear to the participants and inform in detail about the project. Moreover, this indicates that there might be a high risk of rejecting new technology from the target group, which makes it even more important to include nurses into the design from the beginning.

Regarding the features of the wearable device, we could find that, even though it is a core feature of the common patient monitor, silencing or pausing alarms is not appreciated. When forgetting about turning alarms on again, which means that alarms will be silenced for at least 3 minutes, an important alarm could be missed.

Another point we want to discuss is the alarm acknowledgment. Even though the majority of alarms do not require any intervention of a nurse, each of them needs to be evaluated first. A wearable device which provides the possibility of remotely acknowledge alarms may also provide the risk of acknowledging an alarm without checking for the patient. For that reason, the acknowledgement needs to be locked until the the nurse has seen the patient.

In the shadowing session, we could observe the process of "analogously forwarding" an alarm to a second nurse. Either by asking before a long uninterruptible task, or by shouting out of the room, a second nurse has cared for the alarm of the other patient. A personal alarm device would solve the issue of shouting out of the room, but this would require the digitization of the shift planning and patient assignment, which means another change in the actual workflow. However, the digitization of the shift planning, but also of the care documentation is in some ICUs already state of the art and provides many advantages, since the general documentation needs to be digitalized anyways, so this would save one step.

3.4 Summary

Based on our categories from the analysis of the findings, we divide this section into "Escalation", "Alarms", and "Device". Moreover, we want to highlight some aspects of the workflow which need to be considered for further studies.

Escalation

When it comes to an alarm, each second may count. Nowadays, nurses do also care for their colleagues' alarms, but in some cases, a nurse needs to shout for help, when s/he cannot interrupt her task. For that reason, the alarms should be forwarded automatically, in case, the nurse cannot use their hands or s/he is in the rest room, in surgery or too far away to react. Participants wanted alarms to be forwarded to a second nurse before alarming the whole shift in a third step. In case of a critical situation, the alarm should be forwarded directly to each other nurse and also to the responsible physician. Moreover, the participants thought about the feature of an emergency button to call for help.

Alarms

Alarms are divided into three categories: Critical (red), uncritical (yellow), and technical (blue). The most perceived alarms were the uncritical ones. These patterns are well established and cognitive mapped, which means, we should not change them.

Blue alarms are handled as quite unimportant, even though they could cause a critical alarm. The participants mentioned that blue alarms should be signalized as urgent as yellow alarms, so they gain more importance. Regarding the workflow, the first step of the alarm management is to acknowledge the alarm, so "the noise stops". This means, this is the most frequent interaction for patient monitors and in the beginning, we should focus on that in designing interactions.

In some cases, e.g., when changing electrodes, alarms are paused. However, there is a risk that another alarm will be not recognized in this time and some participants had concerns to implement this feature.

Device

Nursing means a frequent movement between different places. Therefore, a new alarm device should be mobile or, based on the fact that hands are often contaminated and need to be disinfected before and after entering a room, rather body-worn. To not affect the workflow, this device should be as small as possible, easy to attach and resizable, so it could be worn by different nurses.

Moreover, we need to consider the following regularities: Nurses are not allowed to wear jewelries. Anything attached on the forearms or hanging on the neck may harm the patient or the nurses themselves during nursing tasks, e.g., mobilization. In case of resistant germs, additional protective clothes needs to be worn over the regular work clothing, when entering the patient room. This would hinder from integrating visible cues directly into the working clothes.

Workflow

The workflow of a nurse consists of physically, cognitively, and precision demanding, as well as social tasks. Sometimes, these loads are claimed together.

During a mobilization, there is a close body contact to the patient, hence with several body fluids. This must be considered during the design and evaluation process. During each task, the nurse needs to evaluate whether she can interrupt her/his task or not. In case of a longer intervention for a patient which cannot be interrupted, s/he needs to care for a replacement during her absence. Another fact that need to be considered is that some diseases are associated with severe odors. This means, other odors will not be recognized reliably.

3.5 Findings

From the results (see par. 3.4), we could 1. derive requirements for a wearable alarm system, 2. develop an alarm distribution and escalation model which shows similarities to the algorithm of Maria Cvach et al. [CFDS14], and 3., we could shape the design space for wearable systems that serve to notify ICU nurses for monitoring alarms.

3.5.1 Requirements

Based on our analysis, a wearable alarm device should fulfill the following requirements to be integrable into the ICU workflow:

To comply with applicable hygiene and clothing standards, the WAS must not be applied to the hands or forearms. It should be shock and water resistant to withstand various circumstances in intensive care units. The nurse should be able to clean and wipe–disinfect the surface of the device to prevent germs or viruses from being transferred from one patient to another. It should be made of allergy-free and breathable material to avoid adverse reactions and sweating. For cost-saving reasons, the hardware components should be easy to detach so they can be used by multiple intensive care nurses. The system should be easily applicable and, moreover, resizable to fit different intensive care nurses. In addition, it should sit tight to the body so that it does not slip or get lost during work. The size of the device should be as small as possible (see Sec. 3.4, *Device*). The WAS should reliably alert with three levels of urgency to distinguish between high priority (critical), low priority (uncritical), and technical alarms. The critical alarms should still be delivered acoustically. The alarms must be easily, reliably, and quickly identifiable. Finally, the device must be easily integrable into the nursing workflow without having negative influence on the quality of nursing (see Sec. 3.4, *Alarms*).
The responsible nurse should have the option to acknowledge, to silent or to

forward the alarm; to call for assistance and for an emergency call. An emergency call behaves like the high priority alarm and will be forwarded to the remaining nurses and the responsible physician. Finally, the alarm display should be visible from all nursing work places (see Sec. 3.4, *Alarms*) [CBH18].

3.5.2 Alarm Distribution Algorithm

Nowadays, a patient monitoring alarm is is audible for every person in the ICU, even though one specific nurse is assigned to the respective patient. This means, to implement a wearable alarm system that notifies just that specific nurse, an alarm distribution and escalation algorithm is needed. Prior work by Cvach et al. [CFDS14] evaluated such an algorithm in American ICUs. However, the workflows in hospitals differ and therefore, we developed an alarm distribution algorithm for workflows in German ICUs that base on the observations of an ICU, our two expert discussions, and the work of Cvach et al. [CFDS14].

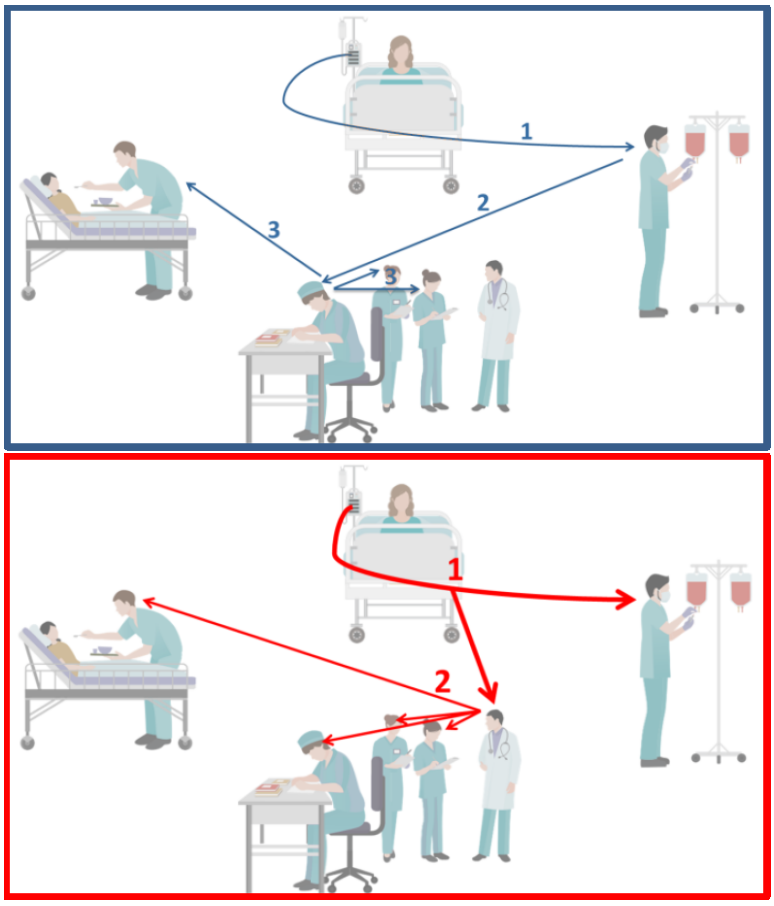


Figure 3.2: Alarm distribution model ((**top**) uncritical alarms; (**bottom**) critical alarms) [CBH18].

(1) Low-priority (uncritical) and technical alarms will be forwarded to the responsible nurse with a 60 s-delay.

(2) If there is no reaction within 60 s, the alarm will be forwarded to a second nurse.

(3) If the second nurse does not react within 60 s, the alarm will be forwarded to the remaining nurses (see Figure 3.2 top).

(4) High-priority (critical) alarms will be forwarded to the responsible nurse and the responsible physician immediately.

(5) If there is no reaction within 60 s, the alarm will be forwarded to the remaining nurses (see Figure 3.2 buttom).

The delay of 60 s is based on WHO indicators, taken from the work of Cvach et al. [CFDS14].

Our findings indicated that the alarms should be forwarded automatically, however, there should be options for nurses to sign yourself off from alarms or to create alarm-free areas to forward alarms immediately to another nurse.

Such an algorithm is an immense intervention into the nursing workflow and needs to be evaluated in the field. Since we are in an early stage of development, the alarm distribution algorithm cannot be evaluated yet and can be seen as first conceptual work and recommendation for similar research.

3.5.3 Shaping the Design Space

Since ICUs are environments which are straining the acoustic channel, we aim to develop a system, which disencumbers this channel, and thus, the stress. To focus on one body location for a wearable alarm device, we evaluated different body parts (head, upper arms, chest, back, hip, legs, and feet) regarding the possibility to

1. display the alarm source, means the causing vital data or sensor as textual information;
2. recognize an alarm via visual cues;
3. recognize an alarm via tactile cues;
4. recognize an alarm via unobtrusive audible cues;
5. wear the device without endangering patients or the nurse;

during different nursing tasks, e.g., mobilization of a patient.

Considering these factors, the most suitable body position constitutes the head. Using a head-mounted display which could be part of the work clothing, we could display textual information in the field of view and alert the user with multiple modalities without having an influence on the patient care.

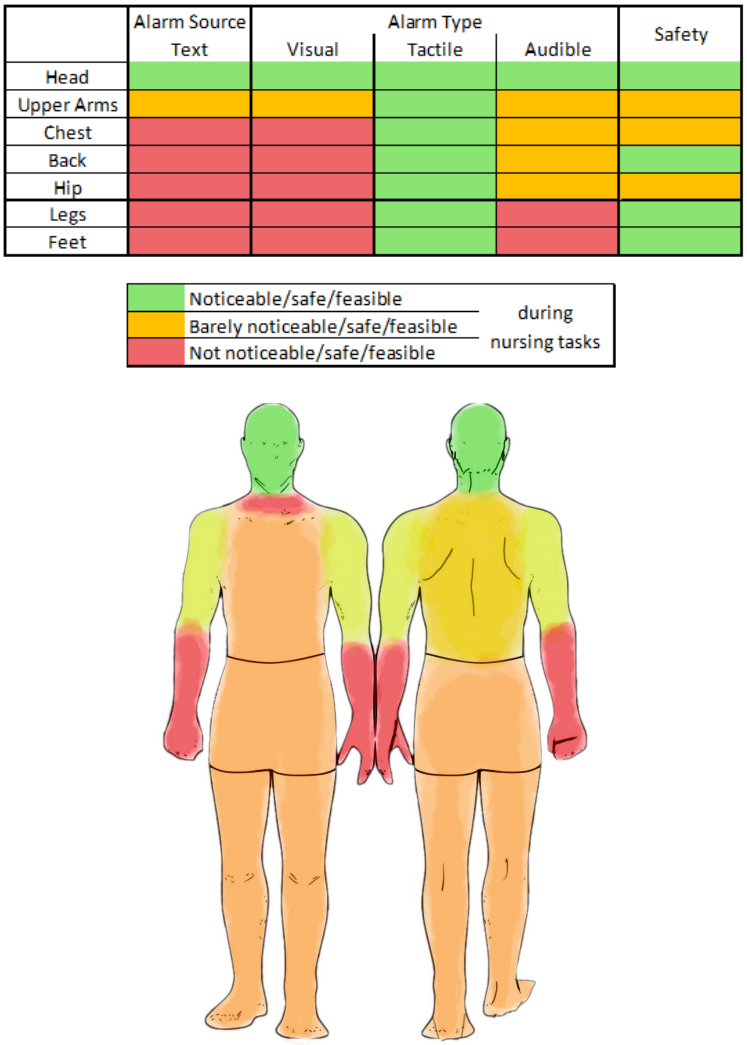


Figure 3.3: Suitability of possible body positions for multimodal personal alarms.

At the other body parts, there is no assurance that visual and unobtrusive audible cues are continuously noticeable, especially during nursing tasks like mobilization (see Sec. 3.4, *Workflow*). Moreover, in case of upper arms, chest and hip, there is a potential risk for the users to hurt a patient or themselves during that task. An overview can be seen in Figure 3.3.

The state of the art for interactive systems allows to communicate with all five sensory channels. However, there are several reasons which kept us from exploring the gustatory, nor the olfactory channel.
First of all, the state of technology is not yet advanced enough to integrate such a system into the ICU in the near future [VAAO17, NM11, Nak13, AM17].
Reason two also follows the state of the art. Since such a system has to be installed

in the mouth or nose, to be fast recognized, communication is impaired. This is an essential part of the care.
The last reason, we want to mention is the reliability of the information representation. ICUs are generally enriched with several smells (drugs, body fluids, disinfectants). This makes identification of further odors more difficult. This does also apply in case of illness, when the nose is blocked, and thus, the taste does not work reliably (see Sec. 3.4, *Workflow*).

Therefore, we focus on the modalities sight, touch, and hearing to deliver patient alarms.
Even though the visual and audible channel are already claimed by nursing tasks, we can address the peripheral vision for visual cues, so alarms can be perceived without interfering with the field of view. To convey unobtrusive audible sounds we consider bone-conduction speakers, thus we can forward audible alarms silently without blocking the ear.
The tactile channel will be addressed via vibration. Vibrotactile cues are the fastest and also most established way to deliver notification tactilely.

Summarized, the conceptual design of our wearable alarm distribution system consists of a head-mounted display which can convey patient alarms via bone-conduction speakers, vibration and peripheral light. Additionally to the alarm, the nurse receives relevant information in his/her field of view. She then can decide whether she needs to acknowledge, silent or forward the alarm. The conceptual design can be seen in Fig. 3.4.

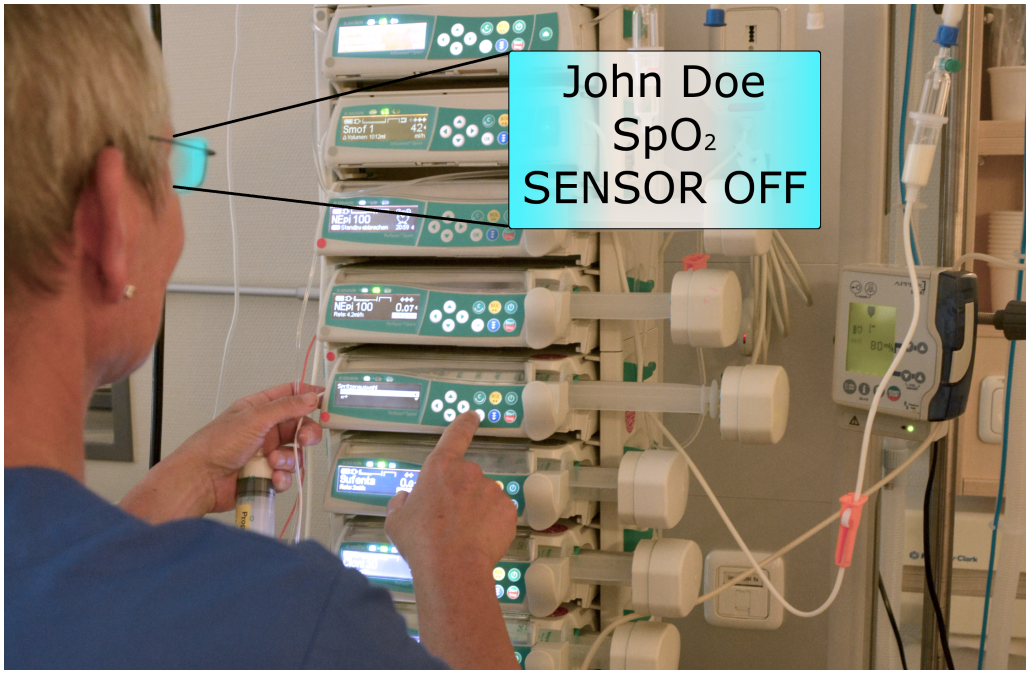
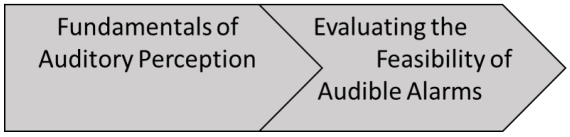


Figure 3.4: Conceptual design of the WAS. [Cob19]

4 Feasibility of Audible Alarms

The common way to convey alarms on ICUs is through the audible channel. These alarms are based on IEC standard 60601-1-8 and well established. Since one important factor for designing an alarm system is to base on an alarm philosophy, we will not change these alarm tones. Instead, we compared the feasibility of a new transmission medium to the state of the art (speaker), in a pilot study.

Starting with fundamentals of the human perception of auditory signals, this chapter describes the feasibility study audible alarms during nursing specific task loads.



Parts of this work are going to be published in 2020.

4.1 Auditory Perception

Three essential functions characterize our auditory system: 1) social communication with other humans, 2) the perception of music, and 3) provide a warning system that informs us about events and significant sounds in our environment. Thus our hearing also informs us of events which are not yet accessible to sight or which can only be perceived through hearing, such as alarms or warning tones.

By detecting vibrations of a sound source, we are able to perceive sounds through solid, gaseous and liquid mediums. These vibrations are called sound waves. The frequency of the sound waves influences the pitch of a sound. The sound pressure level influences the loudness of a sound and is measured in decibel. However, for different humans, the same frequency may be perceived as subjectively different loud [GRH02].

In natural hearing, the sound waves are received by our outer ears, modulated by the middle ear, transmitted to the receptor organ, and converted into electrical signals for neuronal processing (see Fig. 4.1). Headphones are a well-known way to listen privately to audio via air conduction. Headphones, however, are not integrable into the nursing workflow due to frequent necessary communications [CBH18]. Different from the common mode of audio conveyance, bone conduction is a tactile stimulus that leads signals to the inner ear through the bones of the skull [SG05] (see Fig. 4.1). Although there has been more than a century of research for the application of bone conductive technology for physiological and clinical applications e.g., on hearing, the application of this technology in clinical alarm recognition is in the developmental stage. This mode of audio signaling has the advantage that sounds can be conveyed to a single user and con-

veyed without blocking the user's ear canals. Although bone conduction speakers (BCS) have the disadvantage that they are restricted to single channel operation, studies have indicated that bone conduction systems can be effectively used for displaying spatial information with similar results in localization performance as stereo headphones [MHL06]. However, to convey alarms, BCS are a promising solution for wearable alarm devices.

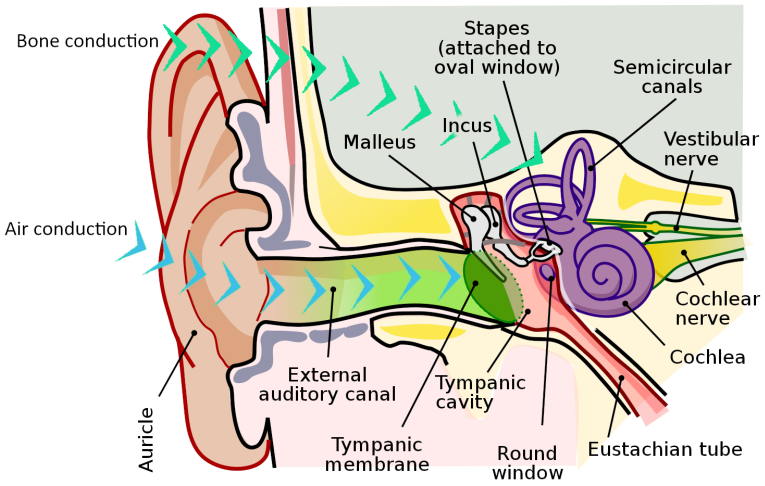


Figure 4.1: Anatomy of the human ear and the way of air and bone conduction [CB19].

We can distinguish the auditory attention into split and selective attention. While we focus just a limited number of properties of various sounds events during the split attention, in selective attention the focus is directed towards the properties of one single sound event. To guide the focus on a sound event, the properties need to highly stimulate the auditory system, which can be caused by high intensity, high contrasts in frequency and high temporal contrasts. Due to this high stimulation, e.g. triggered by an acoustic alarm, the sound event will be focused, attracts our attention and influences our actions [KPLL05].

4.2 Comparing Bone-Conduction Sound to Speakers

In a first pilot study, we examined the use of headset-mounted bone-conductive speakers as a transmission medium to convey alarms to nurses. Therefore, we performed a study with non-clinical participants to determine its feasibility during nursing specific loads in general. To mimic those loads, the participants performed 3 different tasks, representative of tasks common in ICUs. These tasks were occasionally interrupted by alarms either through condition 1, bone-conductive sound speakers (BCS), or condition 2, common acoustic speakers (US). As soon

as the participants recognized the alarm they gave a signal. This was used to measure the time it took to react to an alarm. Afterwards, they answered questions concerning how the alarm was perceived.

With this study, we aimed to investigate if BCS can compete against speakers regarding the factors reaction time, urgency, comfort distraction and recognizability. Therefore, we proved the following hypotheses:
H1: The Reaction time of BCS is shorter than for US.
H2: The perceived urgency is higher for BCS than for US.
Since the alarms were brought directly to the user, we assumed:
H3: The perceived comfort is lower for BCS than for US.
H4: The perceived distraction is higher for BCS than for US.
H5: The recognizability is higher for BCS than for US.

4.2.1 Apparatus

We designed the study with three task setups which can be seen in 4.2:

1. The physical task setup consisted of a bed with a mattress as well as a folded bed sheet placed atop that mattress. At the beginning, the participant was standing in front of one of the long edges of the bed, towards the bed. The task was then to cover the bed with the bed sheet. If the task was finished the participant had to take the sheet off and put it on again.

2. The precision task setup consisted of a table and a chair in which the participant was asked to sit. In front of the participant was the dexterity component of the board game "Operation". The game contained various plastic pieces that should be removed from the game board with metal tweezers without touching the edges of the indents. If the participant finished the task, he should replace the pieces using the metal tweezers and start from the beginning.

3. The cognitive task setup consisted of a table and a chair in which the participant was placed. The participant was then introduced to cross-multiplication. The cognitive task was to finish different cross-multiplication tasks as fast as possible with a calculator.

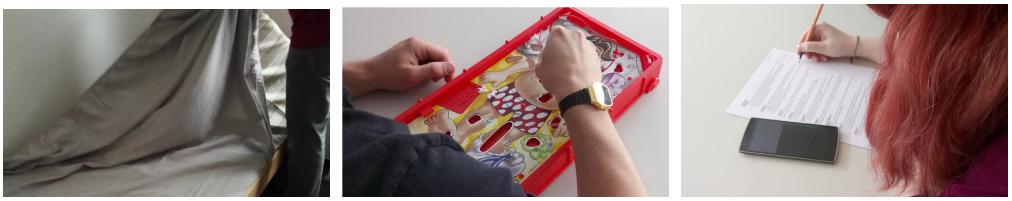


Figure 4.2: Physical, precision, and cognitive task. [Cob19]

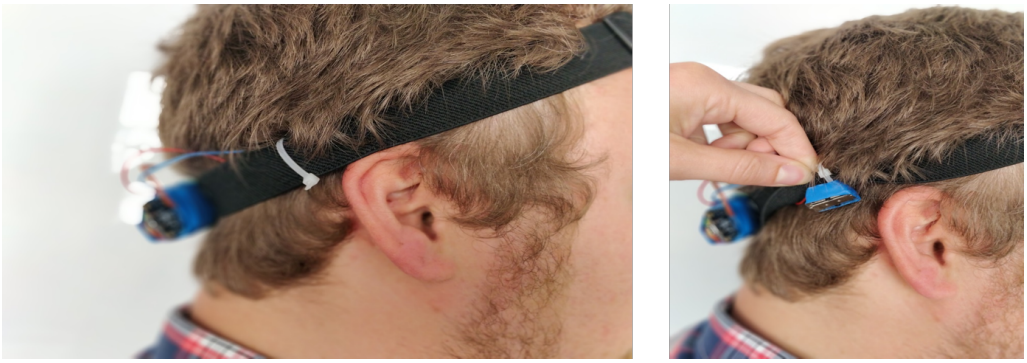


Figure 4.3: The bone-conduction speaker were placed via a headset behind the ears. [Cob19]

The participants were located in front of one of three task setups. A speaker was placed to the back of the participant. It played background noise and the ubiquitous sound alarms. The participants wore a BCS headset from which the BCS alarms were played (see Fig. 4.3). The loudness of the headset was set to a value that was previously determined to be perceived as equivalent to the alarms from the speaker. The alarms were controlled by a second experimenter, the

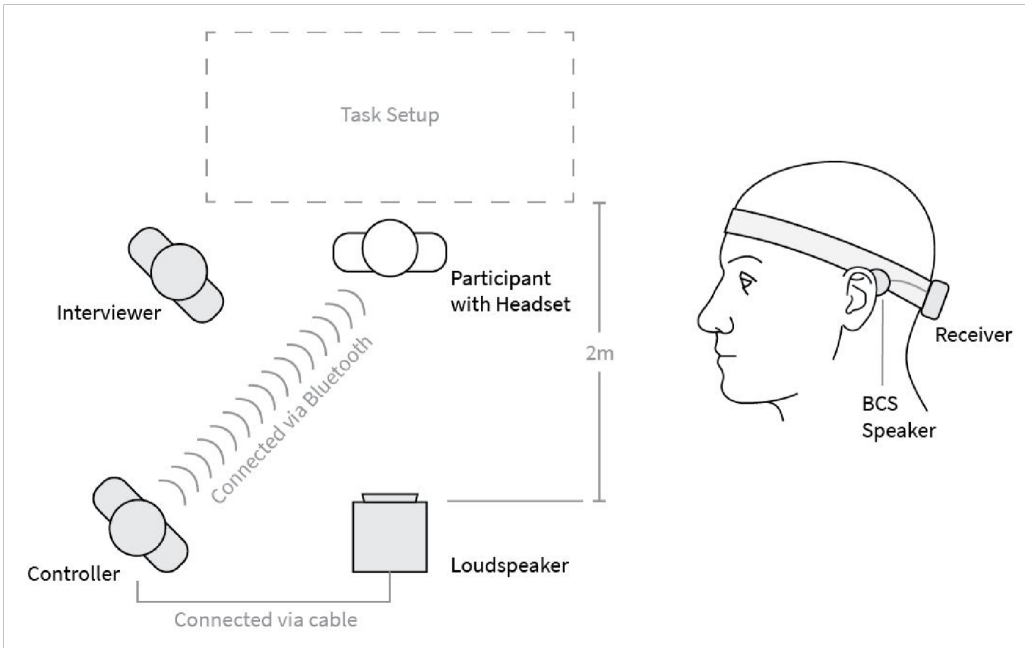


Figure 4.4: Setup for the study

Controller, using a laptop and a cellphone to control the US and BCS alarms respectively. To measure the start of an alarm, a camera filmed the Controller and

the display of the computer and the cellphone. The audio track of that camera was used to determine when exactly alarms started and when the participant recognized them. The whole study setup was visualized in 4.4.

4.2.2 Evaluation

4.2.2.1 Participants

For our study, we recorded data of 11 participants, none of which had any hearing problems. The participants did not receive compensation. 9 participants were male and 2 female, spanning an age range from 21 to 34. For this pre-study, the participants were not restricted to trained nurses, though this was considered in the final study.

4.2.2.2 Study Design

Our study was designed as within-subject and considered three independent variables:

- Type of sound: The type of sound used to emit the alarm. This can be either ubiquitous sound or bone conductive sound.
- Level of alarm: The level of alarm that was played. This can be high priority (critical), low priority (uncritical) or technical. These alarm sounds mirror those already in use in hospitals and are visualized in Fig. 4.5.
- Type of task: The type of task the participant performed before the alarm occurs. This can be physical (changing bed sheets), precision (board game "Operation") or cognitive (cross-multiplication).

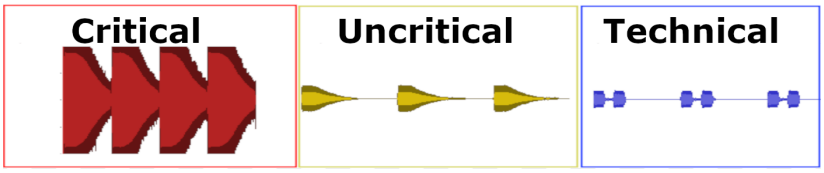


Figure 4.5: Sound patterns used in the study

We measured five dependent variables:

1. The time it took for the participant to notice the alarm and speak aloud that an alarm had occurred.
2. The perceived urgency of the alarm as rated on a Likert scale from 1-5, 5 being the most urgent.

3. The perceived comfort of the alarm as rated on a Likert scale from 1-5, 5 being the most comfortable. Since nurses are exposed to many alarms per shift, the comfort factor is important for a new alarm system.

4. The perceived distraction by the alarm as rated on a Likert scale from 1-5, 5 being the most distracting. This factor should be low for uncritical alarms that does not require the intervention of a nurse but could be high for critical alarms that need immediate reaction.

5. The perceived recognizability by the alarm as rated on a Likert scale from 1-5, 5 being the most recognizable. To evaluate the urgency of an alarm, a high recognizability via the system should be given.

The study consists of performing a given task until an alarm was sounded. At this point, the participant should mention the perceived alarm that occurred and the type of alarm (US or BCS). Each participant performed each possible combination of independent variables once, for a total of 18 trials. Each participant performed the trials in three blocks, one block for each type of task. Both the order of the blocks as well as the order of the six trials within each block were randomized but distributed as evenly as possible.

4.2.2.3 Procedure

After obtaining informed consent, we introduced the participant to the headset and played each alarm level both via BCS and through US and asked the participant to give their preferred name for that type of alarm (suggestions were "high", "low", "technical" or "red", "yellow", "blue"). The order in which the tasks were performed was determined randomly. For each task block, the participants were introduced to the setting of the task and given time to familiarize themselves with it. Once the participant indicated that they were ready to start, a signal was given that they should perform the task. At a random time after the trial started, an alarm was given according to the level of alarm and type of sound specified by the order. As soon as the participant noticed an alarm, they should speak aloud the type of alarm they recognized and stop the task. Following each task the participant was asked to rate the perceived comfort, urgency, distraction, and ease of recognition of the alarm on a scale from 1-5.

4.2.2.4 Results

The first step of the analysis was to determine the reaction time of the participant for each of the trials. To do so, we used the camera recordings to set time stamps, one as soon as the alarm started playing, one once the participant noted that they heard an alarm. With the results we were able to examine each of the research questions both visually and statistically. For each level of alarm or type of task, the values for US vs BCS were compared. Since human reaction time

can generally not considered to be normally distributed, we used the Wilcoxon signed-rank test to determine whether there was a statistically significant effect for the first two questions. In our third question the ordinal nature of data from Likert scales required a non-parametric method. To answer our first question ("Is the reaction time for BCS faster for any of the alarm levels across all task types?") we compared the reaction time for all of our data, divided by alarm level (low BCS vs. low US, medium BCS vs. medium US and high BCS vs. high US). For the second question ("Is the reaction time for BCS faster for any of the task types across all alarm levels?"), we compared the following data: Physical BCS vs. Physical US, Precision BCS vs. Precision US, and Cognitive BCS vs. Cognitive US. For our last question ("How does BCS compare against US for urgency, comfort, distraction, and recognizability across all alarm levels and task types?"), we used the Wilcoxon signed-rank test to compare BCS vs US across all trials for each of the observed variables.

Reaction Time

We visualized the data sets reaction time in Fig. 4.6, left. These diagrams already indicated that reaction times might be faster for bone-conductive sound than for ubiquitous sound in at least some of the alarm levels.

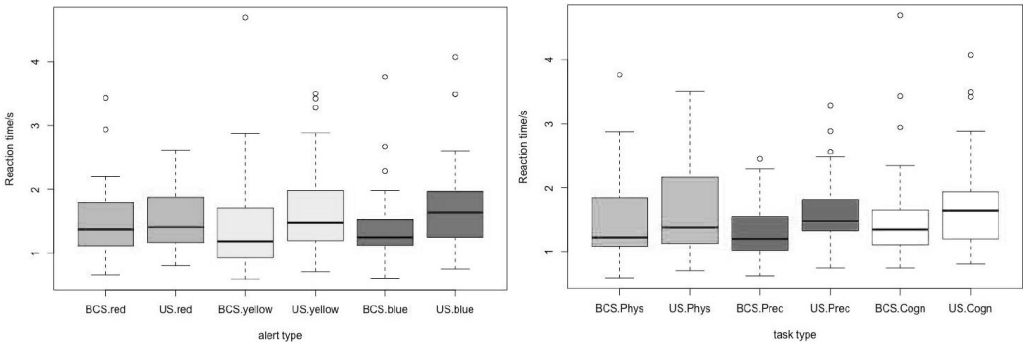


Figure 4.6: Comparison of the reaction time; left: across alarm types, right: across tasks.

We verified this assumption performing a Wilcoxon signed-rank test. The test revealed that reaction times were significantly faster using BCS for each of the alarm levels (see Fig. 4.7). Therefore, we can confirm H1, the reaction time of BCS is shorter than for US.

Also for the different task conditions, we could show significantly better reaction times using BCS (see Fig. 4.6, right, and Fig. 4.7).

reaction time	is	lower	with BCS	for high-priority alarms.	p = 0.028
				for low-priority alarms.	p = 0.004
				for technical alarms.	p = 0.001
				for physical tasks.	p = 0.014
				for precision tasks.	p = 0.001
				for cognitive tasks.	p = 0.009
urgency		higher		across all cases.	p < 0.001
comfort		lower			p < 0.001
distraction		higher			p < 0.001
recognizability		higher			p < 0.001

Figure 4.7: Comparison of bone-conduction and ubiquitous sound.

Urgency, Comfort, Distraction and Recognizability

Using the Wilcoxon signed-rank test to compare perceived urgency, comfort, distraction and recognizability of the alarms for BCS vs US across all trials shows that the perceived comfort is lower for BCS in general, whereas urgency, distraction and recognizability were generally perceived as higher (see Fig. 4.7). This means, we can also confirm H2 - H5.

Visual exploration further indicates that there might be a trend across all conditions (Fig. 4.8 - 4.11), though it was not examined whether there was a statistically significant effect for each of them individually.

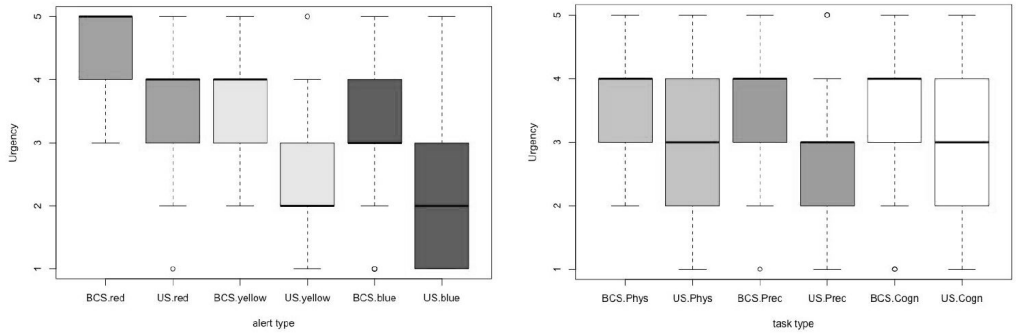


Figure 4.8: Comparison of the perceived urgency; left: across alarm types, right: across tasks.

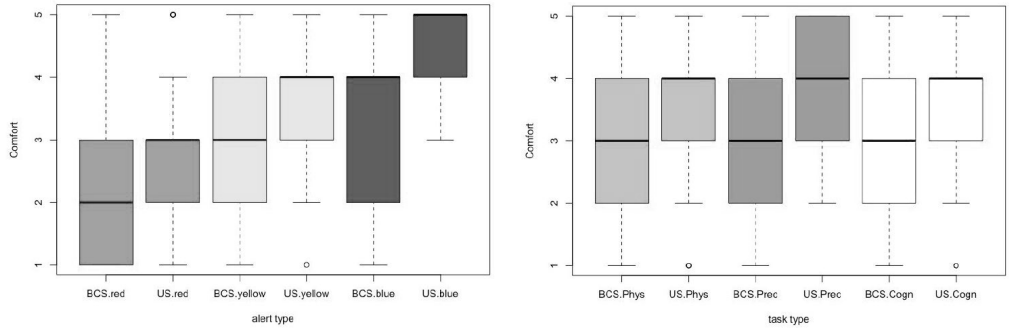


Figure 4.9: Comparison of the perceived comfort; left: across alarm types, right: across tasks.

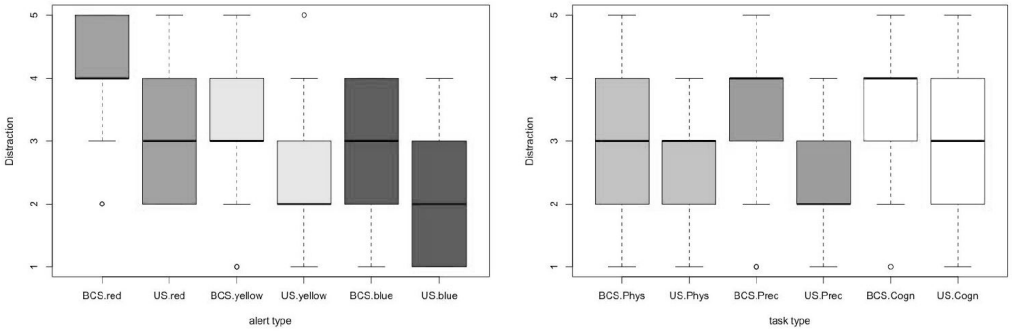


Figure 4.10: Comparison of the perceived distraction; left: across alarm types, right: across tasks.

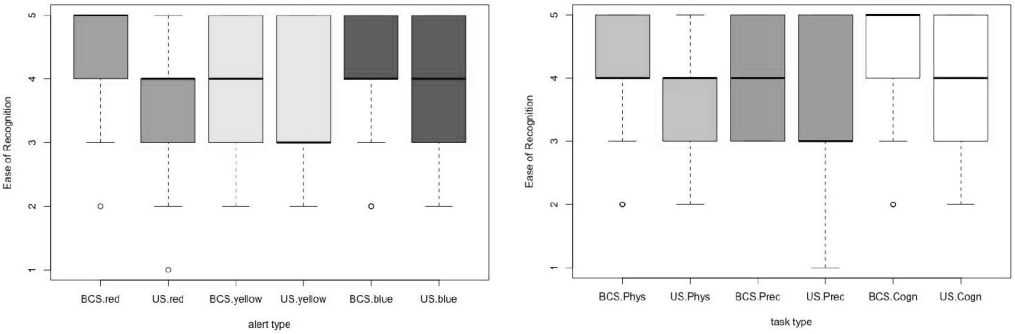


Figure 4.11: Comparison of the perceived recognition; left: across alarm types, right: across tasks.

4.3 Discussion

In this pilot study, we compared the use of bone-conduction sound for ICU alarms against the regularly used ubiquitous sound. The comparison was performed using

reaction time to an alert stimulus and perceived urgency, comfort, distraction, and recognizability across all three alarm levels and three different types of tasks. The analysis of our result showed that the reaction time for bone conductive sound is faster compared to a ubiquitous alarm sound for critical, uncritical, and technical alarms. The reaction time of the participants was also found to be better for all task types. This can generally be considered an advantage of BCS, though improvements of less than 0.5 seconds are rather less beneficial in practical application.

Considering the subjective categories, alarms via bone-conduction were generally rated as more urgent than ubiquitously audible alarms. This can be considered an improvement for high-priority alerts, but it is worth discussing whether this is also appropriate for low-priority or technical alerts or whether these alarms should be transferred via other modalities.

Participants rated the comfort of BCS worse than for US which could contribute to stress in the workplace or hinder adoption. Sounds designed for use with BCS might help in this regard. Moreover, this indicates to use the audible channel via BCS just for critical alarms.

The perceived distraction from the task was higher for BCS alarms. To what extend this is a problem or even a feature in ensuring alarms are taken care of swiftly can be debated, but certainly depends on the type of alarm observed.

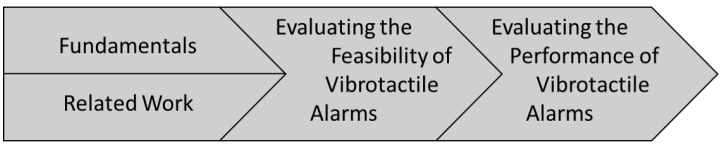
Finally, BCS alarms were considered easier to recognize. On the whole, BCS alarms performed better in some categories, like reaction time and recognizability, but worse and distinctly different in others, like comfort and distraction.

However, these results show limitations, that hinder us from generalize the findings for the clinical setting. E.g., we had a small sample size of 11 participants who were voluntary without nursing knowledge. Similarly, the tasks were chosen to be representative of ICU work, but can, of course, not replicate it entirely. The volumes of the different sound types could not be normalized in advance by a third party, such that subconscious bias of the experimenters might have influenced their relative loudness. Due to hardware limitations, the alarm sounds used consisted only of sine waves modeled after currently used alarm sounds, but were not those sounds themselves. This might have made it harder to distinguish between the alarm sounds than it would usually be. These limitations should be addressed in follow-up studies.

However, the findings indicated that bone-conduction speakers can be a suitable replacement for regularly used speakers, though the alarms would need some adjustment regarding loudness and frequency to be more comfortable. Our results can give better insights for future studies with representative actual nurses as participants.

5 Design of Vibrotactile Alarms

Vibrotactile feedback has been investigated for several years. The related work we present in Section 5.2 provided vibration patterns evaluated for multiple use cases. In a two-part study, we investigated which patterns best suit representation of three alarm categories: technical, uncritical and critical alarms. This chapter is structured as follows:



Parts of this chapter were published in Cobus, Vanessa ; Ehrhardt, Bastian ; Boll, Susanne ; Heuten, Wilko: Vibrotactile Alarm Display for Critical Care. In: *Proceedings of the 7th ACM International Symposium on Pervasive Displays*. New York, NY, USA : ACM, 2018 (PerDis '18). – ISBN 978–1–4503–5765–4, 11:1–11:7.

5.1 Tactile Perception

The skin is one of the largest organs of the human body and protects the inner body against external influences. It is part of our somatosensory system which enables to obtain information about the form and texture of objects we touch.

The information intake via the "skin senses" can be divided into active and passive information intake.

The tactile passive perception of information includes the perception of the surrounding temperature, pain stimuli, and the positional perception of the limbs in a calm posture.

Active information perception via touching objects is directly linked to active movement, and is also called "haptic perception". By actively touching and grasping an object, we can perceive the shape, surface structure, hardness, thermal properties, weight and size of an object. In connection with actively controlled movements, an image of the object can thus be generated by tactile perception [GRH02].

Responsible for the sense of touch are receptors, which are divided into mechanical, thermal and pain receptors and are mainly located in the outer two layers of the skin (see Fig. 5.1. In the following, we will focus on the mechanical receptors. These in turn are divided into four types, which react differently to certain mechanical cues.

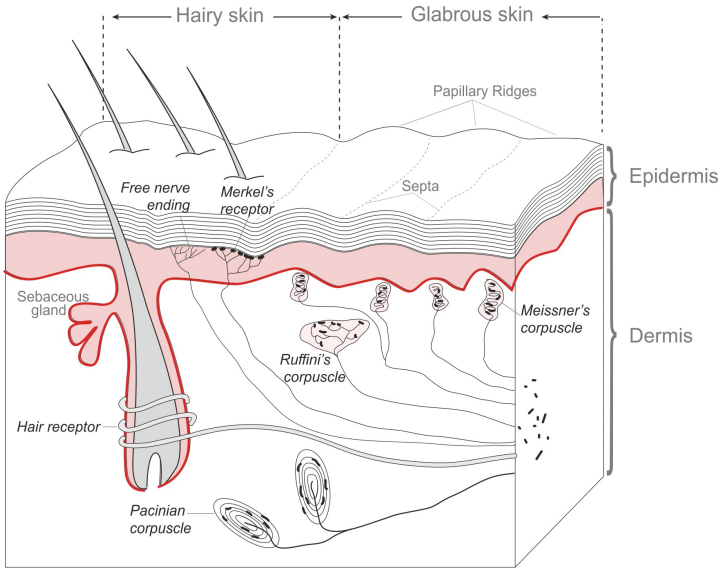


Figure 5.1: Structure of the skin [Has19]

Slowly adapting (SA) receptors respond permanently to permanent pressure, while rapidly adapting (RA) receptors stop responding when the pressure is constant.

The receptors are further differentiated by their bundling on the nerve fibers in type 1 and 2. In type 1, several receptors are bundled onto one nerve fiber, whereas in type 2 only one receptor is connected to one nerve fiber.

The most important feature of the slowly adapting receptors (SA1 Merkel's receptor) is the ability to represent skin deformation and pressure, such as edges, corners and curvatures. They thus provide important information about the shape, size and surface of an object. The smaller the contact area of the skin on which the pressure is applied, the greater the response intensity of the nerve fibers, as the forces and tensions are concentrated on a small contact area.

The SA2 Ruffini corpuscle, on the other hand, respond to tensions in the skin and thus provide both information about the position of the human limbs and information about the three-dimensionality of objects that are palpated. The rapidly adapting receptors are responsible for detecting movement and vibration.

RA1 Meissner's corpuscle can detect events that produce low-frequency skin movement. This also includes, for example, the detection of surface properties and low-frequency vibrations caused by the movement of the hand over a surface.

The RA2 Pacinian corpuscle are the most sensitive mechanoreceptors responsible for high-frequency vibrations in the 30 to 500Hz range [KSJ+13].

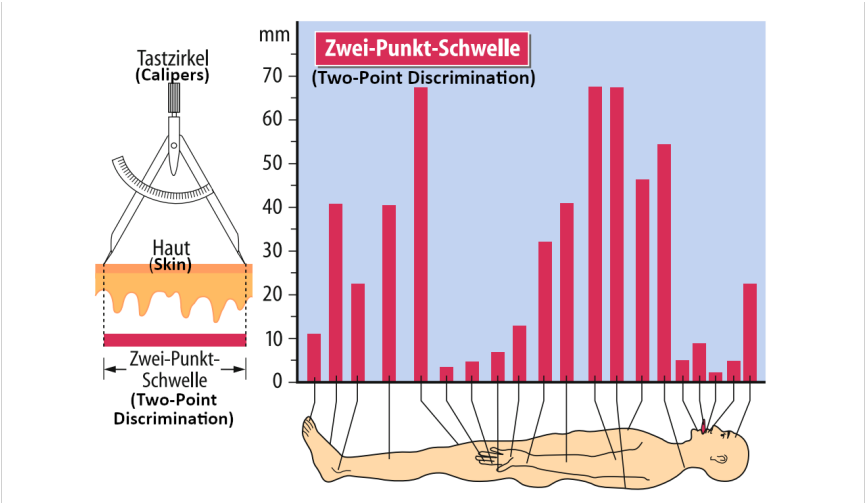


Figure 5.2: Two-Point Discrimination (2PD) by Birbaumer et al. [BS10].

Essential factors for selective exogenous attention are the intensity and duration of the stimulation of the receptors, as well as a high dynamic, e.g. in the frequency of vibration or in the variation of movement on the skin.

The stimulation of the receptor should not be static over time, e.g. slow adapting mechanoreceptors fire faster at constant stimulation at the beginning and then reduce this rate to a value proportional to the exerted pressure. Another factor is the total number of receptors stimulated. Accordingly, stimulation of body regions with a higher density of receptors attracts more selective attention [KSJ+13]. This information should be considered for the development of vibration patterns.

A high density of receptors is resonsible for a high tactile resolution. The resolution or tactile discrimination of the different body regions can be measured by the two-point discrimination (2PD). The 2PD is the smallest distance between two points on the skin that can still be perceived as two individual points, see Fig. 5.2. Between men and women it differs only slightly.

The area around the mouth and the hands have the highest tactile resolution, followed by the toes and ankles with less than 2.5cm, and the head with less than 3cm. The highest resolution was found on the tights, the back, and the upper arms with around 7cm [BS10].

The 2PD is useful to develop wearable vibrotactile display, since it helps to adjust the distance between the vibration motors to be perceived as different points.

5.2 Related Work

In this section, we introduce related work that has shaped our own work, focusing on vibrotactile feedback on wearable devices for medical applications.

In 2005, Jessie Ng et al. [NMF+05] developed a vibrotactile prototype placed on the forearm to inform the user about the patient's heart rate during a surgery. The prototype has two vibration motors located on the inside of the forearm, one near the wrist and one near the elbow. It delivers six different alarms; three levels of change (10, 20, or 30%) in heart rate over the last five seconds combined with the distinction of whether the change is a rise or fall in heart rate. A long initial vibration on the wrist indicates a sinking or long initial vibration at the elbow indicating a rise in heart rate. Subsequently, the level of change is transmitted via the other vibration motor via the number of short vibrations. During the evaluation, the prototype was compared with an acoustic alarm scheme which is commonly used in clinics. The results have shown that the prototype provides a much better result compared to the acoustic alarm scheme. In a subsequent questioning of the subjects, it was noted that the prototype has caught the attention in a noisy environment better. However, the comfort of the prototype has been criticized in the form that it has restricted the freedom of movement due to the fixed elastic mounting strips for the vibration motors and the loose wiring.

Other work that focuses on tactile feedback on the wrists for medical applications was presented by Carlos Rossa et al. [RFU+16]. They present a wrist-worn prototype and multiple vibration patterns to guide a surgeon's hand for a cancer treatment procedure (brachytherapy). The study results showed that the vibration patterns could be successfully identified. Moreover, with a success rate of about 80%, the device could work in tandem with a needle steering algorithm to help surgeons in precision demanding tasks.

However, for hygienic and safety reasons, wearable devices are prohibited below the elbow for healthcare providers. Daniel M. Gay-Betton et al. [GBACS17] compared the perception of vibrotactile cues between wrists and ankles. Their studies revealed that vibrotactile cues are similarly perceived on the ankle, which makes it a feasible alternative position for this target group. The results can be used for future research to re-use vibration patterns which were already evaluated for everyday life scenarios (e.g., to indicate urgency).

The prototype developed by Mia McLanders et al. [MSTS14] aims to keep the wearer informed about a patient's heart rate and oxygen saturation. The prototype was designed for the upper arm and consists of three vibration motors, which are slightly transverse on the outside between shoulder and elbow. In analogy to the placement of the vibration motors (high, middle, low), the user can recognize the threshold of the heart rate of the patient. The number of vibrations represents the threshold value of the oxygen saturation. The results of the evaluation showed that the participants recognized over 90% of the changes in

heart rate and oxygen saturation and that the comfort was rated as appropriately positive.

A vibrotactile belt for medical applications was introduced by Maryam Dosani et al. [DHD+12]. The device aims to support anesthesiologists in monitoring the vital data of patients with four vibration motors (front right, front left, back right, back left). Each motor represents a vital sign. Two short vibrations represent a small increase, one long vibration represents a small decrease of the vital sign. A large increase is represented by five short vibrations, a large decrease by one long and two short vibrations. The prototype was evaluated in the field during an anesthesia. 89.5% of the alarms were correctly detected. In a subsequent usability survey, participants gave positive feedback and reported that detecting the alarms became easier with increasing wearing time.

Based on this work, we designed multiple vibration patterns to alert nurses with our vibrotactile WAS. We validated the suitability of the patterns to represent different levels of urgency and evaluated the usability, comfort and reaction time with nurses in a lab study with simulated nursing tasks.

5.3 Apparatus

As mentioned in the work of Myles et al. [MK10], the head is a sensitive region for vibrotactile cues. Since we wanted to compare multiple vibration patterns, we built a first prototype for the upper arm to avoid a negative bias due to discomfort. Based on our design space analysis (see Chpt. 3), the upper arms are (especially for vibrotactile cues) suitable as alternative for the head. The prototype consists of an armlet with three relocatable vibration motors. The prototype can be seen in Figure 5.3.

Our prototype consists of an *Adafruit Feather M0 Bluefruit* micro controller board, three relocatable coin cell vibration motors (10mm dia), two buttons and one RGB LED. With a size of 51mm x 23mm x 8mm, a weight of 5.7 grams, and

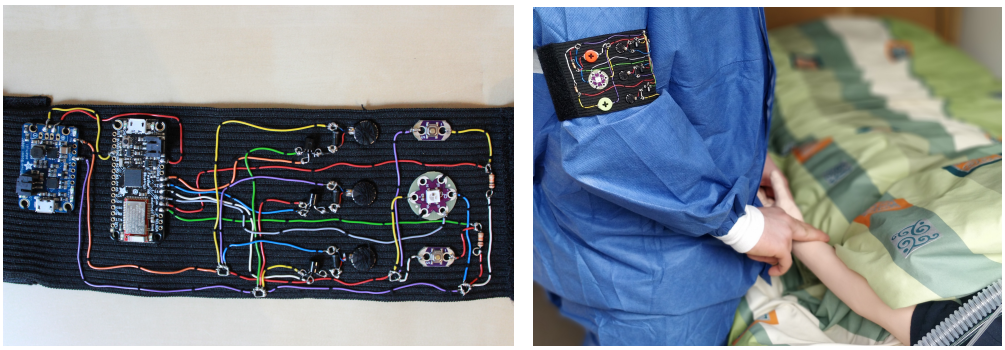


Figure 5.3: Vibrotactile alarm display as an armlet [CEBH18b].

20 GPIO pins, the Adafruit Feather is a suitable board for wearable prototypes. To keep the weight as low as possible, we used a 400mAh 3.7V LiPo battery combined with a *1000c Adafruit PowerBoost* which converts the battery output to 5.2V. We used npn transistors which serve as a switch to control the current flow to the board and to address the individual vibration engines targeted. As buttons, we used two *LilyPad Button Boards* which are explicitly designed for wearable prototypes. Due to the small pressure point of the buttons a button was sewn over each button to simplify the interaction with the device. The RGB LED used to be an additional visual cue for the alarm. In the described studies it serves as a status LED to minimize the independent variables.

Based on literature [CEBH18b], we implemented eight sets, each consisting of three vibration patterns to represent three different urgency levels. A visualization of each set is shown in Figure 5.4. The patterns are distinguished by vibration frequency, number of repeated vibrations, transition of the vibration intensity, and position of the vibrating motor. The urgency level increases from Pattern 1 to Pattern 3. For *Set 1* to *Set7* the vibration motors are placed in a line from top to bottom. *Set 1* is based on the work of Rossa et al. [RFU+16]. The patterns simulate a movement on the skin and thus, they are differentiated by the direction of the moving vibration. Pattern 1 is a movement from top to bottom, vice versa, Pattern 2 from bottom to top. The third pattern consists of a recurring vibration of the middle motor (Motor 2). The vibration duration is 400ms with pauses of 200ms.

Set 2 is also based on the work of Rossa et al. [RFU+16]. Pattern 1 shall represent an increment or opening by starting with a vibration of Motor 2 (400ms),

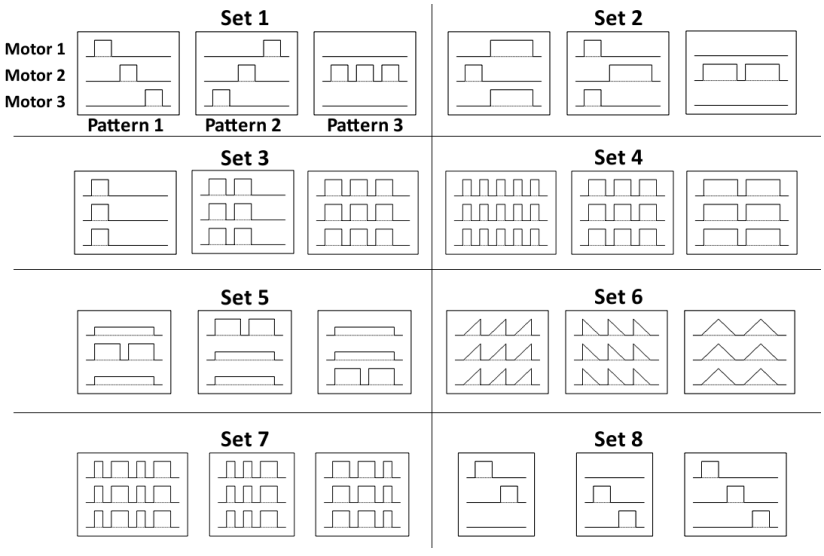


Figure 5.4: Overview of the implemented vibration pattern sets [CEBH18b].

a pause of 200ms, and finally, a vibration (800ms) of the outer motors (Motor 1 and Motor 3). Vice versa, Pattern 2 starts with long vibrations of the outer motors, followed by a short vibration of the middle motor. Pattern 3 consists of a recurring vibration of Motor 2 (600ms) with pauses of 200ms.

Likewise the work of Ng et al. [NMF+05], the patterns of *Set 3* are differentiated by the number of vibrations. Respectively, Pattern 1 consists of one, Pattern 2 of two, and Pattern 3 of three recurring vibrations with a length of 400ms and a pause of 100ms between the vibrations. The pattern itself repeats after an 800ms pause.

In *Set 4*, the length of the vibrations and accordingly the frequency of the patterns decreases from Pattern 1 to Pattern 3. In pattern 1, the length of the vibrations and pauses is 100ms, in the second pattern 200ms, and the third 400ms. This set is based on the work of Dosani et al. [DHD+12].

Similar to the vibration patterns of McLanders et al. [MSTS14], the patterns of *Set 5* are differentiated depending on which of the three vibration motors is active. In the first pattern, the middle Motor 2 vibrates with a length of 800ms and a pause of 200ms. On the other hand, the motors 2 and 3 vibrate very weakly and continuously in order to assist in the classification or localization of the correct vibration motor. In Pattern 2, Motor 1 vibrates with a length of 800ms and a subsequent pause of 200ms, and motors 2 and 3 vibrate weakly, and in the last pattern, Motor 3 vibrates 800ms in length and motors 1 and 2 vibrate weakly.

Set 6 is based on the patterns of Rossa et al. [RFU+16] and includes patterns which are differentiated by different intensity levels. All motors run synchronously. In Pattern 1, the vibration intensity increases steadily from zero to the maximum. When the vibration level reaches the maximum, the vibration immediately drops to zero and pauses for 600ms. Vice versa, in Pattern 2, the vibration level starts at the maximum and drops steadily to zero and then pauses for 600ms. Pattern 3 is a combination of the first two patterns. First, the vibration level increases and then decreases again to pause for 400ms.

The patterns of *Set 7* are differentiated by the order of short and long vibrations. Pattern 1 starts with a short vibration (200ms) followed by a long vibration (400ms). Pattern 2 starts with two short and ends with a long vibration. Pattern 3 starts with two long vibrations and ends with a short one. Between each vibration there is a pause of 200ms. This set is based on the work of Mayuree Srikulwong et al. [SO11], who developed a waist belt to navigate pedestrians.

Based on the work of Lee et al. [LS10], we arranged the vibration motors in form of a right triangle for *Set 8* - Motor 2 and 3 at the bottom and Motor 1 above Motor 2. Pattern 1 consists of an alternating vibration (400ms) from Motor 1 (top) to Motor 2 (bottom), with a pause of 200ms between the vibrations. Pattern 2 means a vibration from Motor 2 (left) to Motor 3 (right). Pattern 3 simulates a rotating movement of the vibration from Motor 1 via Motor 2 to Motor 3.

5.4 Evaluation

We divided our evaluation into two parts with a between-subject design. To find a suitable set of vibration patterns, we first evaluated the perception of the patterns regarding error rates, response time, learnability, distinctness, and diversity of urgency presentation. After that, we evaluated the overall prototype with actual nurses during cognitively and physically demanding tasks.

5.4.1 Evaluation of Vibration Patterns

We conducted a lab study to find out which set of vibration patterns best suits our wearable system. For this study, we invited 12 participants (five female), between 27 and 53 years old (average 35.9 years). Since there is no need for profession-specific knowledge to evaluate vibration patterns, we did not focus on the target group to recruit participants. The study itself consisted of two parts, an initial learning phase and the actual evaluation of vibration patterns. In the learning phase, each set was first explained to the participant on a print-out with a visual representation and then presented on the body-worn prototype. The order of the sets was randomized. After this phase, the vibration patterns were evaluated within the respective sets. Therefore, we sent each pattern of a set three times in randomized order via smartphone to the device. By sending the trigger, a timer was started. As soon as the participant was able to identify a pattern, s/he had to tap on the matching visual representation. Subsequently, we stopped the timer and thus the pattern remotely. We recorded the response time and the error rate for the identification of each pattern within a set. Additionally, the participant assessed the perceived perceptibility, distinctness, learnability and the diversity of urgencies for the vibration patterns in a five-point Likert scale.

5.4.1.1 Results

Figure 5.5 shows the average reaction times and error rates of the participants for each pattern and set. The Shapiro–Wilk test revealed a normal distribution of the data ($p < 0.01$). The fastest response times were measured for Set 4, which has a median of 1.19 s with a low dispersion. The response time of Set 3 was slightly but significantly worse (Wilcoxon signed-rank: $p < 0.05$) with a median of 1.59 s but with a similar dispersion. Generally, the reaction times of Set 3 and Set 4 showed significant differences in comparison with all other sets ($p < 0.05$).

Regarding the error rates, the data are also normally distributed ($p < 0.05$). Figure 5.5 shows that the vibration patterns in Set 3 were detected correctly in all cases. A similarly good recognition rate shows Set 4 with an error rate of 1.85%. However, there are no significant differences.

The subjective rating of perceptibility showed that all sets were perceived at least as good (median 4.0) or really good (median 5.0), whereas Sets 3, 4 and 7

had the lowest standard deviation. Regarding the distinctness of the vibration patterns of each set, Sets 3 and 4 were ranked best with a median of 5.

The participants rated Sets 3 and 4 also as easiest to learn (median 5) followed by Set 7 (median 4.5).

The perceptibility of diversity of urgencies was rated best for Sets 3 and 4 (median 5.0). The remaining sets got an average rating of 3.0 and 4.0, except Set 5 with an average rating of 3.0.

Overall, Sets 3 and 4 stand out with the best response time and the lowest error rate. Set 4 shows a slightly better response time then Set 3. Figure 5.6 shows that the reaction time of the Set 3 patterns increases from Patterns 1 to 3 because participants had to wait for the number of vibrations to identify the pattern. This may also be the reason for the better response time of Set 4. With Set 4, the pattern can be identified directly with the frequency of the vibrations, which results in a constantly low response time. In contrast, Set 3 shows a lower error rating with 0%. However, Set 4 shows an acceptable error rate as well (1.85%). Set 7 shows similar results in response time and error rates, but participants mentioned that Pattern 3 seems confusing and should be adjusted. The remaining vibration patterns can be excluded by a too high error rate for our safety-critical

	Response Time															
	MEDIAN			SD			ERROR %			Perceptibility		Distinctness		Learnability		Urgency	
	Pattern		Set	Pattern		Set	Pattern		Set	MEDIAN	SD	MEDIAN	SD	MEDIAN	SD	MEDIAN	SD
	P1	2,87			1,17			11,11									
Set 1	P2	2,38	2,24		1,01	1,10		8,33	6,48	4,50	0,78	3,00	1,15	4,00	0,87	3,50	1,24
	P3	1,70			0,93			0,00									
	P1	2,46			1,61			8,33									
Set 2	P2	2,28	2,14		1,11	1,23		27,78	13,89	5,00	0,51	4,00	1,29	4,00	1,00	4,00	1,06
	P3	1,89			0,45			5,56									
	P1	1,42			0,34			0,00									
Set 3	P2	1,64	1,59		0,33	0,42		0,00	0,00	5,00	0,29	5,00	0,29	5,00	0,00	5,00	0,39
	P3	1,75			0,48			0,00									
	P1	0,88			0,24			0,00									
Set 4	P2	1,32	1,19		0,36	0,46		2,78	1,85	5,00	0,00	5,00	0,45	5,00	0,45	5,00	0,49
	P3	1,31			0,52			2,78									
	P1	3,61			2,42			38,89									
Set 5	P2	3,80	3,93		2,78	2,44		47,22	38,89	4,00	1,00	1,00	0,89	3,00	0,90	2,00	1,14
	P3	4,59			2,26			30,56									
	P1	2,29			1,51			11,11									
Set 6	P2	1,92	2,29		1,07	1,38		19,44	18,52	4,50	0,67	3,50	0,87	4,00	1,09	3,00	1,00
	P3	2,55			1,42			25,00									
	P1	2,19			1,77			2,78									
Set 7	P2	1,95	2,12		1,07	1,29		2,78	4,63	5,00	0,29	4,00	0,83	4,50	0,52	4,00	0,79
	P3	1,94			0,60			8,33									
	P1	3,09			1,25			8,33									
Set 8	P2	2,61	2,70		1,53	1,30		8,33	7,41	5,00	0,79	4,00	0,98	4,00	1,04	3,00	1,06
	P3	2,40			1,08			5,56									

Figure 5.5: Response time and error rates [CEBH18b].

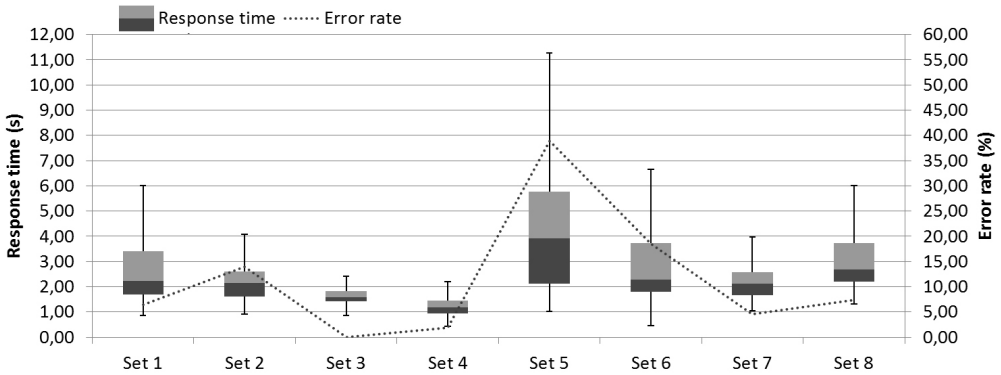


Figure 5.6: Response time and error rates [CEBH18b].

application. The order of the errors did not indicate a learning effect. Thus, Set 3 and Set 4 are implemented for the evaluation of the WAS.

5.4.2 Validation of the Vibrotactile Alarms

The results of the former study indicated that for Set 3 a lower error rate but longer duration to identify a pattern comes about than for Set 4. Since this study was conducted without a simulated load, we want to investigate if there are similar results with actual nurses during simulated nursing tasks. This led us to the following hypotheses:

Hypothesis 1 (H1). *The response time of the participants to the vibration patterns of Set 3 is equal to that of Set 4.*

Hypothesis 2 (H2). *The response time of the participants to the vibration patterns of Set 4 is lower than that of Set 3.*

Hypothesis 3 (H3). *The error rate of the participants for Set 3 is lower than that for Set 4.*

To confirm those hypotheses, we conducted a within-subject lab study with 12 participants (10 female) with an average age of 37.6. All participants were fully trained nurses and three of them trained ICU nurses. The study was divided into a short training phase in which the prototype, its functions and the vibration patterns were introduced to the participant, followed by the actual study. The study design consists of two main conditions—one with a cognitive load and another with a physical load for the participant. This approach was supposed to represent two typical kinds of loads that humans in general and nurses and

physicians in particular often bear. In the cognitive task, the participant sat at a table and had to filter out a given four-letter word in a series of similar four-letter words and mark it with a pen. In the physical task, the participant had to remove the duvet cover of a blanket and then cover it again. Both conditions were divided into two subconditions by presenting Set 3 and Set 4. The order of the conditions was counter-balanced. During the task, the participant wore the WAS on the upper arm and got alarms of the respective set with different urgencies delivered. The alarms were triggered remotely via a smartphone. As soon as an alarm was triggered, a timer started automatically. While focusing on the task, the participant had to name its urgency level. Furthermore, s/he had to press the red button for a critical alarm (Pattern 3) and the green button for an uncritical alarm (Pattern 1 or 2). We recorded the error rate of the pressed buttons as well as the response time from sending the trigger to the identification of a pattern. Each kind of alarm was triggered three times in a randomized order.

Finally, each participant had to fill out a System Usability Scale (SUS) [Bro96] to rate the usability, and a Comfort Rating Scale (CRS) [KB05] to rate the overall comfort of the prototype.

5.4.2.1 Results

In Figure 5.7, the response times and error rates for both conditions are visualized. The response times and error rates are both normally distributed ($p < 0.05$).

Compared to the vibrating pattern study, in which the participants were able to concentrate fully on the vibration patterns, the response times to the two sets during the execution of both tasks are noticeably higher. During the cognitive load, the response time of both sets is almost equal with a median of 2.29 s for Set 3 and 2.34 s for Set 4.

During the physical load, the response times were generally slightly higher. Both sets showed similar response times with a mean of 2.58 s for Set 3 and 2.51 s for Set 4. However, Set 4 shows a higher dispersion in the response time. There were no significant differences.

Regarding the error rate, the results of Set 3 were similar to the first study. During the cognitive load, no mistakes were made. In the physical task, the error rate for Set 3 is 0.93%. In comparison to the first study, the error rate for Set 4 increased, with 7.4% during the cognitive load and 12.04% during the physical load. A Wilcoxon signed-rank test revealed that the error rate for Set 4 is significantly higher than for Set 3 ($p < 0.05$).

The analysis of the SUS revealed a score of 95,42 which means a very good usability. Regarding the single parameters, there were deficiencies in the integration of functions. Several participants mentioned concerns regarding the usage of buttons for hygienic reasons. The results of the CRS showed also positive results (see Fig. 5.8). However, there were limitations in the affect to the movement of the

			Cognitive Load						Physical Load					
			Set 3			Set 4			Set 3			Set 4		
			Low	Middle	High	Low	Middle	High	Low	Middle	High	Low	Middle	High
Response Time	MEDIAN	Pattern	2,08	2,32	2,35	2,46	2,68	1,88	2,63	2,42	2,70	2,56	2,63	2,17
		Set	2,29			2,34			2,58			2,51		
	SD	Pattern	0,82	0,69	0,55	0,82	0,62	0,45	0,64	0,47	0,62	0,91	0,79	0,61
		Set	0,69			0,73			0,58			0,80		
	ERROR	Pattern	0,00	0,00	0,00	11,11	11,11	0,00	2,78	0,00	0,00	16,67	13,89	5,56
		Set	0,00			7,41			0,93			12,04		

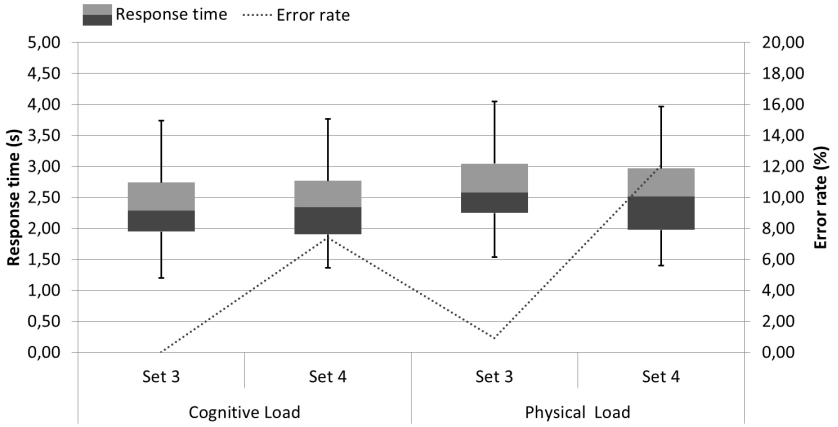


Figure 5.7: Results of the experiment [CEBH18b].

participants (median 2.5) and the attachment on the body (median 1,5), induced by the early state of development.

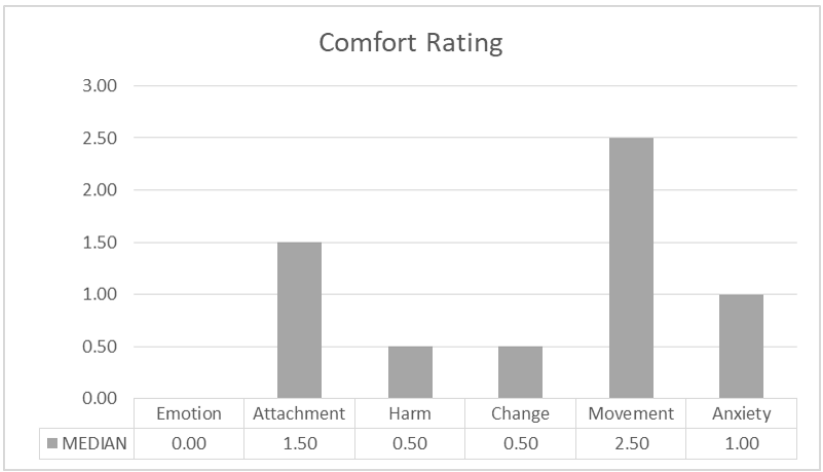


Figure 5.8: Results of the Comfort Rating Scale

5.5 Discussion

The evaluation of the prototype with nurses showed positive results regarding the error rate and response time in identifying a vibrotactile pattern. With at least two sets of vibration patterns, we could represent three different levels of urgency. From the study results, we learned that there is a higher error rate as well as a higher response time for both sets during physically demanding tasks.

Since there are no significant differences in the participants' response time for both sets, we have to reject = H2 and accept H1, respectively. Regarding the error rate, Set 3 shows significantly better results than Set 4, thus, we can accept H3 with $p < 0.05$. Even though for both sets, the response time is almost equal with a median of 2.29 s for Set 3 and 2.34 s for Set 4, we have to reject Set 4 based on the error rate. Since we aim to develop a WAS for an ICU, which means a safety-critical environment, the error rate for Set 4 is not acceptable. Therefore, the patterns of Set 3 will serve to represent vibrotactile alarms for our WAS.

For further iterations of the prototype, another interaction method should be considered. Several participants mentioned concerns regarding touching a button, due to the fact that nursing provides the risk of getting in touch with infectious body fluids. Thus, the risk of a cross contamination will be increased with the button.

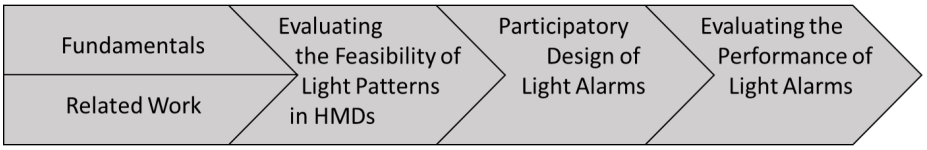
Finally, our prototype was rated with a very good usability as well as a good wearing comfort during simulated nursing tasks. This means, a vibrotactile alarm display could also serve as a stand-alone notifier.

In the next chapter, we will describe the design and evaluation of peripherally visual alarm light patterns.

6 Design of Peripheral Light Alarms

Many PMS highlight the source of the alarm (e.g., the relevant vital parameter) on the information display with the colors red (critical), yellow (uncritical) and blue (technical). However, the design space for light patterns contains more parameters than just the hue. In prior research we could show that other parameters, such as, e.g., the blinking frequency or brightness, affects the perceived urgency of the delivered information [MCM+15]. For that reason, we conducted a participatory design study to design light patterns that represent three levels of urgency, based on the given color mapping.

This chapter is structured as follows:



Parts of this chapter were published in Cobus, Vanessa ; Meyer, Hannah ; Boll, Susanne ; Heuten, Wilko: Towards Reducing Alarm Fatigue: Peripheral Light Pattern Design for Critical Care Alarms. In: *Proc. of the 10th Nordic Conference on Human-Computer Interaction*, ACM, 2018 (NordiCHI '10).

6.1 Visual Perception

By receiving light waves reflected from objects in our environment, we can see these objects with our eyes (see Fig. 6.1).

The incident light is refracted by the cornea and the lens, and projected onto the retina. In order to display the incident light rays as a focused image on the retina, the lens can influence the refractive power.

The retina consists of three cell layers and has the task of converting the incident light into electrical impulses, which are then transmitted via the optic nerve for further processing. The transduction of light waves into electrical signals occurs through photoreceptors which are located in the outer cell layer [GRH02].

We distinguish the receptors between rods and cones, whose names are based on their shape. Rods are more light-sensitive than cones and are responsible for twilight vision. Cones, on the other hand, are less light-sensitive, but differ in S, M and L cones, which react to the different wavelengths (short, medium and long) of light and are therefore responsible for color vision. On the retina there are about 100 million rods and 6 million cones, which are distributed differently.

The fovea is a small area of the retina on which the image lands in the central field of vision. This area contains no rods, but a large number of cones, and is

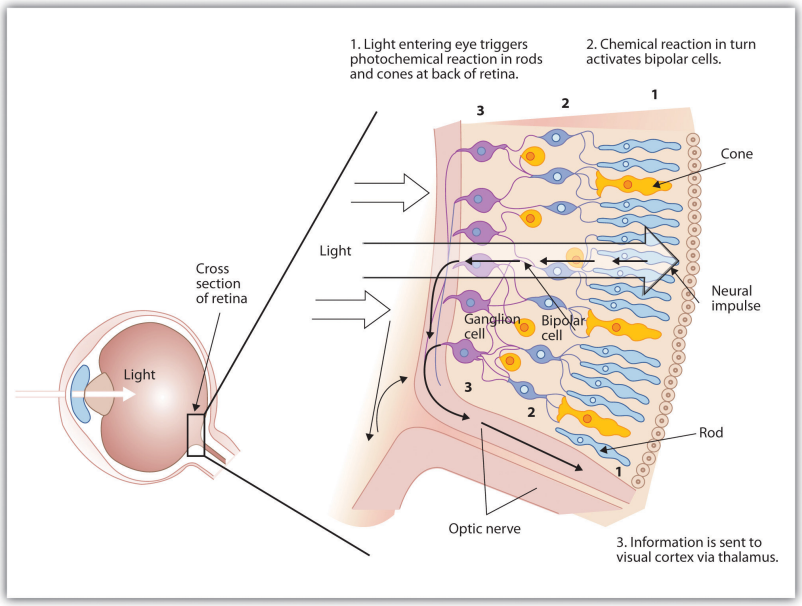


Figure 6.1: The process of seeing [n.a19].

responsible for visual acuity during daytime vision. In the area outside the fovea, however, the number of rods clearly exceeds the number of cones [KSJ+13]. The fovea centralis enables to see objects sharp and clearly. The so called foveal vision is only possible in the approx. 1° wide center of the visual field.

In contrast, the peripheral vision, or visual perception, begins outside the 5°-10° wide central area and extends from the center 60° and 75° up and down, 60° nasal and 100° temporal [BHW09]. In the peripheral field of vision, movements are perceived and processed very quickly in order to quickly draw attention to possible dangers outside the focus. Light signals are therefore more likely to attract attention if they are dynamic [AMM+16]. The perception of colors varies depending on the angle. In the outer visual field the eye can only distinguish between black and white, further inside between yellow and blue and is still further inside sensitive to red and green (see Fig. 6.2)[SR76].

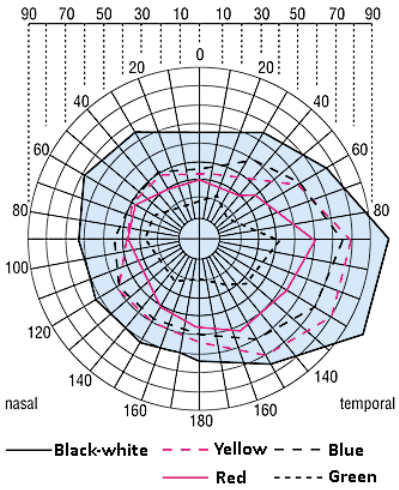


Figure 6.2: The field of view for color perception [SR76].

The color perception is the ability to visually separate objects from each other and moreover, to highlight an object from the background. The perceived color

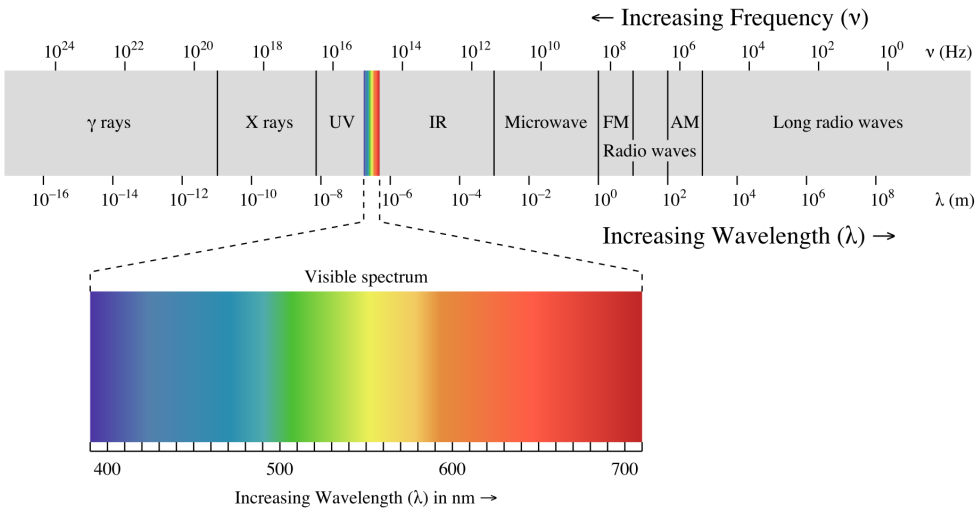


Figure 6.3: Electromagnetic spectrum [Ron19].

results from the wavelength of the light ray that was reflected by the respective object and received by our eyes [GRH02]. The wavelengths and the matching colors can be seen in Fig. 6.3. Likewise the auditory attention, the visual attention can be divided into split and selective attention. In split attention, attention is given to several objects at the same time, but the human capacity for this form is very limited. However, due to the small fovea, the anatomy of the human eye is designed on selective attention, which means attention is given to certain objects and others are hidden. In order to capture a scenery, the fovea is repeatedly aligned to objects that are to be processed more closely. These fixations are usually performed three times per second and are also subject to both endogenous and exogenous factors. Objects with bright colors and high contrasts, as well as flashing lights with high frequencies, have a high stimulus and are more likely to attract attention [GRH02].

6.2 Related Work

Past research showed that peripheral light is a suitable modality to represent information within ambient systems in several domains. Chang et al. investigated the use of a noise-sensor light alarm in a newborn ICU [CPL+06]. The device in the form of a flower was installed on a central wall of the ICU. It lights up when the noise level exceeds 65 dBA. The study results indicated that this peripheral light alarm has positive effects in reducing the environmental sound in the newborn ICU.

One example from the office domain is the *Ambient Timer*, developed by Heiko Mueller et al. [MKP+13]. This ambient display is placed on the back of a monitor

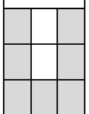
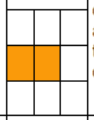
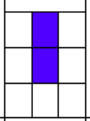
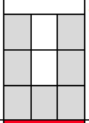
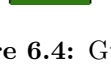
Name	Light Pattern	Description	Situations		Information Class
			Suit best	Suit worst	
LP1		Color linearly fading from green through yellow to red with linearly increasing brightness	1) Timer (time -> no time) 2) Presence (few -> many)	Direction (Turn-by-Turn, Compass)	Progress
LP2		Color linearly fading from red through yellow to green with static brightness	1) Goal (start -> reached) 2) Physical Activity (few - many)	Direction (Turn-by-Turn, Compass)	
LP3		Color linearly fading from blue through yellow to red with static brightness	1) Temperature (cold -> warm)	Direction (Turn-by-Turn, Compass)	Status
LP4		Color linearly fading from blue through green to red with static brightness	1) Temperature (cold -> warm)	Direction (Turn-by-Turn, Compass)	
LP5		Color stepwise fading from green through yellow to red with static brightness	1) Timer (time -> no time) 2) Presence (few -> many)	Direction (Turn-by-Turn, Compass)	
LP6	Front 	LEDs light up only in white color additionally to the central, but NOT diagonally	Direction (Turn-by-Turn)	Temperature, Presence, Physical Activity, Notification (urgent)	Spatial
LP7	Left 	LEDs light up in different colors additionally to the central, but NOT diagonally	Direction (Turn-by-Turn)	Temperature	
LP8	N 	LEDs light up in different colors additionally to the central, including diagonal	Direction (Compass)	Notification (urgent, unimportant)	
LP9	N 	LEDs light up only in white color additionally to the central, excluding diagonal	Direction (Compass)	Temperature, Speed, Presence, Distance, Notification (urgent, unimportant)	
LP10		Blinking red light	Notification (urgent)	Direction (turn-by-turn, Compass)	Notification
LP11		Blinking white light	Notification (unimportant)	Direction (turn-by-turn, Compass)	
LP12		Blinking green light	Notification (unimportant)	Direction (turn-by-turn, Compass)	

Figure 6.4: Guidelines to map information to light patterns [MCM+15].

and emits the light patterns via LEDs on a wall behind the monitor. With a color change from green to orange/red, *Ambient Timer* grabs the users attention and indicates the remaining time until an upcoming event. The results of a

lab experiment showed that this system is at least competitive with traditional reminding techniques (e.g. checking the clock, notification pop ups).

In prior research in cooperation with Andrii Matviienko et al. [MCM+15], we developed guidelines to map information to light patterns. We structured similarities in existing light encodings and defined four information classes based on that:
Progress – relative indication of goal achievement
Status – absolute current value
Spatial – direction to a point-of-interest
Notification – information that grabs attention.
Matching those information classes, we defined everyday life scenarios (e.g., elapsing time as progress information, temperature as a status information or urgent/low-priority notifications) and did a two-parted participatory design study. The resulting patterns can be seen in Fig. 6.4. The focus was placed on color and brightness of light as well as LED position. The derived light patterns have been evaluated with a second group of participants.

Our findings deduce options on how to encode these information classes and derives nine design guidelines for ambient light systems but is limited to portable devices laying on a table. Based on this work, we implemented notification light patterns, to evaluate their feasibility on an HMD under different task conditions.

In 2014, Jutta Fortmann et al. [FCHB14b] developed a wearable device to remind users to drink water. The device in form of a bracelet indicates the elapsed time since the users last water consumption using peripheral light and finally an additional vibrotactile notification as a reminder event. Study results confirmed significantly that drinking inputs were in more than 90% made before the vibrotactile reminder event. This work demonstrates, that light can be used to grab attention if positioned in the user's peripheral vision.

Researchers investigated the usage of peripheral light on HMDs already for different domains. In 2012, Benjamin Poppinga et al. [PHF+12] evaluated the light encoding of spatial information on an HMD with *AmbiGlasses*. This is a pair of glasses with 12 LEDs that illuminate the periphery of the user's field of view. A user study revealed that participants were able to locate the correct LED with 71% accuracy. Furthermore, this work shows that light spots on the left, right, and bottom of the glasses were detected very accurate, while the light spots located in the center showed misclassifications.

Unlike *AmbiGlasses*, Takuro Nakuo et al. [NK16] presented an HMD that consists of a pair of 3D printed glasses with two 8x8 dot matrix modules on the left and right side of the glasses, driven by an Arduino Nano. The authors gave insights into the initial evaluation and a recommendation for animation patterns.

One HMD aiming at the reduction of noise from mobile phones was engineered by Enrico Constanza et al. in 2006 [CIP+06]. It consists of a peripheral display

(EYE-Q) built from two arrays of LEDs embedded next to the lenses in ordinary glasses. Studies showed that the flashing LEDs are generally perceivable and that the level of perceptibility can be manipulated by brightness and velocity of the cues. Bright and fast cues were noticed faster than dim and slow ones. It was also demonstrated that the level of perceptibility depends on the wearer's level of workload. In contrast to this, we want to compare the perceivability of light patterns during different kinds of load that simulate nursing tasks.

Evangelos Niforatos et al. [NFEL17] showed positive results of using peripheral light cues to improve the user's perception in a physically demanding task: skiing. They embedded three LEDs into a ski helmet. The *Smart Ski Helmet* detects other skiers approaching from behind and alerts the user with peripheral light cues. The helmet was evaluated by 26 participants and improved the user's peripheral perception by 50% in an off-slope experiment and by 35% on a traverse slope.

6.3 Apparatus

To design and evaluate peripheral light cues, we developed an HMD, based on safety glasses with a diffused peripheral LED display next to each eye. We removed the plastic glasses and used only the frame to avoid a distracting effect in the users vision. We attached 7 *Adafruit Neopixel*-LEDs on each side of the glasses (3 vertical, 4 horizontal), outside of the field of view. As an additional diffuser, we used *Gorilla plastic*. We used an *Arduino Feather m0* as a micro controller board to program the LEDs. The implemented patterns are presented in each associated study. The prototype is shown in Figure 6.5.

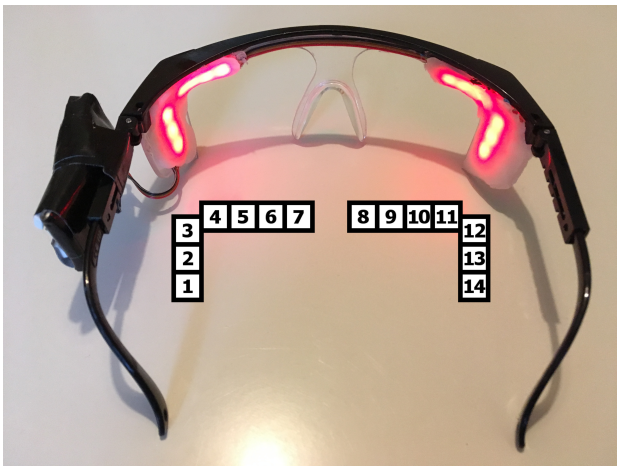


Figure 6.5: Head-mounted display and the numeration of LEDs [CMBH18].

6.4 Evaluation

We conducted a study to design alarm cues for the alarm categories “critical alarm”, “uncritical alarm” and “technical alarm”. We divided our study into two conditions, a design study and a validation of the patterns.

Due to their very demanding shift work, conducting studies with nurses as participants may present several issues for them, e.g., the time needed to participate in the study or the competing commitments for clinical practice.

Since this study took place in a preliminary stage of exploring light patterns to represent different urgent alarms, we conducted the first user studies outside the target group to finally take the findings from our work to nurses.

6.4.1 Feasibility Study

In ICUs, evaluating an alarm’s criticality is determinant for nurses whether to interrupt a task or not. Thus, it is important that each alarm is well perceivable and distinguishable from each other.

In our first study we wanted to evaluate if this requirement can be fulfilled if information is presented with peripheral light on an HMD. Based on the work of Matviienko et. al [MCM+15], we implemented verified light patterns matching the information category "notification" using a blinking in red, yellow, and blue (see Fig. 6.6). The patterns differ in the blinkin frequency in terms of priority. The brightness values were adapted due to former pretests.

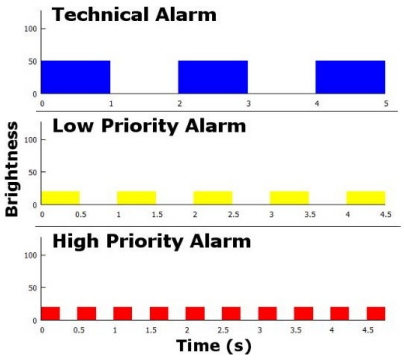


Figure 6.6: Patterns used in the feasibility study.

We were generally interested in the following questions behind that issue:
How perceivable are the implemented patterns on an HMD?
Is it sufficient to display the peripheral light cues on just one eye?
Can they be distinguished from each other?
How much do the patterns distract the user from his or her actual task?
We also especially wanted to validate the following hypotheses:

H1: The urgent notification patterns are as well perceivable as the less urgent ones.

H2: The error rate for the pattern recognition is lower by presenting them to both eyes instead of one eye.

For that purpose we conducted a user study with eleven participants (six female), who were aged between 18 and 41. Each participant had a normal or rectified vision (through contact lenses). None of them were color blind. Because a simultaneous wearing of glasses and the prototype is not possible, we excluded wearers of glasses from the study. During the acquisition, we particularly paid attention not to choose exclusively technology-oriented participants. Seven of the participants rated themselves as technophile. In preparation for the study, the light patterns of each category were presented to the participants on the prototype laying on the table (see Fig. 5.3). The name of each pattern was communicated to them. In doing so, we wanted to make sure that we did not test the implemented patterns itself, but the feasibility of them on HMDs. We also placed print-outs of the design of the light patterns on all relevant locations in the study room.

The study itself consisted of two main conditions – one with a cognitive and another with a physical load for the participant. This approach was supposed to mimic common loads that nurses as well as physicians in particular are often exposed to. In condition "Cognitive Load" the participant was asked to perform the n-back-task on a tablet PC. This task is commonly used to claim the working memory [SLSS11] which is also comparable to a patient handover at the end of a shift.

In contrast, in condition "Physical Load", the participant was supposed to carry a box with four books of 7kg from one area to another. There were three areas in total and when the participant arrived at one of them, s/he was supposed to place the books on a marked field of the same color. This task can be compared to carrying portable medical devices to a patient.

The order of the conditions was randomized. Since we did not want to measure the task performance itself but create a realistic environment in this study, no scores have been recorded. This was improved by an occasional conversation between the participant and the conducting researcher. Both settings were subdivided into presenting patterns only on the right eye and on both eyes. The decision for testing the right and not the left eye was due to the fact that about 70% of the people prefer to use their right eye for viewing [Car01]. The order of the sub-tasks within the two main tasks was also randomized. Hence, the study was overall divided into the conditions

- Cognitive load, light patterns on right eye,
- Cognitive load, light patterns on both eyes,
- Physical load, light patterns on right eye and
- Physical load, light patterns on both eyes.

Every participant was supposed to attend all conditions. Throughout these conditions the participant wore the prototype and the implemented light patterns were presented in random order and in intervals of one minute. Each pattern was shown to them three times during every condition. Each time the participant noticed a light pattern, s/he was asked to communicate the matching category

(from his/her point of view) to the researcher. If the participant could not name the pattern, s/he was nevertheless asked to communicate that s/he noticed a light.

The researcher noted the perceived patterns (potentially with their stated types) in a protocol, and also recorded missed patterns. In addition, the participant ranked each perceived pattern by its noticeability and level of distraction on a five point Likert scale in a questionnaire. In the very first part of the study each participant had an extended interval of two minutes after the first presented pattern to get used to that scale. During the whole study the participant was asked to think aloud. At the end of the study we asked questions about the level of pleasantness, informativeness and intuitiveness of this kind of information transfer in general, for both eyes and for the right eye. The participant was asked to write down his preferred kind of information transfer: On the right eye or on both eyes. S/he should also state if there had been patterns which were particularly poorly perceivable, hardly distinguishable or highly distractable. Finally, s/he had been given space to add further annotations.

6.4.1.1 Results

In the following paragraphs, we differentiate between the error rate, the subjective rating of the patterns and the final rating of the perceived information transfer with one or two eyes and generally over all patterns.

Error Rate

If a participant missed a pattern, stated the wrong pattern type or could not indicate the type at all, we counted this as an error. The average error rate was 4.2%. In detail, Low-Priority Alarm showed the highest error rate (5.3%), followed by Technical Alarm (4.5%) and the pattern High Priority Alarm has the lowest error rate (3%)(see Fig. 6.7). There were no significant differences between the patterns. However, when we take a closer look at the errors made by the participants, we can recognize certain features: In 47% of the errors the pattern has been mistaken for another pattern. 41% of the errors were missed patterns. For the remaining 12% no type of pattern was stated. This only affects the pattern *Low Priority Alarm*.

When comparing the conditions "Both Eyes" and "Right Eye", one can see a remarkable difference in the average error rates (0.05% versus 8.0%) as well as in the error rate of each pattern (see Fig. 6.7, right). Moreover, all missed patterns occurred at the "Right Eye" condition. A Wilcoxon signed-rank test ($p < 0.05$) showed a significant difference between the error rates. The average error rates of the conditions "Physical Load" and "Cognitive Load" are almost similar with 1.9% and 2.3%, respectively. This difference is not significant ($p = 0.06$), which indicates that the task load has no effect on the error rate of the light patterns.

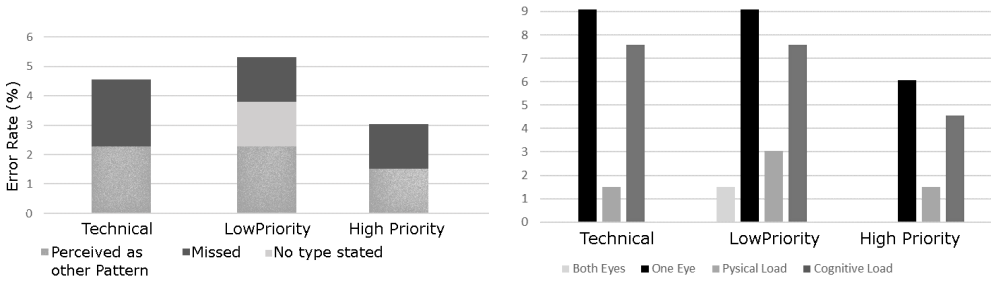


Figure 6.7: Error rate per pattern: Type of error (left), divided into conditions (right).

Subjective Pattern Evaluation

	Distraction		Perception	
	Mean	SD	Mean	SD
Physical L.	1,98	0,99	4,2	0,6
Cognitive L.	2,5	0,5	4,1	0,6
Both Eyes	2,1	0,7	4,4	0,4
One Eye	2,4	0,7	3,8	0,7
High Priority	2,1	0,8	4,3	0,5
Low Priority	2,3	0,7	4,1	0,6
Technical	2,1	0,7	4,2	0,7

		Median	SD
How pleasant?	General	2	0,6
	Both Eyes	2	0,8
	Right Eye	3	1,1
How informative?	General	2	0,9
	Both Eyes	2	0,8
	Right Eye	3	1,0
How intuitive?	General	2	0,9
	Both Eyes	2	0,6
	Right Eye	2	1,1

Table 6.1: Summary of the rating results.

The subjective rating of the perceptibility and distraction can be seen in Table 6.1. The diagram in Fig. 6.8 shows the following tendencies: Patterns at "Both Eyes" seem to be less distracting and better perceivable than patterns at "One Eye". Furthermore, patterns at "Physical Load" appear to be less distracting than patterns at "Cognitive Load" while there seems to be no difference in the perceptibility. We calculated the mean ranking of each pattern for each condition. In this respect, we encoded the rankings from "very poorly perceivable / not at all distracting" to "very well perceivable / very much distracting" with the numbers 1 to 5 (see Fig. 6.8). A Friedman test revealed that there are no significant differences between the perceptibility ($p = 0.162$) or distraction ($p = 0.159$) among the patterns. When comparing the means of "Both Eyes" and "One Eye" with each other, we found a significant difference in the perceptibility ($p = 0.006$) using a Wilcoxon signed-rank test. The same kind of test showed no significant difference in the distraction among these conditions ($p = 0.083$). There have also been no significant differences regarding perceptibility and distraction between the conditions "Physical Load" and "Cognitive Load" ($p = 0.359$ and 0.083).

Information Transfer

We compared the perceived pleasantness, informativeness and intuitiveness of the information content on both eyes (mean=1.91, SD=0.83) with that on one

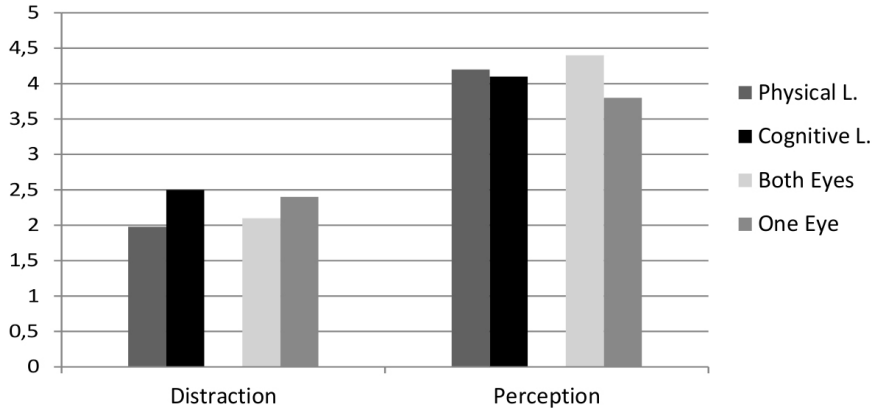


Figure 6.8: Perceived Distraction (left), Perceivability (right)

eye (mean=3.0, SD=1.0), whereas "1" means very pleasant/informative/intuitive and vice versa. There was a significant difference in the informativeness of the two variants ($p = 0.02$). However, the other two criteria showed no significant differences ($p = 0.128$ and 0.058). When asked where they would prefer the information transfer, nearly all participants (82%) indicated "Both Eyes". The reason was mainly a better perceptibility and thereby a lower probability to confound or miss the light signals. Two participants also mentioned a lower level of distraction given that one would not have to focus on the light signals. The remaining two participants (18%) preferred an information transfer on "One Eye" – a favorite side has not been stated. One of them noted that this would be less distracting, the other one that it would be more pleasant (less glaring) but the signals would sometimes be hard to perceive or distinguish.

Qualitative Feedback

Nine participants preferred the condition with "Physical Load" for different reasons. Six of them noted that the patterns were easier to perceive or distinguish, one assumes this could be the case since one is "not focused to one point [...] but also perceives peripheral areas". Five participants considered the patterns shown at the physical task as less distracting. A participant supposed that this could be caused by the fact that the n-back-task is an ongoing process. An interruption by a light pattern may prevent from performing in the n-back-task correctly for a short time since one may have missed the former position of the square.

6.4.1.2 Discussion

This study served to test the general feasibility of verified light patterns notifications presented on an HMD using the colors red, yellow and blue. Our results showed that the implemented patterns are generally perceivable and distinguishable on an HMD with an acceptable amount of distraction. As there is no significant difference between cognitive and physical demanding task, we assume

that these patterns are also feasible during nursing tasks. Even the average error rate of 4.2% is critically high for an alarm communication method, it has to be considered that the error rate has been originated by mistaking patterns in almost 50%. This affirms that the light patterns, have to be modified for HMDs. Moreover, we could show that, with $p > 0.05$, there is no significant difference in the perception of the notification patterns but a tendency that urgent notifications are better perceivable. Therefore, we can reject H0. With $p = 0.02$ we can confirm our hypothesis H1 and propose that peripheral light patterns should be presented on both eyes.

6.4.2 Participatory Design Study

For the design study, we invited ten participants (six female), between 18 and 33 years old, without a specific background. Each participant had a normal or rectified vision (through contact lenses). None of them were color blind. In the first condition, the participants were asked to design two urgent light patterns for the color red and two less urgent light patterns for the colors yellow and blue. We made these colors mandatory because they are already established in several ICUs for the different alarm categories.

We provided a laptop on which the light pattern was programmed via the *Arduino IDE*. To simplify the design of the light patterns, we predefined functions that let the participants adapt: (1) the brightness levels (from 0 to 255), (2) the brightness transition (stepwise/smooth), (3) the duration of the lighting/smooth transition, and (4) individual LEDs that should light up.

These functions, a description, and a scheme with the numeration of the LEDs on the prototype were placed on a table next to the study laptop, always visible for the participants. Every design was directly uploaded and shown on the prototype and, if necessary, corrected. The participants were asked to think aloud during the design process and to justify their design solutions afterward. In the end, they had to choose, for each color, which pattern they prefer.

6.4.2.1 Results

Since every participant developed individual light patterns, we derived the following similarities:

Stepwise Transition The light pattern includes a stepwise brightness transition.

Smooth Transition The light pattern includes smooth brightness gradient.

Different LED Positions The light pattern includes the use of different LED positions.

The frequency of the general use of each parameter is shown in Table 6.2. The number in parentheses states the frequency of the used parameter within the preferred patterns.

Table 6.2: Used parameters within all designed light patterns [CMBH18].

	Red	**Yellow**	**Blue**
Stepwise Transition	12 (4)	2 (1)	2 (0)
Smooth Transition	1 (1)	3 (1)	2 (1)
Stepwise + Smooth Transition	3 (3)	5 (2)	6 (5)
Different LED Positions	4 (2)	10 (6)	10 (4)

Regarding the preferred light patterns, the majority of the red patterns included a stepwise brightness transition or at least a combination with a smooth transition (e.g., a fading out). The majority of the yellow patterns included the use of different LED positions such as a chasing light or only the outer LEDs blinking. The blue patterns were mostly designed with a combination of stepwise and smooth transitions as well as with different LED positions.

During the thinking aloud process, the following statements have frequently been made: three participants stated that the lateral LEDs appear to be brighter than the top ones. Three other participants mentioned that the urgency was intrinsically encoded by the color. It was especially remarked that yellow is more urgent than blue (5), yellow and red are more urgent than blue (4) and that red is more urgent than yellow and blue (2). Nearly all participants (9) perceived higher blinking frequencies as more urgent, and five participants considered dimmed ("soft") brightness modification as less urgent. Four participants referred to more LEDs switched on and to an increasing brightness as being more urgent, respectively. Finally, three participants stated that they had based their pattern designs on commonly known alarms.

The results indicate that the color blue appears less urgent than yellow or red and yellow appears generally less urgent than red. This complies with the general perception of colors. Furthermore, a lower urgency was represented with smooth brightness transitions. This has to be considered for the final design.

Deriving from the results, we implemented five light patterns for each color, which are shown in Figure 6.9. The patterns are distinguished by blinking frequency, brightness, brightness transition, and the position of the blinking LED.
Pattern 1 – Red blinking, varying length, repeated three times. All LEDs light up two times for 0.1s with a brightness value of 100 and one time for 1s with a brightness value of 70. Between each flash there is a 0.4s break and the pattern repeats after 1s.
Pattern 2 – Red blinking, constant length (short). All LEDs light up seven times for 0.1s with a 0.4s break in between and a brightness value of 100.
Pattern 3 – Red blinking, constant length (medium). All LEDs light up five times

for 0.4s with a 0.4s break in between and a brightness value of 70.
Pattern 4 – Red blinking, constant length (long). All LEDs light up seven times for 1s with a 0.4s break in between and a brightness value of 50.
Pattern 5 – Red dimming down. All LEDs are dimmed five times from brightness value 150 to to 0 over 0.8s with a 0.2s break.
Pattern 6, 11 – Yellow/blue dimming down. All LEDs are dimmed five times from brightness value 200 to to 0 over 0.8s with a 0.2s break.
Pattern 7, 12 – Yellow/blue dimming up. All LEDs are dimmed five times from brightness value 0 to to 200 over 0.8s with a 0.2s break.
Pattern 8, 13 – Yellow/blue pulsate. All LEDs are dimmed five times from brightness value 0 to 200 and back to 0 over 0.8s with a 0.2s break.
Pattern 9, 14 – Yellow/blue blinking sides. LEDs 1, 2, 3 and 12, 13, 14 light up five times for 0.4s with a 0.4s break in between and a brightness value of 100.
Pattern 10 – Yellow chase, two times repeated. Two LEDs light up pairwise, chasing from the outside (LED 0 and 14) to the inside (LEDs 7 and 8).
Pattern 15 – Blue, additively switching on, three times repeated. Every 0.4s two LEDs will be successively switched on, beginning from the outside (LED 0 and 14) to the inside (LED 7 and 8). The pattern repeats after a 0.1s break.

The frequent use of stepwise transitions for high priority alarms confirms the guidelines for urgent notifications of Matviienko et al. [MCM+15]. Therefore, we designed four light patterns using stepwise brightness transitions. They differ in the frequency of blinking and the brightness. One pattern is based on the preferences in the designed red patterns including a combination of stepwise and smooth transitions. Since yellow and blue patterns shall appear similarly urgent, we implemented similar patterns. Three of them include a combination of stepwise and smooth transition, one is a pulse, and one is a chasing light. Durations and brightness values are based on former pretests.

6.4.3 Validation of the Peripheral Light Alarms

In a further study, we wanted to evaluate which of the shown patterns is best suited for representing three different types of alarms. Moreover, we wanted to find out whether blue light patterns appear, generally, independent from the design of the pattern, less urgent than red or yellow. This study served for evaluating the implemented light patterns (see Figure 6.9) with regard to subjectively perceived urgency, comfort and distraction. Moreover, we wanted to derive at least one feasible light pattern for each alarm.

For this evaluation, we invited 20 participants (11 female), between 18 and 41 years old. Each participant had a normal or rectified vision (through contact lenses). None of them were color blind. During the user study, the 15 light patterns (see Figure 6.9) were shown to the participants on the HMD in intervals of one minute. Each pattern was repeated three times; the order of the patterns

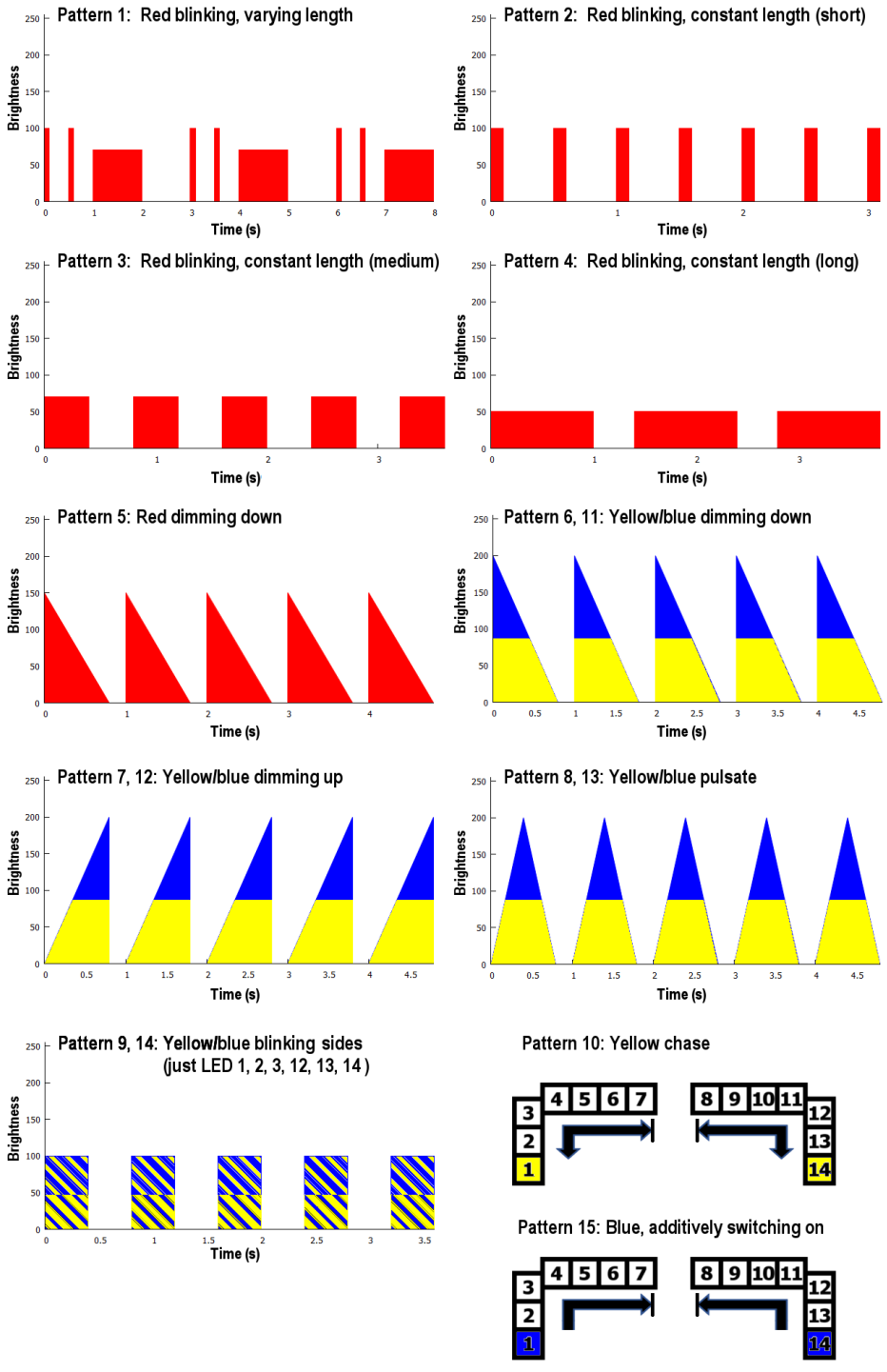


Figure 6.9: Overview of the implemented light patterns [CMBH18].

was randomized. To prevent the participants from getting tired or irritated, we split the study into three conditions with different precision-demanding tasks [EB13, YJ15]. The tasks should also represent a load similar to that on ICUs (e.g., giving injections). The order of the conditions was counterbalanced. The first task was a wire loop game in which the participant has to remove plastic items from cavities inside the patient with a pair of tweezers without touching the edges of that cavity [EB13]. If s/he touches an edge, the game board gives a visual and audible signal. In the second task, the participants had to play another wire loop game in which they must try to guide a wand along a wire without touching it. As soon as the wand touches the wire, a sound occurs (see Figure 6.10). In the third task, the participants had to refill syringes with exact predefined amounts of water. Between each condition the participant was given the ability to pause for a while.

Each time the participant noticed a light pattern, s/he was asked to rate it regarding its perceived level of urgency, pleasantness, and distraction from the performed task. This was done based on a five-point Likert scale. These factors were chosen to find a suitable light pattern that appears urgent for the user but not distracting from the actual task. Since the HMD should be worn during a whole shift, we also paid attention to the comfort factor of a light pattern. The participant should also state one first association s/he had regarding the pattern. The results were logged by the researcher to minimize the distraction caused by the rating process. To help the participant remember, the rating criteria and their Likert scales a print-out of them was placed in viewing distance. At the end of the study, the participant was asked to note their age and gender on the protocol. There was also space given for further annotations.

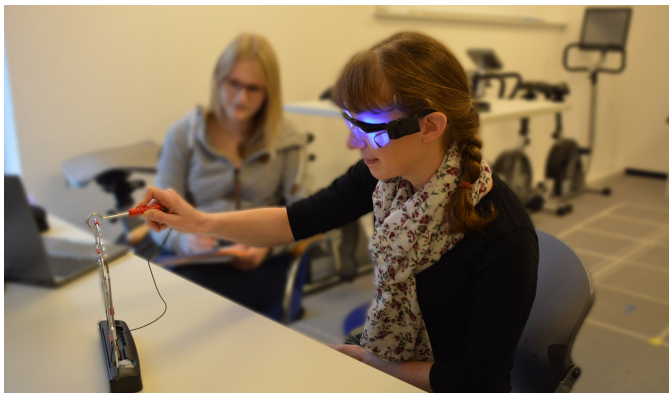


Figure 6.10: Participant doing a precision task wearing the prototype [CMBH18].

6.4.3.1 Results

Quantitative Results

In the following, we use *LP1–LP15* for Pattern 1–Pattern 15. We regard patterns rated with an average score higher than 3.5 as relevant. For the color red, all patterns except the constantly long blinking pattern (LP4) were perceived as urgent, with a range between 4.25 (SD = 0.67) for LP2 and 3.71 (SD = 0.98) for medium long blinking pattern (LP3). Of the yellow patterns LP6, LP7, LP8 were perceived as urgent but with no significant differences between the patterns. LP15, the additively on-switching LED, was the only blue light pattern perceived as urgent with a rating of 3.88 (SD = 0.95). There was a significance between LP 15 and all other blue patterns except LP11 ($p < 0.01$).

Regarding the distraction, LP1 (mean = 3.87, SD = 1.02), LP2 (mean = 3.5, SD = 0.9) and LP7 (mean = 3.8, SD = 1.05) were perceived as distracting. LP4 was significantly less distracting than LP1 and LP2 (both $p < 0.01$). Within the blue patterns, LP15 was significantly more distracting than LP12, LP13 and LP14 (all $p < 0.01$).

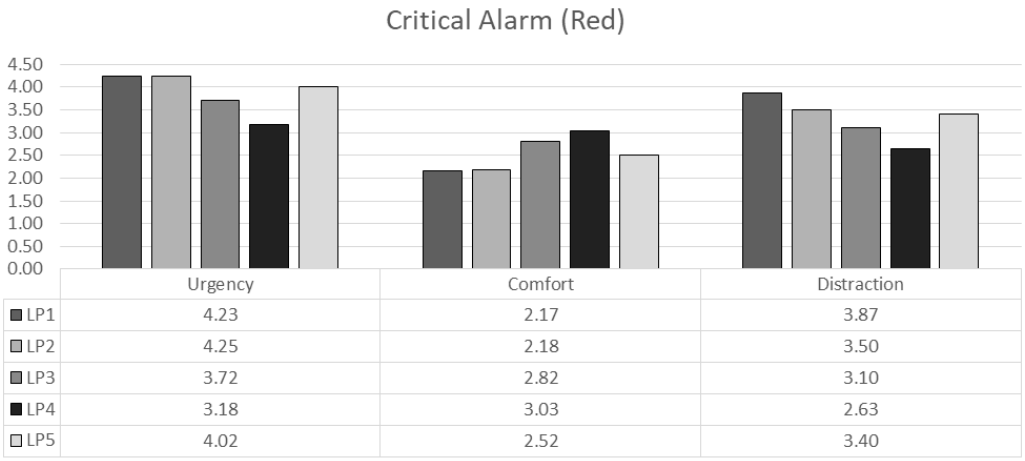
None of the red nor one for yellow light patterns were perceived as comfortable. However, the constantly long blinking pattern (LP4) was perceived as significantly more comfortable than LP1 ($p = 0.0031$) and LP2 ($p = 0.0052$) and LP9 is more comfortable than LP7 ($p = 0.0025$) and LP8 ($p = 0.0049$). All blue light patterns except LP15 were perceived as comfortable, with a range between 3.87 (SD = 1.11) for LP11 and 3.65 (SD = 1.04) for LP13. There were no significant differences. An overview of the results can be seen in Figure 6.11.

Regarding the color groups, a Wilcoxon signed-rank test showed significant differences of the perceived urgency, distraction and comfort between blue and red or yellow patterns, overall $p < 0.01$, which means that blue light patterns are generally less urgent and distracting but more comfortable. Red and yellow in general showed no significant differences in any of the factors. Nevertheless, there are combinations of red (LP1, LP3 or LP5) and yellow (LP9) patterns that show significant differences ($p < 0.01$). The results are visualized in Figure 6.12).

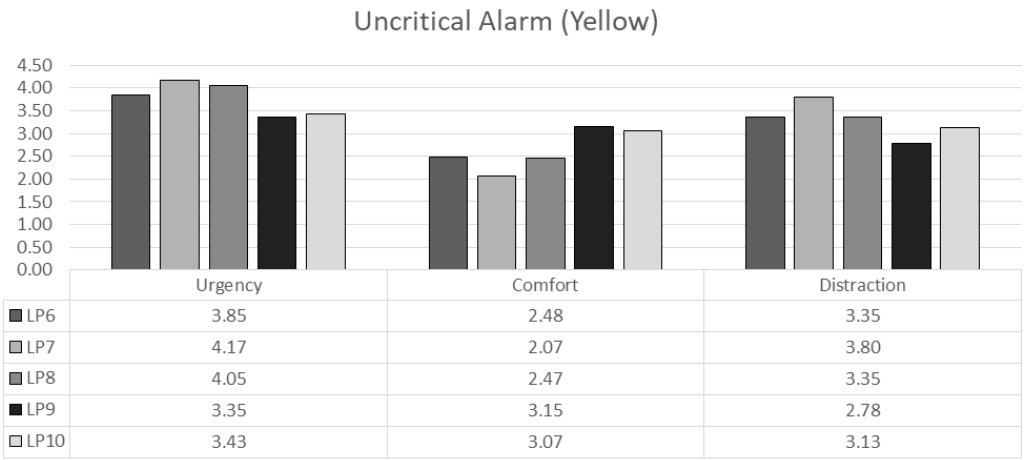
Pearson correlation test revealed a correlation between the perceived urgency and distraction ($r(298) = 0.70$, $p < 0.01$). Moreover, there is a negative correlation between urgency and comfort ($r(298) = -0.54$, $p < 0.01$).

Qualitative Results

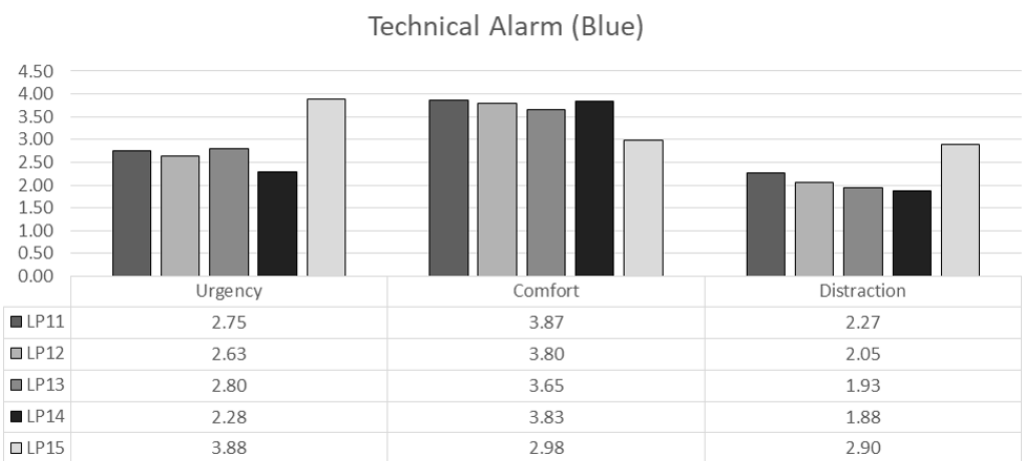
After the presentation of each pattern, the participants were asked to mention an association with it. For red patterns, participants mentioned overall 74 times an association with “alarms”, “danger” or “emergencies” and 23 times an association with “warnings” or “errors”. All 20 participants associated LP2, and 18 participants LP1 and 15 LP5 with alarms. LP3, the constantly medium long



	Urgency	Comfort	Distraction
LP1	4.23	2.17	3.87
LP2	4.25	2.18	3.50
LP3	3.72	2.82	3.10
LP4	3.18	3.03	2.63
LP5	4.02	2.52	3.40



	Urgency	Comfort	Distraction
LP6	3.85	2.48	3.35
LP7	4.17	2.07	3.80
LP8	4.05	2.47	3.35
LP9	3.35	3.15	2.78
LP10	3.43	3.07	3.13



	Urgency	Comfort	Distraction
LP11	2.75	3.87	2.27
LP12	2.63	3.80	2.05
LP13	2.80	3.65	1.93
LP14	2.28	3.83	1.88
LP15	3.88	2.98	2.90

Figure 6.11: Overview of the results for each pattern [CMBH18].

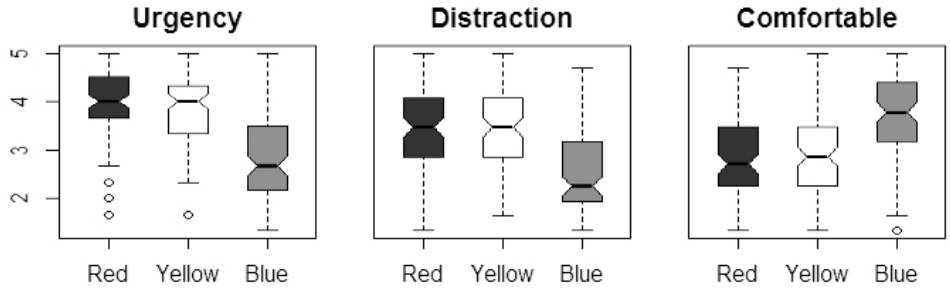


Figure 6.12: Summary of the perception between colors [CMBH18].

blinking pattern, had 13 associations with “alarms" and 10 with warnings like “stop!”. LP5 was called “bright” or “dazzling” 10 times. Another association with the red patterns was “annoying”/“too long”, which was mentioned overall 30 times, evenly distributed.

The same association was made with the yellow patterns 21 times. The most prominent association with the yellow patterns was “bright”/“dazzling” with 76 mentions, which affected mainly LP6 and LP8 with 18 mentions and LP7 with 24 mentions. LP10 was associated with “party” or “fair” 19 times and with “confusing” nine times. The association with “alarms” was made 33 times, evenly distributed between LP6, LP7, LP8 and LP9.

The blue patterns were mostly associated with “alarms”, like a police blue light (74 mentions). Another association, mentioned 62 times, was “pleasant”. This was related to all blue patterns except LP15. This pattern was called “too long” or “hectic” 17 times.

6.5 Discussion

The results showed that the implemented blue light patterns appear overall less urgent than red or yellow ($p < 0.01$). Since blue patterns shall represent technical alarms and may indicate that a sensor does not measure the data reliably, ignoring a blue alarm due to an erroneously underrated urgency could lead to missing a critical incident. Thus, this result may indicate that light is not sufficient to represent an urgent blue alarm reliably. One option could be to extend this alarm by another sensory stimulus.

On the other hand, it is conceivable that nurses may perceive the blue pattern as urgent after a period of familiarization. This must be evaluated in a long-term study.

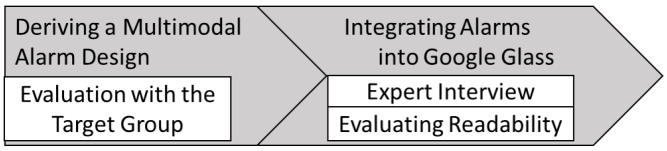
A correlation test revealed that the perceived urgency correlates with the perceived comfort of a light pattern ($r(298) = 0.70$, $p < 0.01$). This means for us

that we have to compromise between those factors while choosing a light pattern for each alarm type.

Regarding all factors, the constantly short blinking pattern (LP2) is the most feasible pattern for red alarms. Even though it is the second most distracting light pattern, it appears most urgent. Red alarms require immediate reaction; accordingly, this alarm needs to grab attention. Adapting brightness and frequency, this alarm could become more comfortable. For the low priority alarm, we consider LP9, the constantly blinking lateral LEDs. As uncritical alarms are the most frequent alarms in ICU, we chose the most comfortable and less distracting light pattern for this alarm, which was still associated with alarms. As a technical alarm, we consider the constantly pulsating pattern, LP13, which is the second most urgent and also the second most comfortable pattern.

7 Integrating Modalities and Components

With our prior studies, we could confirm that bone-conduction speakers can convey audible alarms reliably during cognitive, physical and precision tasks. Moreover, we could derive vibrotactile and peripherally visual light alarm patterns that represent three different levels of urgency. However, we needed to confirm and compare those patterns under realistic conditions with the target group, actual ICU nurses, to derive a final, multimodal alarm design. This study was described in Sec. 7.1. In a further study, we integrated the resulting suitable modalities into Google Glass. With this prototype, we evaluated the readability of alarm relevant information on a near-eye display in combination with personal alarms under nursing specific loads. This study was described in Sec. 7.2.



Parts of this chapter were published in Cobus, Vanessa ; Heuten, Wilko: To Beep or Not to Beep? Evaluating Modalities for Multimodal ICU Alarms. In: *Multimodal Technologies and Interaction* 3 (2019), Nr. 1. `http://dx.doi.org/10.3390/mti3010015`. – DOI 10.3390/mti3010015. – ISSN 2414–4088 and Cobus, Vanessa ; Busse, Steffen ; Heuten, Wilko: Glass++ Evaluating Multimodal Alarms on Google Glass. In: *Mensch & Computer*, GI / ACM, 2019, S. 795–799.

7.1 Deriving a Multimodal Alarm Design

We conducted an experiment to evaluate (1) the performance, suitability and feasibility of multimodal alarms compared to the state of the art (speakers) and (2) the usability and comfort rating of a multimodal head-mounted alarm display. The study was conducted under task conditions that mimic the load of care tasks.

7.1.1 Participants

For the study, we acquired 12 ICU nurses (seven female) from two different hospitals, between 22 and 51 (M = 33.8, SD = 10.3) years. Their years of experience in ICUs ranged from 3 months to 19 years (M = 8.92 years, SD = 6.92). Five of them had a corrected rectified vision through glasses, one of whom was blind in one eye. None of the participants were color blind.

7.1.2 Apparatus

Since we are in an early state of development, there are several safety factors that kept us from testing in the field. For that reason, we conducted the study in an unused ICU treatment room of a cooperating hospital, equipped with a patient bed, a desk, and a chair (see Figure 7.1). To create a realistic environment, we prepared a sound file as background noise containing talking and laughing people, clinking glass containers, ringing telephones and the sounds of a respirator. We explicitly excluded further alarm sounds of clinical devices.

Moreover, we prepared additional speakers in the corner of the room with a distance of ∼1 m to the working place and ∼1.8 m to the patient bed to simulate the state of the art using a notebook with the acoustic alarms as mp3-files. To present the multimodal alarms, we augmented our prototype from the light patterns study (see Figure 7.2). It consists of an *Adafruit Feather m0 WiFi* as micro controller combined with a *Music Maker FeatherWing* as amplifier, powered by a 3.7 V LiPo battery. In addition, 12 RGB LEDs are attached in the peripheral field of view (six on each side, three above, three next to the outsides of the eyes), diffused with *Gorilla Plastic*. We attached two ERM vibration motors (⌀ 10 mm) on the temples behind the ear for vibrotactile cues. Two bone conduction speakers (14 mm × 21.5 mm) were attached on the temples above the ear (one on each side) which convey acoustic alarms without blocking the ear channels. To ensure a firm hold for different head sizes, we attached an elastic band on the prototype.

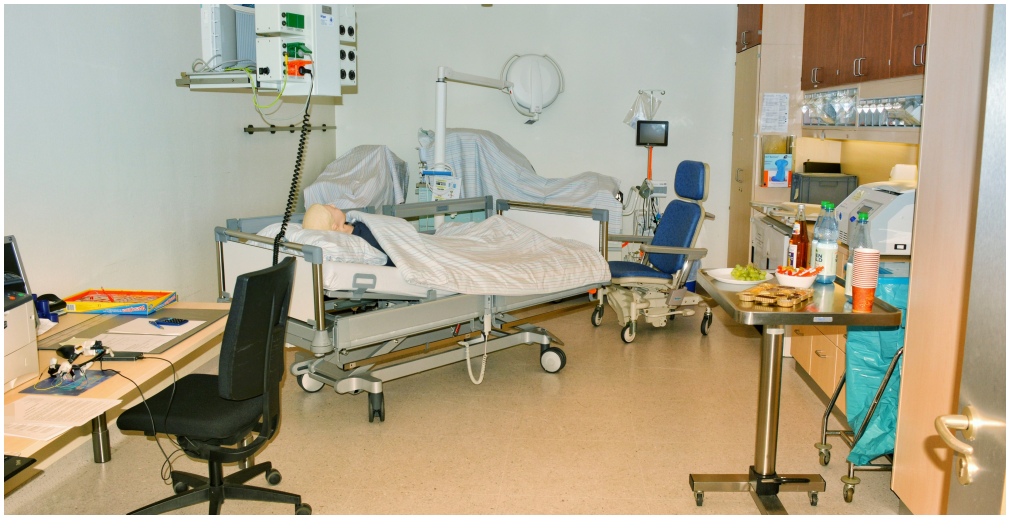


Figure 7.1: Study setup in an intensive care treatment room. [Cob19]

We used the following alarm designs for our experimental conditions based on our previous studies described in Chapter 5 and 6. The acoustic alarms are based on the sounds of a commercial patient monitoring system.
Light patterns: To represent critical alarms, we used a red blinking. All LEDs light up for 0.1 s with a 0.4 s break in between and a brightness value of 100. For

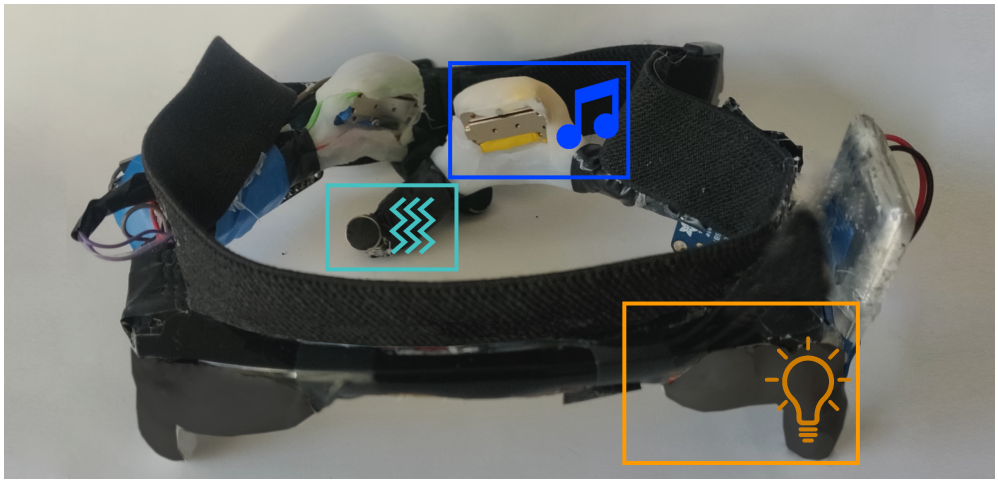


Figure 7.2: Multimodal head-mounted display for visual, vibrotactile and personal audible alarms. [Cob19]

the uncritical alarm, we used a yellow blinking. Just the side LEDs light up for 0.4 s with a 0.4 s break in between and a brightness value of 100. The technical alarm is a blue pulsating of all LEDs from brightness value 0 to 200 and back to 0 over 0.8 s with a 0.2 s break.

Vibration patterns: With increasing priority of the alarm, the number of vibrations increases. Respectively, the technical alarm consists of one, the uncritical alarm of two, and the critical alarm of three recurring vibrations with a length of 400 ms and a pause of 100 ms between the vibrations. The pattern itself repeats after an 800 ms pause.

Sound patterns: The sound patterns are based on the original sound files of a commercial PMS. With increasing priority of an alarm, the loudness and frequency and pitch of the beep increase. The patterns are visualized in Figure 7.3.

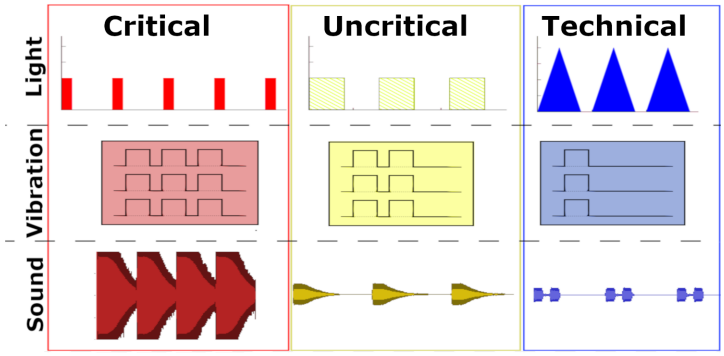


Figure 7.3: Visualization of the used patterns for each modality.

The vibrotactile and light alarm patterns were hard-coded on the Feather. The acoustic alarms were stored as mp3-files on a micro-SD-card, read by the FeatherWing. We tested loudness, brightness and intensity of each condition and the background noises in prior pilot tests. These alarms were triggered via an Android app using a WiFi-connection to a web server that was started up by the Feather.

7.1.3 Study Design

For our study, we used a within subject design with the alerting medium as independent variables. It consisted of four main conditions, based on the used modalities: visual via peripheral light, tactile via vibration, and auditory via bone conduction speakers as experimental conditions, and finally auditory via speakers as control condition.

The essential key tasks of a nurse include i.e., the shift handover, a routine control, and the admission of new patients, which are mainly cognitively demanding. Furthermore, there are physically demanding tasks like mobilization of the patients or accompaniment of their transport, and, finally, there are precision demanding tasks like the application of medication or dressing changes. For that reason, we divided our study into three tasks that are cognitively, physically and precision demanding to represent realistic workloads according to the workflow.

For the *cognitive task*, we prepared several cross-multiplication problems that should be solved using the Rule of Three. This method is commonly used in nursing education and for calculating the dose of medication for patients. To avoid discrepancies between the math knowledge of the participants, we provided an explanation, including an example for the Rule of Three as well as a calculator.

For the *physical task*, the participants were asked to perform a mobilization on a training manikin (Resusci Anne), which weighs 12 kg and is about 1.5 m tall (see Figure 7.4, left). We chose this manikin to avoid fatigue effects caused by repeating the task, since awake patients usually support the nurses and heavier patients will be mobilized with at least two healthcare professionals.

The *precision task* consisted of a wire loop game in which the participant had to remove plastic items with a pair of tweezers from cavities inside the patient without touching the edges of that cavity. If s/he touched an edge, the game board gave a visual and audible signal and the participant had to choose a different item (see Figure 7.4, right). This hand-eye-coordination task should represent a load similar to giving injections or taking blood and was performed in former studies, e.g., by Englert et al. [EB13].

During each task, all conditions were evaluated. Therefore, every participant performed each task and experienced three alarm levels per condition: critical, uncritical and technical alarms. The order of the conditions, alarm levels, and

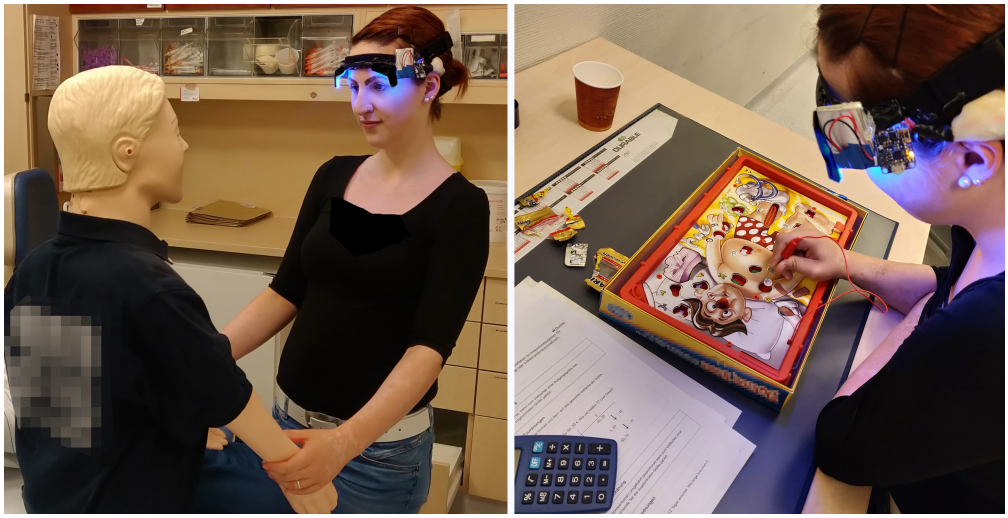


Figure 7.4: Left side: physical task, right side: precision task. [Cob19]

tasks was counter-balanced randomized. A possible setup for one participant is visualized in Figure 7.5. The experiment took approximately 60–90 min including

Participant 1	Physical Task	Light	Urgency 1	Urgency 2	Urgency 3
		Vibration	Urgency 2	Urgency 3	Urgency 1
		Bone Conduction	Urgency 3	Urgency 1	Urgency 2
		Speakers	Urgency 1	Urgency 2	Urgency 3
	Cognitive Task	Light	Urgency 2	Urgency 3	Urgency 1
		Bone Conduction	Urgency 3	Urgency 1	Urgency 2
		Speakers	Urgency 1	Urgency 2	Urgency 3
		Vibration	Urgency 2	Urgency 3	Urgency 1
	Precision Task	Vibration	Urgency 3	Urgency 1	Urgency 2
		Light	Urgency 1	Urgency 2	Urgency 3
		Speakers	Urgency 2	Urgency 3	Urgency 1
		Bone Conduction	Urgency 3	Urgency 1	Urgency 2

Figure 7.5: Exemplary study setup for one participant.

setup, initial learning phases and final interview.

The nurses received their actual hourly wage for participation.

7.1.4 Measures

We measured the following dependent variables to compare the experimental conditions to the control conditions:

General suitability of the modality, suitability of the modality for the performed task, perceivability, distinguishability, comfort, and level of annoyance: (5-point

Likert scale, 5—the most suitable—annoying): for each task after each condition, every participant rated the respective factor for the modality.

Perceived workload: for each condition during each task, every participant filled out a Raw-TLX Scale [HCG+11].

Error rate: each time a participant named the wrong or no alarm level, we counted that as an error and logged it to the specific alarm.

Reaction time: we measured the time between presentation of the certain alarm and the identification by the participant.

Usability: at the end of the study, every participant filled out a System Usability Scale [Bro96].

Comfort of the prototype: at the end of the study, every participant filled out a Comfort Rating Scale [KB05].

7.1.5 Procedure

After obtaining the informed consent, we collected the participants' demographic data (age, gender, years of ICU experience) and explained the overall procedure.

For each condition, we introduced the respective alarm design to the participants and gave them an initial learning phase. The study started when the participant felt confident with the alarm design. The background noise was started and the three alarms of the respective condition were sent to the prototype or speaker. By sending the alarm, a timer was started automatically. As soon as the participant recognized an alarm, s/he had to name the type (red for critical, yellow for uncritical or blue for technical alarm) and we stopped the timer. After each alarm, we asked the participant to rate the suitability of the design for the respective alarm level, the suitability for the performed task and the perceivability on a 5-point Likert scale. At the end of the certain condition, we asked the participant to fill out a Raw-TLX scale and to rate the general suitability, task suitability, perceivability, distinguishability of the alarms, comfort and level of annoyance for the respective condition, also on a 5-point Likert scale.

This procedure was repeated for each condition during each task. At the end of the study, the participants were asked to fill out a system usability scale as well as a Comfort Rating Scale. Finally, we asked the participant which modalities they would prefer for their personal alarm system.

7.1.6 Results

In the following, we present our results in the respective evaluated factor. A Shapiro–Wilk test revealed that all data are normally distributed, so we used a

Wilcoxon signed-rank test to test for significant differences with a significance level of 1%. A summary of the results can be seen in Figure 7.6.

		Light	Vibration	BC	Speakers
Task Suitability	Suitability	4	3	4	3
	Cognitive	4	4	4	3
	Physical	4.5	4	4	3
	Precision	5	3	4	3
	Perceivability	5	5	4	3
	Distinguishability	5	3	4	3
	Comfort	4	3	4	3
	Annoyance	2	3	3	3
	Error rate	0	0.028	0.093	0.093
	ReactionTime(s)/SD	2.02/0.6	3.15/1.06	3.37/1.7	3.71/1.74

Figure 7.6: Summary of the results.

Suitability of the modality: For the general suitability, the participants rated light and bone conduction sound (in the following named as BC) significantly best, with a median of 4 ($p < 0.01$). Regarding light, the comments included that this modality is "really secure" (P1), "safe" (P1, P3, P7), "clear, unique" (P2), and "not distracting" (P1, P3–P7, P9). A representative quote of a participant for BC was: "Somehow distracting. However, it SHOULD distract me in a specific way. It is so weird because it is in my head. Maybe I could get used to it." (P2)—Vibration and speakers were both rated with 3, which means a medium suitability.

Task suitability: For the task suitability, we regarded the ratings in the respective task. For each task, light and BC performed significantly better than the control condition, which had an overall rating of 3/medium ($p < 0.01$). Except for the cognitive task, light performed with a rating of 4.5 for the physical and 5 for the precision task even better than all conditions ($p < 0.01$). However, one participant (P9) was concerned during the physical task about how the patient would perceive that. Vibration performed better than the control condition for the cognitive ($p < 0.01$) and physical task (not significant, $p = 0.03$). During the precision task, two participants (P4, P12) were concerned that they would be afraid to get out of place with the needle during taking blood. For this task, vibration was rated as medium suitable.

Perceivability: Regarding the perceivability, all experimental conditions performed significantly better than the control condition. Comparing light and vibration (both 5, best perceivable), there is no significant difference but eight participants mentioned a rather negative or annoying perceivability for vibration. In contrast, light was described as "Fast perceivable, especially with background noises" (P1).

Distinguishability: The distinguishability of the alarms was rated significantly best (median = 5) compared to all conditions for light ($p < 0.01$). Worst distinguishable were vibration and speakers, with a medium rating (3). For vibration, one participant (P8) mentioned: "Sure, they are distinguishable. However, I have to concentrate on that and count the vibrations, so they are actually not!"

Comfort: The participants rated light ($p < 0.01$) and BC with as "comfortable". Two participants (P2, P11) were concerned that light could be exhausting for the eyes, and one of them mentioned that s/he was "tired and had headache during the shift. Bright light doesn't make it any better. Maybe there should be a mode to switch to something different." (P11). Vibration and the control condition were rated as medium comfortable. *Level of annoyance:* Regarding this factor, just light showed a better score, with 2 (not annoying). One participant (P12) described light as "distracting but positively distracting. Opposite to the speakers, I see that immediately, I don't have to interrupt my task." All other conditions were rated medium.

Error rate: The most errors were made with acoustic alarms. Both speakers and BC showed an error rate of 9.3%. Each mistake was a confusion between the uncritical and technical alarm. Five participants mentioned that they got used to hearing an alarm and look to the PMS display to realize which one it is. With one error, vibrotactile alarms showed an error rate of 2.8%. No error was made for light alarms.

Generally, the time stamps for the mistaken patterns did not indicate a learning effect for the patterns. *Reaction time*: With 2.02 s (SD = 0.6), the participants had the fastest reaction time in identifying the light alarms. Generally, all experimental conditions performed significantly better than the control condition (3.72 s, SD = 1.74).

Perceived workload: The analysis of the Raw-TLX showed that there are overall high scores, which means a high workload. However, there is also a high standard derivation for each factor (see Figure 7.7). The participants perceived the lowest work load in all categories with light alarms. Compared to the control condition, vibration showed worse results in all categories except in "Overall Performance". BC performed just slightly better than the control condition except for the factor "Frustration". However, these results are not significant. *Usability and Comfort*: With a SUS-score of 80 (SD = 8.53), the participants rated the prototype with good usability. The median of the Comfort Rating is 4 (0 means best comfort), which means good comfort, considering the prototypes early state development. However, Figure 7.8 shows that the lowest rating applies to the attachment of the prototype (median = 16.5). *Qualitative feedback:* Regarding the final feedback, none of the participants wanted to adhere to the state of the art. The majority of the participants (11 of 12) preferred the light alarms. Two participants mentioned that light would be sufficient for each alarm level. However, five of them remarked that they could imagine that other nurses could prefer vibrotactile alarms and

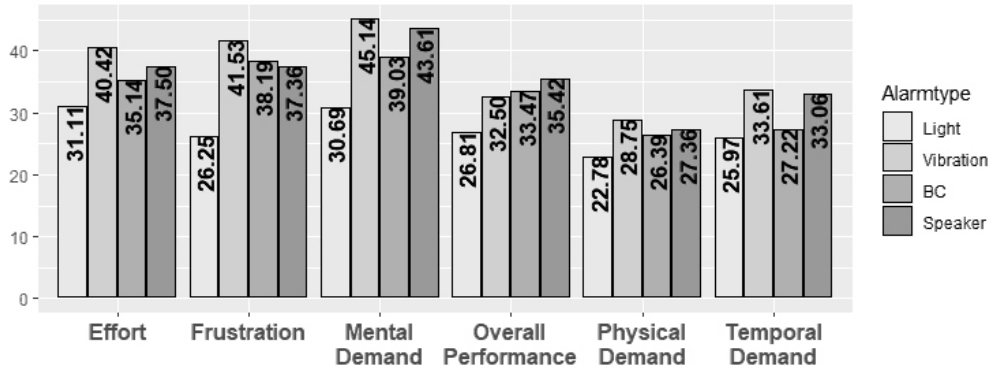


Figure 7.7: Rating of the perceived work load.

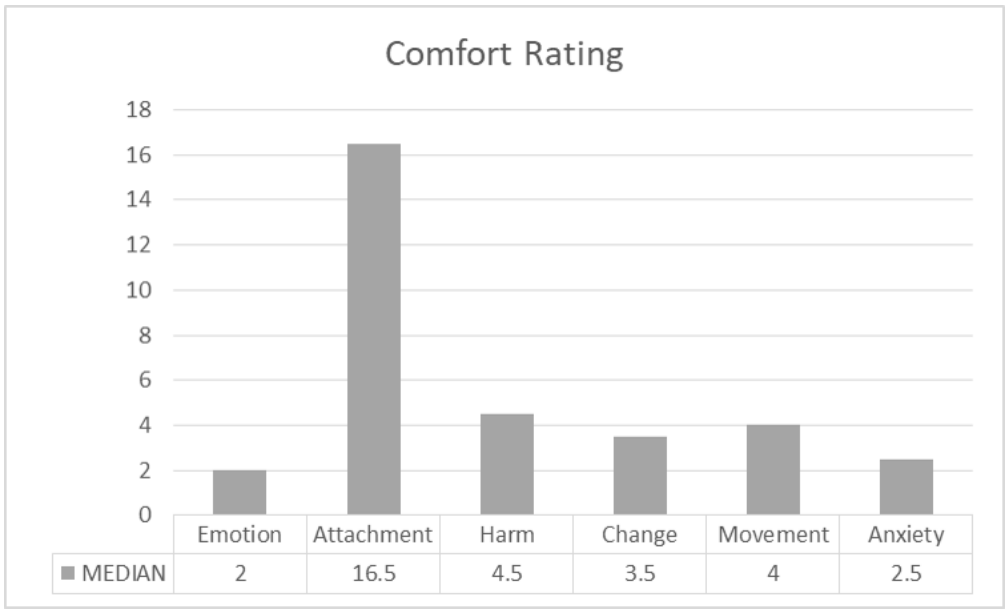


Figure 7.8: Results of the Comfort Rating Scale.

we should consider making the alerting method customizable. One participant preferred BC as single method to be alerted, since s/he reacted sensitively to light, especially, when s/he is sick. The other participants preferred a combination of modalities for specific alarms. For example, 9 of 12 participants wanted a combination of light and BC for critical alarms. Ten of 12 participants preferred just a visual solution for uncritical alarms. Regarding the technical alarm, there was no clear result. Five participants preferred the light alarms for this, two the acoustic, and two the vibrotactile solution. Two participants suggested a combination of vibration and light and one participant considered a combination of all modalities because the technical alarm is usually underestimated and ignored, since a missing sensor could also cause a critical alarm.

7.1.7 Summary

In this study, we evaluated the noiseless alarms, we have designed and explored in the prior chapters, in a lab study under realistic task conditions with the actual target group.

Regarding all factors, we suggest using a combination of light and BC for critical alarms, and just light to represent uncritical and technical alarms. However, even if light performed best in all categories, there was a high variability of the preferred signal types.

Therefore, we consider to use the vibrotactile patterns to escalate. Looking back to our proposed alarm distribution algorithm (see Chapter 3), an alarm will be forwarded to a second nurse, when the responsible nurse does not react. To symbolize for the second nurse that the incoming alarm is already persistent for a longer time, this alarm could be amplified using a low priority vibration pattern, and for the second escalation a high priority vibration pattern, respectively. In case of critical alarms, the escalation should be directly symbolized with a high priority vibration pattern.

Another possibility would be to enable an opt-out for light alarms and, at least for uncritical and technical alarms, and opt-in for a vibrotactile alerting, which needs to be configured individually. This option could also be useful to switch the modality for specific tasks.

The suitable modalities will be now integrated into AR glasses to evaluate the feasibility in combination with detailed information on a near eye display.

7.2 Integration of Noiseless Alarms into Google Glass

With designing noiseless alarms, we did a first step to reduce the alarm load on ICUs. Since the evaluation of alarms does also require relevant information, like, e.g., the causing vital data, we needed to evaluate the feasibility near-eye displays showing patient data combined with noiseless alarms during nursing loads. Therefore, we integrated the necessary hardware components for peripheral light alarms into Google Glass. The choice of hardware is based on prior expert interviews after testing two of the (to that point) latest systems on the market.

7.2.1 Expert Interview

Two prominent examples for AR-Glasses that are used in industry are the Google Glass Enterprise Edition and the Vuzix M300. Both glasses are monocular HMDs which means, the display is placed in front of one eye.

The main difference between those glasses is the type of display, which is transparent and firmly integrated to the right side of the frame for the Google

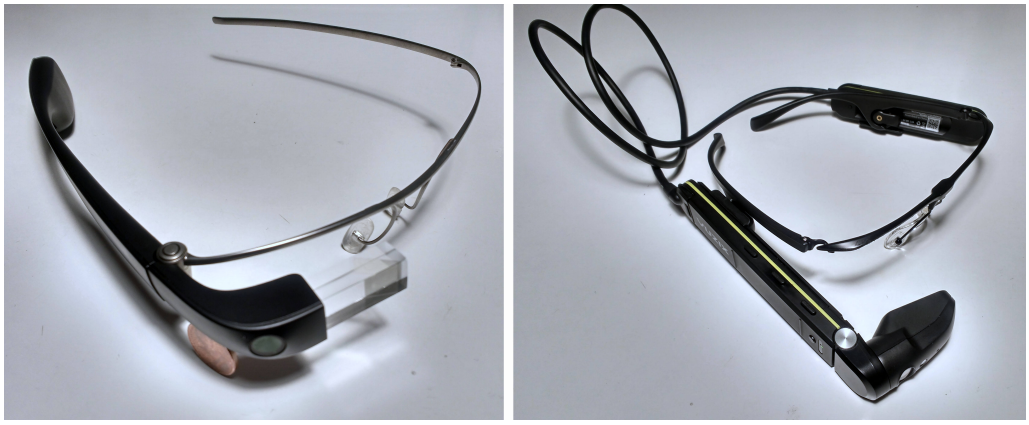


Figure 7.9: Google Glass Enterprise (left), Vuzix M300 Smart Glasses (right)

Glass (see Fig. 7.9, left) and opaque for the M300 but flexibly attachable on both sides and variable in the distance to the eye.

Since both glasses are developed for working context, we wanted to explore, which of these suits best for ICUs, especially regarding its integrability into the nursing workflow.

Therefore, we did a semi-structured expert interview with three ICU nurses of different experience.

7.2.2 Procedure

The interviews took place in an empty treatment room of an anesthetic ICU and took 15min per Participant.

Both HMDs were handed out to the participants one after the other and after a short briefing they were to be tested independently. The interviewer was always available to support and answer technical questions.

In the first part of the interview we wanted to investigate whether the glasses and in particular the respective display types are suitable for this task. The following questions serve as guiding questions.

- General wearing comfort: Could you imagine wearing these glasses for several hours?
- During your shift, there are a variety of activities that vary in their demands. Could you do all these tasks with these glasses well?
- Is the display obstructing your vision?
- Does the glasses distract from the environment?

- Is the display bright enough?
- Is the display content easy to read?
- Are there any other remarks or anomalies?

Afterwards, the participants were asked to compare the glasses regarding the comfort, readability, and the type of display (fixed vs. adjustable, and opaque vs. transparent).

Finally, we asked the participants which glasses were more suitable to be integrated into the workflow.

7.2.2.1 Results

The Vuzix M300 was described by all participants as heavy and massive, but still not uncomfortable. However, the M300's non-transparent display was perceived more as a visual obstacle and also restricted the lateral field of vision. The display is permanently present in the field of vision and therefore rather distracting. One participant mentioned that he felt "one-eyed". Two of the participants feared that the glasses could slide down during some clinical tasks, such as lowering the head.

The Google Glass, on the other hand, has been described as light and compact, firm and yet generally comfortable to sit on. The transparent display is unobtrusive and easy to ignore. The glasses would not interfere with typical activities. One respondent remarked that the Google Glass wore like ordinary glasses.

Overall, the Google Glass was rated as more comfortable, even though the test persons could imagine wearing both glasses for several hours at a time.

The displays of both glasses were described as well readable and the contents as clearly recognizable. However, the non-transparent display of the M300 tended to be more pleasant and easier to read. None of the participants saw a particular advantage or disadvantage in a fixed or height-adjustable display. In answer to the final question as to which of the two glasses the test persons considered the more suitable, they all opted for Google Glass glasses.

Even though two of the three test persons found the M300's display to be easier to read, all participants favored the Google Glass, above all because of its higher wearing comfort and more compact design. Based on the results of the expert interview, Google Glass were used to integrate our final alarm design.

One participant noted that he was already familiar with the use of pagers to relay alarms and considered augmented reality glasses to be a promising alternative for this task.

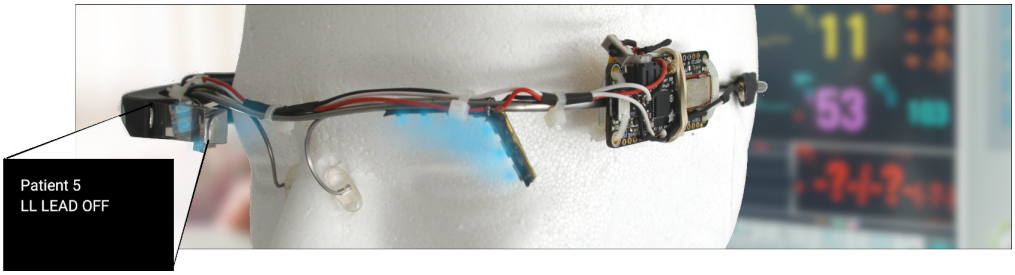


Figure 7.10: Peripherally visual actuators enhance Google Glass EE for multimodal alarm distribution with additional alarm relevant information. [Cob19]

7.2.3 Apparatus

7.2.3.1 Hardware

We implemented the three different urgency levels (technical, uncritical and critical) using bone-conduction sound and peripheral light. The prototype alerts the user with three different urgency levels (technical, uncritical and critical) using bone-conduction sound and peripheral light. We used a micro-controller (Adafruit Feather M0 Bluefruit) to control the LEDs(see Fig. 7.12, bottom), and used the integrated bone-conduction speakers of Google Glass for the sounds.

We attached the micro-controller on the left temple, so the opposite side of the Glasses' main unit, to avoid an imbalance.

We attached seven Neopixel LEDs as strips at each side of the frame for the visual alarms. The Feather M0 will be powered by a Li-ion battery (400mAh, 3.7V). The final prototype can be seen in Fig. 7.10.

7.2.3.2 Software

To start or stop alarms on the prototype, we use an Android smartphone. We developed an application which let the user control the modality (sound, light) and the urgency level (technical, uncritical, critical). This app does also create a WiFi hotspot to connect the Google Glass to the smartphone. The communication between Google Glass and the Adafruit Feather works via Bluetooth.

In case of a peripheral light alarm, a respective command with the number the priority level of the alarm is sent to the Feather M0, which in turn controls the respective actuator. For the light patterns, we used a blue pulsating blinking for technical, a yellow blinking for the uncritical and red, faster blinking for the critical alarms [CH19].

In case of an audible alarm, the corresponding sound file is played directly via the speakers of the glasses. The acoustic alarms are based on the sounds of a commercial patient monitoring system.

Additional to this alarm, respective data will be presented on the display of the glasses. The displayed information consists of three text lines: 1. the affected patient, 2. the cause of the alarm, and 3. the respective value to the cause (see Fig. 7.11). The exemplary alarm causes and values chosen to be displayed on

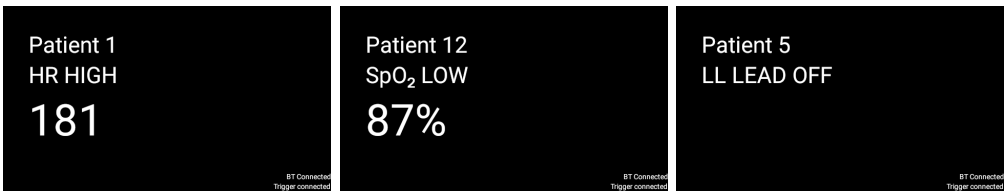


Figure 7.11: Design of the alarm relevant information: Critical alarm (l), uncritical alarm (c), technical alarm (r).

the near-eye display and randomly selected by the trigger app are based on the alarms from a training guide for a commercial patient monitor.
A schematic representation of the whole concept can be seen on the top of Fig. 7.12.

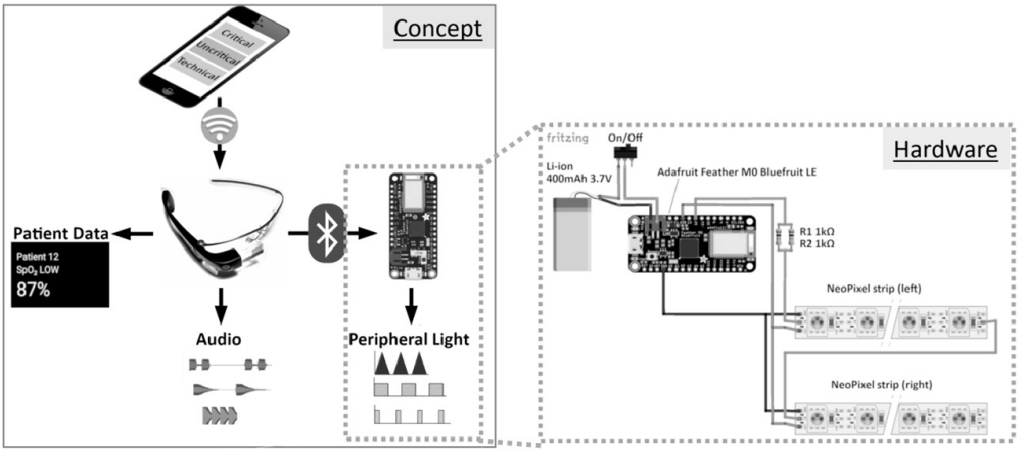


Figure 7.12: Using a smartphone, alarms will be triggered via WiFi on the prototype. The respective patient information to the alarm will be displayed on the display of Google Glass [CBH19a].

7.2.4 Procedure

Since this study took place in a preliminary stage development, we conducted the first user study outside the target group to finally take the findings from our work to nurses. For the evaluation, we invited 15 participants (7 female), between 22 and 60 years old. None of them were color blind.

The study was designed as within-subject design and consisted of two conditions, sound and light. The order was counter-balanced randomized. Both conditions

consists of two main tasks which simulated typical nursing loads: a cognitively and a precision demanding task. The cognitive task were calculations using the rule of three. This method is commonly used in nursing education and for calculating the dose of medication for patients. For the precision task, the participants were asked to play a wire loop game called "operation". This hand-eye-coordination task should represent a load similar to giving injections or taking blood and was performed in former studies, e.g., by Englert et al. [EB13]. The order of the tasks was also randomized. At the beginning, all participants were introduced to the monitoring alarms, their priorities and the implemented designs. During the whole study, all participants wore the prototype. While the participants did the primary task, the researcher sent a random alarm via the app with a random delay between 15 s and 25 s. When noticing it, the participants should interrupt their current task and identify the alarm. Each time, the participants missed or named a wrong alarm, we counted this as an error.

After each alarm, the participants had to rate the identifiability of the alarm, the readability of the patient information, and the perceived distraction of the alarm using a 5-point Likert scale. For each task, each alarm was triggered once.

Finally, the participants were asked to fill out a Comfort Rating Scale to evaluate the comfort of the prototype [KB05]. Since they just served to simulate a specific load, we did not measure or analyze the task performance.

7.2.5 Results

In the following, we describe the results of the study, categorized in errors, suitability rating and comfort rating.

7.2.5.1 Errors

Regarding the visual alarms, there were two errors made by one participant who thought a yellow, uncritical alarm was a red, critical one. Several participants had problems to distinguish between the critical and uncritical alarm, since they associated a "double-beep" with a higher priority. This resulted in an error rate of 13.3%.

7.2.5.2 Suitability Rating

A Shapiro test revealed that the data of the Likert rating was not normally distributed ($p < 0.05$), so we used a Wilcoxon-signed-rank-test to determine whether there are significant differences. Regarding the tasks, the participants rated a higher perceived distraction during the cognitive task (2.17) compared to the precision task (1.77, $p < 0.05$)). However, the readability of the information was significantly higher during the cognitive task (4.6 vs. 4.4, $p < 0.05$).

Visual alarms were significantly better identifiable, but textual information were worse readable. Both conditions were rated as similar undistracting ($p < 0.05$). A visual representation of the results can be seen in Fig. 7.13.

We could also identify differences between the alarm categories of visual alarms. The red and yellow light pattern were both significantly more distracting then the blue, technical one ($p < 0.05$).

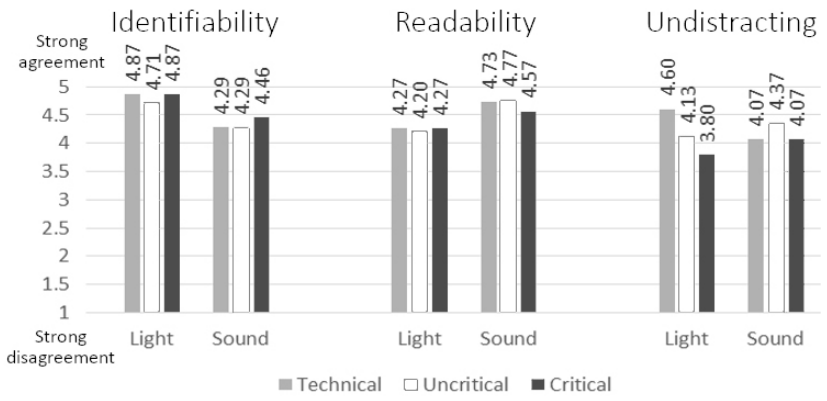


Figure 7.13: Results of the Likert-scale, divided into condition and alarm priority.

7.2.5.3 Comfort Rating Scale

A summary of the average comfort rating can be seen in Fig. 7.14. The participants rated the factor "attachment" worst. Some participants mentioned that the prototype would slide down when looking down. This did also lead to the higher values of the factors "perceived change" and "movement", since some participants avoided sudden movements and directly looking down. Other participants, who usually wear glasses, mentioned that the prototype feels like normal glasses and that they would not feel any differences. Some added, that they felt differences in the beginning but they got used to it after a while. The factors "harm", "anxiety" and "emotion" were rated as good. Several participants mentioned that would wear such a prototype in the work environment as "supportive tool", but would feel "weird wearing it in public".

7.3 Discussion

In the first study, we could show that noiseless alarms compete with the state of the art, but also perform better in several factors. The final alarm design addresses two modalities, the visual and the audible channel. The worse performance of vibrotactile alarms, however, is limited on the application on the head. Therefore,

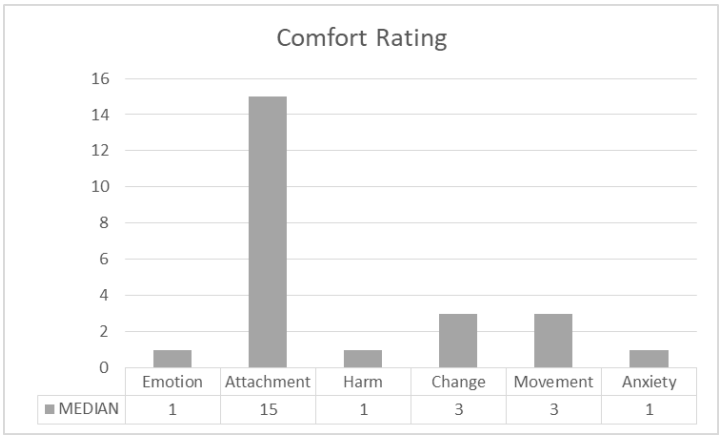


Figure 7.14: The prototype was rated as generally comfortable but with was criticized regarding the loose attachment.

we propose the usage of the patterns just in case of escalating to another nurse. This would symbolize that the alarm is persistent for a longer time.

However, the findings from Chapter 5 indicate that the vibrotactile alarm design shows potential to be investigated further for the upper arms.

Even if the time stamps of the measured errors did not indicate that there was a learning effect, it should be considered that this may be caused by the small sample size and could be clarified in a long-term study. Moreover, the high error rate for sounds may be explained by the fact that nurses are generally used to getting additional information on the monitoring system for the specific alarm to identify its urgency.

The high means of the Raw-TLX have to be regarded in combination with the high standard derivation. This may be caused by the fact that some participants attended our study right after their shift, which could mean that they might have been exhausted. Another possible reason could be the low number of participants. If we take a closer look at the single factors of the Comfort Rating Scale, the overall median represents the rating for the factors “Emotion”, “Harm”, “Perceived Change”, “Movement”, and “Anxiety”. However, the factor “Attachment” was rated with a median of 16.5, which means a physical feel of the device on the body. This is caused by the early state of development, in which we focused on the functionality of the prototype.

Although we could show significant results that support the use of personal multimodal alarms, our results are still limited. At this point, we did not evaluate the combination of the modalities, and, moreover, the task performance. Even if the qualitative feedback did not show any indications in case of light and BC, we still need to measure whether the multimodal alarms have a negative influence in performing nursing tasks.

Moreover, it needs to be evaluated if multimodal alarms perform as well in a long-term study. Thus, we can exclude fatigue due to the new alarm signaling.

Another point that needs to be evaluated is the long-term use of HMDs in the medical context. There is a risk that "yet another technical device" will be neglected as soon as the novelty effect ends. To avoid this, a WAS would have to be made mandatory for the specific ICU as part of the general work clothes.

However, for a long-term evaluation, the WAS needs an approval for medical devices to be tested in the field. Until then, we aim to create a more realistic test lab for preliminary explorations.

The results of the second study indicated that visual and audible alarms can be integrated into Google Glass to show additional textual relevant alarm information while alerting them.

Regarding the high error rate of audible alarms, it needs to be considered, that the participants were no trained nurses and had to learn and map these new sounds. For the light patterns, the priority could be easily derived via the color, which also lead to the high values of the identifiability.

The higher rated distraction during the cognitive task may be traced to the fact that the calculation were perceived as harder than the operation game and most participants had to start calculating from the beginning after being interrupted.

Even though the readability of the display was significantly worse for visual alarms than for audible alarms, we need to consider that the average value was 4.25 of 5, which still means a good readability.

Since critical alarms may indicate a life threatening situation which require a fast reaction, the higher rated distraction for these alarms is still acceptable. The low average values of the Comfort Rating Scale could show that the prototype is comfortable and might be also wearable in a longer term. The criticism regarding the loose attachment can be counteracted with individualized frames.

Regarding the Google Glass itself, they emerged from the expert interview as the more suitable pair of glasses, but there is still room for improvement. For example, the battery is not replaceable as it is the case with the M300, but is permanently installed. Another disadvantage of the Google Glass is that until today only models with a fixed display in front of the right eye exist. A modular display like the M300 would probably be more useful.

Since we could not evaluate the prototype with the target group so far the results of our second study are not generalizable. This does also include that the number of alarms we showed to the participants does not represent the reality. These limitations should be addressed in future work.

8 Exploring Touchless Alarm Acknowledgment Methods

In the prior chapters we described the design and evaluation of noiseless alarms for a wearable, multimodal alarm distribution system. We evaluated the feasibility of the integration of our alarm design into Google Glass but to acknowledge alarms, a method to interact is still needed.

Since nursing requires a direct patient contact, and thus contact with potentially bacterial infected body fluids, a touch-interaction provides a high risk of a bacterial contamination, and moreover, a cross-transmission of microorganisms by the hands [RCRG15]. To address this issue, we explored touchfree interaction methods to interact with patient alarms of a wearable alarm system as a proof of concept. We started with a semi-structured interview with ICU nurses to gather the concrete needs for interaction with an alarm.

In a pilot study with ten participants who were not the target group, we evaluated the feasibility of an alarm acknowledgement gesture on the head, the upper arms and the ankles during a physically and cognitively demanding tasks. This should mimic the concrete load of nursing tasks.

In this chapter, we describe our approach to acknowledge alarms without using the hands, as well as the results of a feasibility study.

This work is going to be published in 2020.

8.1 Related Work

Hands-free or rather touchless interaction has been investigated for several use-cases so far. The following examples have give an overview of the design space of touchless interaction.

Corey Pittman et al. [PLJ14] evaluated head-gestures to remotely control drones. They found head rotations to be preferred for that context. To select targets efficiently for mobile contexts, Andrew Crossan et al. [CMBMS09] suggests head-based (tilting) gestures.

Other projects presented jaw-based, which used sensors stuck into the ear to measure jaw movements [BBP+15], and cheek-based gestures, using EMG [NPI+18] as promising discreet input methods.

A more commonly examined input method of the head are the eyes. Blink and Wink interactions have been used as alternative input methods for users with severe disabilities and allow complex interactions, though at a reduced speed [MB10]. On the other hand, eye gaze based interactions have been shown to have a very high selection performance, as long as the targets are sufficiently coarse [Ohn98, SJ00]. Ishan Chatterjee et al. [CXH15] have further proposed combining eye tracking with gestural input, two combine strengths of both approaches.

Finally, several projects have examined the use of foot-based gestures as an input modality in hands-free interaction. Jeremy Scott et al. [SDYT10] identified heel rotation and plantar flexion as the preferred gestures when using the whole foot, but required a wake-up gesture to start recognition. Jason Alexander et al. [AHJ+12] explored a wide variety of food-based gestures as to their guessability and further examined different kick-based gestures in regards to navigation. Compared to that, Koumei Fukahori et al. [FSI15] introduced foot plantar-based gestures, which consider only the pressure on various parts of the sole, thus allowing very discreet gestures which can be performed with no outwards sign.

For the hospital context, which requires efficiency, reliability, but most importantly sterility, the work of Nicola Dell et al. [DDB15], as well as Anke Reinschluessel et al. [RTH+17] proposes mid-air hand gestures to interact touchlessly.

However, within the ICU context interfaces need to be usable even though the hands are already used for other tasks. For these situations, several systems have been proposed. Reinschluessel et al. [RTH+17] explored also foot-based gestures as an input channel, compared to talking with an assistant and hand-based gestures. Alternatively, Charles Templeman et al. [TOSR16] suggested a design using head-based gestures and language input as a promising approach to avoid touch inputs.

These works helped us creating new ideas for a feasible touchless interaction method for ICUs.

8.2 Brainstorming

To gather new ideas, we invited three experts in usability and user experience designing to a brain storming session. We first introduced them into the problem. Afterwards, we asked them to identify design constraints for the ICU context and write them down on a flip chart. Finally, we them to collect three ideas for a touchfree alarm interaction method, each. As a next step, the participants should give their ideas to the next participant to improve their ideas. This was repeated one more time until each participant supplemented each idea. At the end, the ideas were collected and evaluated.

8.2.1 Results

Based on the brainstorming session, we were able to generate a comprehensive overview over the expected utility of different interaction methods.

All modalities were evaluated regarding their feasibility while performing four types of tasks:

Physical Load Tasks, in which the nurse is exercising force to move substantial loads, for example mobilizing a patient.

1. Dexterity Tasks, in which the nurse has to work precisely and cannot greatly alter position, for example administering a needle.

2. Cognitive Load Tasks, in which the nurse has to keep their concentration on the current subject or has to keep information in short-term memory, for example when scanning medical data for keywords. In regards to this task, none of the modalities where considered to be truly good since any type of alarm and the conscious selection of an answer will take a toll on concentration.

3. Social Tasks, in which the nurse is talking with patients or relatives and in which the interaction with the device should not be misinterpreted as communication towards the other party or interrupt the conversation.

In addition, specific advantages and disadvantages of individual modalities were also considered while formulating the recommendations.

Mid-Air Hands Gestures

One of the most common touchfree interaction methods are hand gestures in front of glasses. This model would be easy to learn and would support a wide variety of gestures. However, it is not usable when considering physical load or precision demanding tasks, making it not feasible in an ICU setting.

Language

The other common solution to this kind of problem would be speech recognition. This technique excels in physical load and dexterity tasks, however, it is very disruptive to natural speech and does thus not fit with social tasks. An even bigger concern, however, is the use of always-on microphones in a privacy-sensitive context such as a hospital.

Gaze Tracking

Using a glasses-mounted gaze tracker, the user could select their response using only eye movements. A potential interface for this could include a head-up display

indicating in which gaze direction different options are located and confirmation via dwell time or pupil dilation. Due to the very localized effort required by eye movements and their subtle nature, this input method is well-suited both for physical load and Dexterity tasks, as well as social interaction. Even though this method may require use of an additional HUD, all components of the system could be contained within a single device. While current technology still has a very distinct outward appearance, future developments are expected to minimize its footprint and allow discreet integration into an HMD.

Blink/Wink Gestures

As an alternative to Gaze Tracking, eye-based interaction could also focus on eyelid-based gestures, such as blinking and winking. While this approach shares many of the advantages of Gaze Tracking, namely the applicability to a wide variety of use cases, subtlety and integratability into a single device, earlier blink-based interfaces have been prone to recognizing false positives from natural blinking. It would therefore be necessary to establish whether a reliable recognition can be achieved.

Nose Gestures

One could imagine an interface that utilizes inputs performed using movements of the nose. In an interface that already utilizes an HMD for output, this could, for example, be tracked using simple accelerometers in the glasses. Such an interface would allow for somewhat discreet interactions, though if noticed by patients the gesture could easily be misinterpreted. Involuntary miming while exerting force could also lead to an increased number of recognition errors during Physical Load Tasks. Finally, only one gesture can reasonably be expected to be performed, severely limiting the ability to choose between different options. On the whole, Nose-based Gestures, at least by themselves, do not appear to be a viable candidate for our input system.

Ear Gestures

Similarly, wiggling ones ears presents another rarely examined option for input using subtle facial gestures. Unfortunately, this shares the problem of a limited input vocabulary with Nose-based gestures. In addition, this input method is entirely inaccessible to large parts of the population since the ability of voluntarily wiggle ears is assumed to be based on a genetic factor, making it unfeasible for a commonly-used interface.

Head Gestures

Other than parts of the face, gestures can also be performed using the head itself, for example by tilting it to one side, nodding or shaking the head. For this, the

gestures would need to be carefully selected to ensure that they do not lead to miscommunication. It would also need to be examined whether additional head movement could increase strain when the body is already under tension during Physical Load tasks. However, if these two concerns can be alleviated, head-based Gestures promise to be a versatile and easy to learn input method.

Head Direction

Similar to the Gaze Tracking interface mentioned above, one could also use the orientation of the head itself to select between different options. The user would point a small head-mounted camera at different markers by orienting their head accordingly. While such an interface would be easy to learn and could perform reasonably well in all examined tasks, the unacceptability of a camera in a privacy-conscious setting like the ICU leaves this not a viable option for our use cases.

Shoulder Gestures

For a shoulder-based gesture interface, users can perform various gestures using their shoulders or upper arms, and upper bodies, such as shrugging one or both shoulders. Similar to Head-based Gestures, this could potentially be a viable interface if it can be ensured that the gestures are not misinterpreted by conversation partners and if the gestures do not cause undue stress during physical tasks.

Foot Gestures

As the counterpart to traditional hand gestures, foot-based gestures prove another promising avenue for interaction, taking form as tapping, turning or kicking the foot for input. Since even small gestures can be detected, these can be selected such that they do not hinder normal conversation, making them suitable for Social Tasks, while also being possible to perform under load during Physical Load Tasks.

Toe Gestures

An extension of foot-based gestures, a device could measure the pressure on different parts of the sole of the foot, allowing for inputs that are performed using only movement of toes. Similar to foot-based gestures, we expect this interface to perform well even with physical tasks while being even more discreet, ensuring that patients will not be disturbed by interaction with the system.

8.2.2 Conclusion

On the whole, we expect the best-performing interfaces for our scenario to utilize gaze tracking, foot- or toe-based gestures due to their overall robustness in recognition, suitability to different tasks and subtlety. Bases on our analysis, we can also give tentative recommendations for eyelid-, head- and shoulder-based gestures if user tests prove them to be sufficiently accurate in recognition and free of undue strain when performed under load.

In the following, we focused on head-, shoulder- and foot-based gestures.

8.3 Expert Interview

To determine the special requirements for a touchless interaction method from the target group, expert interviews were conducted with three ICU nurses from an anesthetic ICU. With the help of these expert interviews subjective and subject-related opinions are to be obtained and questions are to be answered, which were not covered with the literature research. In addition the daily routine of a nurse, as well as the operational sequence with different alarm situations should be examined, in order to attain further knowledge over requirements at the prototype. The interviewees were also asked about possible mounting options for the prototype and, based on their professional experience, possible implementable gestures for operation.

8.3.0.1 Results

The interviewees were all already familiar with technical devices such as Smart home products or Smart watches. When asked about the interaction desired for the prototype, the first intention was to acknowledge or mute/pause alarms. In the further course of the discussions, extended functions such as the input of patient ID's or the adjustment of alarm limits were often desired.

The experts considered such a system to be consistently helpful and usable in everyday life, whereby slight concerns were expressed that alarms could be acknowledged with this technical aid too lightly without an expert opinion of the patient.

Based on the three intended test points (upper arm, ankles, head), the experts were asked for suitable attachment points. None of the interviewed experts was in favor of attaching them to the head, as this was not very intuitive. The attachment to the upper arm was generally discussed as quite practicable, but there was a clear unanimity in the attachment to the ankle. The experts independently determined that this part of the body was at least used in daily work, that the attachment was not disturbing and that a simple input should be guaranteed. The experts were asked whether they would prefer a certain form of gesture, such

as circular or lateral movements. There was no clear opinion on this question as to what might be due to the fact that the interviewees had little or no experience with motion detection on the proposed body parts and therefore could not draw on the experience of what forms of gestures were intuitive and easy to perform.

In the subsequent open discussion and demand for concerns or improvements, there was little additional input.

8.4 Pilot Study

We conducted a proof of concept study to evaluate which body location (head, upper arms, or feet) for input gestures to acknowledge alarms suits best during physically demanding tasks.

8.4.1 Participants

Since we are in a fundamental stage of research in which no specific knowledge is required, we did not include the target group for this proof of concept. We invited ten people aged between 22-64. The average age of the participants was 37.2 years.

8.4.2 Apparatus

The study took place in the bedroom of a life-lab for ambient assisted living with a real bed inside (see Fig. 8.1). To compare the feasibility of the three body locations, we developed a prototype consisting of a flexible nylon band and the actual hardware. The hardware consisted of a Spark Fun 9DoF Razor micro-controller board which has i.a. an integrated LED, gyroscope, and accelerometer, which helped us detecting a gesture. The micro-controller and the power supply were embedded into a 3D-printed case (see Fig. 8.2)

An alarm acknowledgement gesture was implemented so that the on-board LED responds to a double movement gesture away from the body. This means, e.g., the user executes a double movement with his upper arm or ankle (depending on the mounting location) within a certain period of time and a certain force, the prototype responds. Therefore, we addressed the gyroscope and accelerometer. In the particular case of head mounting, lower thresholds were selected in the test, as the optimum value between unintentional triggering by random movements and conscious head operation is lower. Likewise, the force required for triggering at the head had to be reduced for reasons of usability.

The thresholds for the specific location were chosen based on prior pretests. The prototype can be seen in Fig. 8.3.

Figure 8.1: Life-lab for ambient assisted living (IDEAAL).

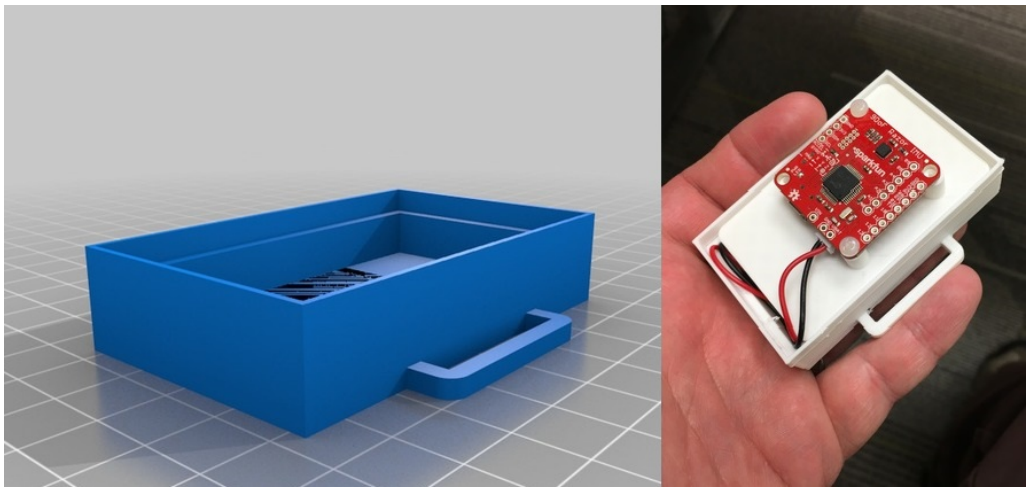


Figure 8.2: Left: 3D-model of the case, right: Prototype to be attached on a flexible nylon band.

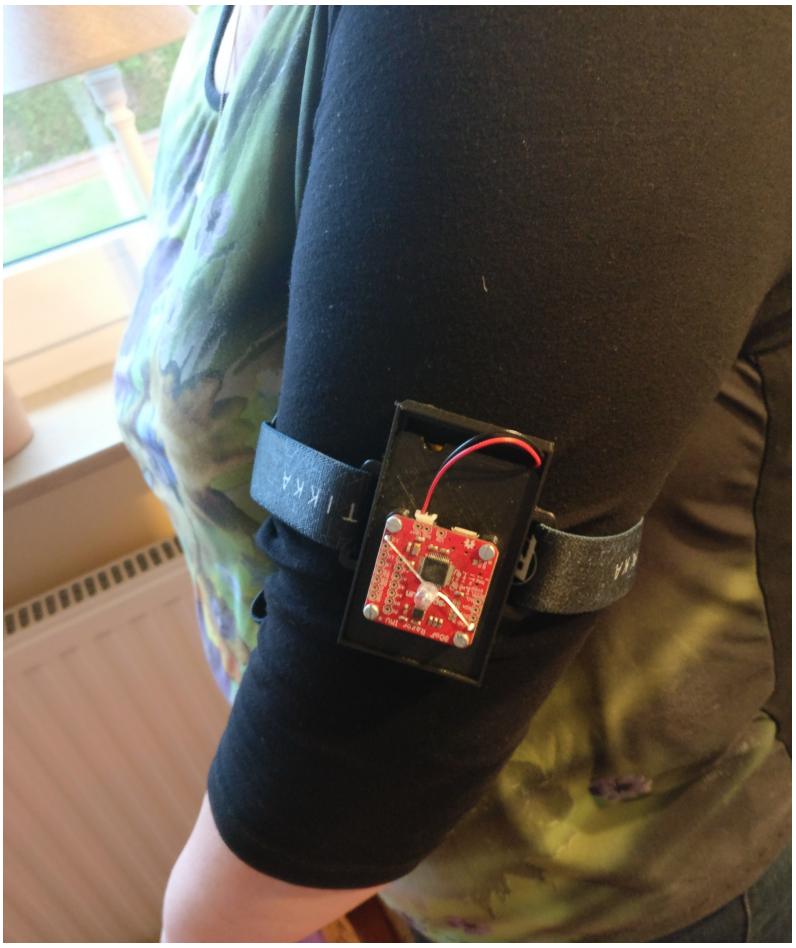


Figure 8.3: Prototype attached on the upper arm of a participant. [Cob19]

8.4.2.1 Study Design

The study was designed to be within-subject. Each user did five test runs, divided into five conditions. The conditions are the measuring points head, upper arms (dominant/non-dominant) and ankles (dominant/non-dominant). The order of the conditions was counter-balanced randomized. After being introduced to the functionality of the prototype, the participants were given tasks that do not require any further expert knowledge, but are nevertheless miming the physical and cognitive load of nursing tasks.

The primary task consisted of changing bed sheets repeatingly to represent a physical load (see Fig. 8.4).

During this task, questions were asked from a prepared questionnaire, all of which had to be answered yes or no. This should represent the decision process after an alarm, and thus, the cognitive load. If the user can answer the question with yes, s/he should trigger the prototype with the prescribed gesture. Otherwise s/he should continue the task.

In order to obtain comparable data, the questions that could be answered positively were asked at the same time. Since each participant took a different time for the single tasks, the triggering times were as follows:

1. After the prototype was attached,
2. After covering the mattress,
3. While covering the duvet,
4. After covering the duvet, and
5. After covering the pillow.

S/he then had to fill out a Comfort Rating Scale [KB05] and a questionnaire regarding different factors of usability. The questionnaire consisted of five five-point-Likert scales (from 0 - 4, the higher, the better) considering the general usability, learnability, habituation of use, if the usage was cumbersome, and finally, how the participants generally felt while using it.

For each condition, we did also measure the error rate, based on misentries. Then we continued with the next condition.

The participants were asked to think aloud during the whole study. Finally, after all conditions, we asked which body location the participant preferred.

8.4.2.2 Results

We start reporting our findings with the error rate. Even though the results indicated that the non-dominant parts has shown a higher error rate, these results

Figure 8.4: Participant performing the primary task. [Cob19]

were not significant ($Wilcoxontest : p = 0.03$). Considering the different ages, we could see that there is a significantly higher error rate for participants older than 34 ($p < 0.01$). Regarding the different conditions, the right foot had the lowest error rate with 16%. The left upper arm, which was in most cases the non-dominant arm, and the left foot, which in turn was also in most cases the non-dominant foot, had the highest error rates with 28%. Overall, the participants performed worse with the upper arms (25% error rate) compared to the head (22%) and the feed (22%)(see Fig. 8.5). However, none of these results were significant.

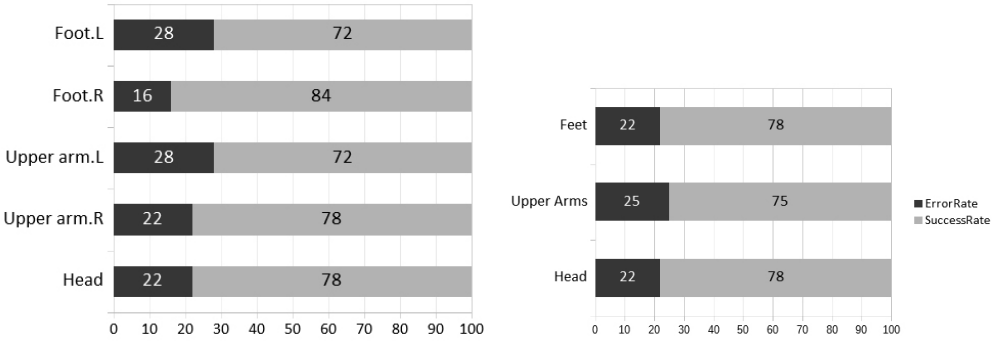


Figure 8.5: Left: Error rate for each condition, Right: Overall error rate per body region.

Regarding the respective tasks, we could observe that the highest highest number of misentries were made while covering the mattress, with 26% of the overall errors (see Fig. 8.6).

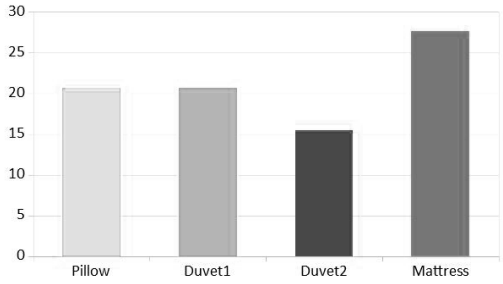
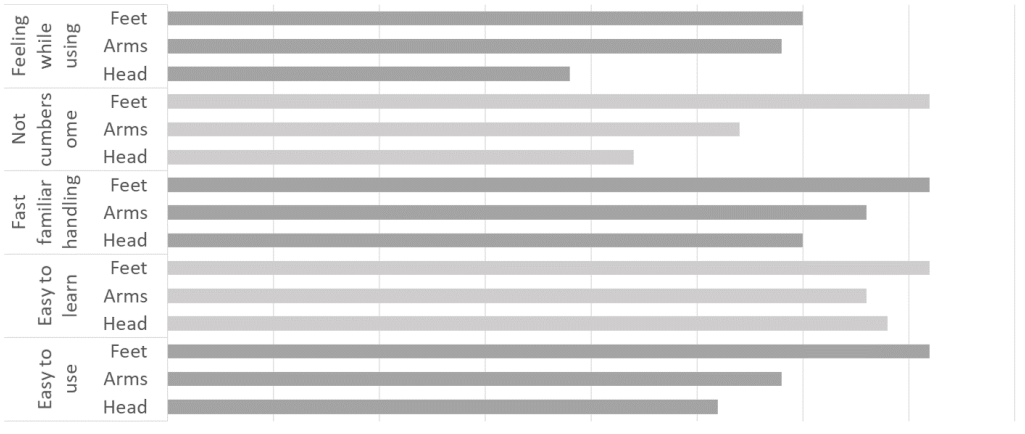


Figure 8.6: Error rate distributed on the tasks

The analysis of our questionnaire revealed that in all factors the feet were rated best (see Fig. 8.7. Despite the factor "learnability", the head performed worst in all questions. Calculating the mean over all factors, there was a rating of 2.62 of 4 for the head, 2.98 for the upper arms and 3.48 for the feet.

These results were also reflected within the comfort rating (the lower values, the better). Participants rated the ankle attachment as the most comfortable, followed by the upper arm option and preferred the head least. However, there is an outlier for the upper arms regarding the factor of restriction in the participants' movement with 2.4 points.

In the final interview, 8 participants preferred the attachment on the feet.



	Easy to use			Easy to learn			Fast familiar handling			Not cumbersome			Feeling while using		
	Head	Arms	Feet	Head	Arms	Feet	Head	Arms	Feet	Head	Arms	Feet	Head	Arms	Feet
Average	2.6	2.9	3.6	3.4	3.3	3.6	3	3.3	3.6	2.2	2.7	3.6	1.9	2.9	3

Figure 8.7: Analysis of the usability questionnaire.

	Head	Arms	Feet	Head	Arms	Feet	Head	Arms	Feet	Head	Arms	Feet	Head	Arms	Feet	Head	Arms	Feet
	Emotion			Attachment			Harm			Change			Movement			Anxiety		
Average	3.1	1.5	1.2	2.4	2.3	1.9	2.1	1.7	1.1	2.7	2.2	1.3	1.1	2.4	1.1	1.3	1	1

Figure 8.8: Analysis of the Comfort Rating Scale

8.5 Discussion

Overall, we provided a list of pros and cons for several touchfree interaction methods to be used in the ICU context. We evaluated the feasibility of gestures based on the head, the upper arms and the feet during physically and cognitively demanding tasks.

The results of our user study indicates that the feet suits best to perform a touchfree alarm acknowledgement gesture regarding the comfort, factors of usability and the tendency of a lower error rate than the other conditions.

The high error rate of above 20% is based on the early stage of development. Since we implemented a lo-fi prototype, our algorithm compared different locations of the gyroscope in a certain time with a certain power of just one axis. If the participant now changed their body axis, they implicitly did a misentry. We could observe that this was the case, when the participants had to cover the mattress.

As shown in Figures 8.4 and 8.1, in the study setup the bed was located on a wall and was only accessible from one side. Depending on their height, the participants had to bend far forward to be able to move the mattress. The changed body axis and thus center of gravity often caused problems in the correct operation of the prototype at the same time. For example, the leg was practically pulled up instead of moving the ankle sideways, which would have been necessary to trigger the prototype. This should be addressed in further iterations of the prototype. E.g., the gesture itself should be redesigned to be easier performed, but not too easy.

Regarding the comfort, the feet performed also best, followed by the upper arms. The outlier in the rating of the perceived moving regarding the attachment onto the arms was caused by the fact that the participants had problems with the prototype getting stuck in the duvet. This will also be solved by a higher fidelity of the prototype.

At last, the attachment of the head was perceived as "unnaturally" and "uncomfortable". Moreover, some participants could not imagine to wear such a system in public.

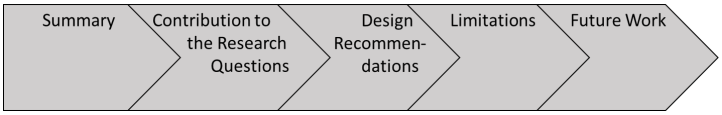
Overall, we our results are limited, since we could not find any significant differences. Our sample size was too small to generalize the findings and should also be tested by the target group.

However, we could show that a feet gesture can be performed during physically demanding tasks without being perceived as uncomfortable. The high error rate can be solved by better algorithms and a gesture design which is designed to be executable using more than just one axis. We would suggest to integrate ultrasonic sensors under the patient bed which can be triggered using the feet. This would address the nurses concerns from the interview of frivolous alarm acknowledgement, since the nurse would have to go to the patient to acknowledge an alarm. Furthermore, the gesture itself would be easier to perform, nevertheless, accidental entries need to be avoided.

Finally, we only explored a small part of the huge design space of touchfree interactions. We highly propose to investigate other opportunities we proposed to acknowledge alarms without using the hands.

9 Conclusion

In this chapter, we conclude the work we have described in the previous chapters. We start with a brief summary, followed by contributions to research questions. We then highlight important limitations and finally, give directions for future work in the field of developing wearable alarm systems for safety critical environments.



9.1 Summary

In this thesis, we present the results of our research on multimodal alarm distribution systems for ICUs. We investigated three research questions addressing the design space of wearable alarm systems, the design of noiseless alarms and the touchless interaction for the medical context. We followed the human-centered design process, to design and evaluate ICU alarms using different modalities.

In several design studies, we found suitable light and vibration patterns to represent three different urgency levels for patient alarms. We conducted a user study under task conditions that mimic concrete loads of nursing tasks with 12 nurses in an ICU lab. We compared different modalities for representative monitoring alarms on our HMD to the state of the art: ubiquitous sound. Our results show that noiseless alarms presented on an HMD perform better than speakers regarding the factors of reaction time, error rate, perceived suitability, perceivability, and level of annoyance. Moreover, our prototype shows good usability and comfort. Based on this research, we propose a multimodal alarm design to present three different types of urgency over different escalation steps.

This design was integrated into Google Glass Enterprise Edition to evaluate the readability of alarm relevant information, e.g., the concerning patient, the respective vital data, or the sensor issuing, during nursing task loads.

In cooperation with experts from user experience design as well as ICU, we gathered possible touch-free interaction methods to acknowledge alarms. As a proof of concept, we evaluated different body locations as a touch free interaction method during physical demanding tasks.

Overall, we provide the design space and guidelines for wearable multimodal alarm systems with intent to reduce the alarm load on ICUs.

Generally, our approach of a wearable alarm distribution benefits from the distribution of the alarms among only the responsible nurses. This means, in average case, a nurse would receive only the alarms of their own patients, as well as those of the colleagues they represent.

Moreover, by replacing the majority of audible alarms (uncritical and technical) with light, we would reduce the number of audible alarms according to literature, by approx. 80% [Cva12].

Our findings contribute in supporting medical engineers, but also designers to create wearable solutions to forward alarms to the responsible person.

We expect that in future, head-worn devices will be a part of the regular work clothing in the safety critical domain, to improve workers' situation awareness and support them in their working life.

9.2 Contributions to the Research Questions

Overall, this work contributes with empirical evaluations of noiseless alarms for the ICU context. Our results indicate that multimodal alarms can not only compete with the state of the art, but do also perform better in several factors, which in term might reduce the alarm load on ICUs. However, this presupposes that it is produced as a medical product.

In the following, we highlight our contributions to the single research questions that we have addressed in this thesis.

RQ1: What constitutes the design space for wearable alarm systems for critical care?

To identify the design space for wearable alarm systems applied in ICUs, we worked in close cooperation with healthcare professionals. Based on several expert interviews and a shadowing session in an early shift on an anesthetic ICU, we could derive requirements for wearable alarm systems. Theses were concretized within expert discussion groups with healthcare professionals from different hospitals with different levels of experience. We found, that an alarm system that does not distract the nursing workflow should be as small as possible and not interfere with patient care.

We contribute with a rating for body locations to attach a wearable alarm device with regard to address unobtrusive modalities, to show textual information for alarm relevant details, and to not endanger the patient or the user during patient care, e.g., mobilization. Moreover, we gave suggestions for suitable modalities to convey alarms. The findings can be found in Chapter 3

RQ2: How must noiseless alarms be designed to alert with different levels of urgency?

Based on the results for RQ1, we focused on exploring audible, vibrotactile, and peripheral visual cues to convey alarms. To answer the research question, we divided our work into three parts to address each channel individually.

We provide different ways to transfer alarms to the user, starting with audible alarms. In a user study, we found that bone-conduction speakers can compete with common speakers during nursing specific loads. This means, even if a user refuses the multimodal alarms, the already established audible alarms can be conveyed in an unobtrusive way.

For vibrotactile cues, we suggest patterns that are well distinguishable and represent three different levels of urgency. Although the vibrotactile patterns did not compete with the peripherally visual and audible alarms, our results we described in Chapter 5 have shown that the vibrotactile patterns are suitable to be conveyed on the upper arms.

In Chapter 6, we describe our approach to design and evaluate light patterns for critical care alarms. We adapted the blinking frequency, the LED location, and the brightness transitions to convey different levels of urgency using the colors red, yellow, and blue (which were already mapped to the specific alarms).

Finally, in cooperation with healthcare professionals, we derived a multimodal design which can alert the user via a HMD while showing alarm relevant information on a near-eye display (see Chpt. 7).

Overall, our contribution consists of three unimodal and one multimodal designs for noiseless alarms and suggestions for suitable mediums to convey them.

RQ3: Which interaction methods for alarm systems are suitable for nursing tasks in ICU?

Research question 3 focused on touchless interaction with patient alarms. To answer this question, we involved experts from ICU, but also from the field of user experience design in our design process.

We contribute to RQ3 with a list of pros and cons for potentially possible touchless input methods to acknowledge alarms. We evaluated them regarding the executability during physically demanding tasks, but also social tasks, e.g., conversations with relatives, and implemented a gesture based touchless alarm acknowledgement. Another contribution constitute the findings of a user study, described in Chpt. 8. These indicate that foot gestures are a suitable way to interact during physically demanding tasks in environments that does not allow to interact with hands.

9.3 Design Recommendations

To address all requirements, we suggest to develop wearable alarm systems in form of head-mounted devices. The head is a location, which is not physically involved into nursing tasks, therefore, an attachment of hardware would not influence patient care. Moreover, an attachment on the head enables to address different modalities to alert, and display additional alarm relevant information via a near-eye display, integrated in one device. To alert nurses, we propose alarm designs for peripheral visual and audible alarms, to be conveyed via the HMD (see Fig. 9.2).

In case of escalating to a second nurse, we would propose to amplify this alarm using a low priority vibration pattern to symbolize that the incoming alarm is already persistent for a longer time. For the second escalation a high priority vibration pattern, respectively, should be used to increase the urgency of the pattern (see Fig. 9.1).

In case of critical alarms, the escalation should be directly symbolized with a high priority vibration pattern.

The proposed patterns can be integrated into, e.g., Google Glass for displaying textual information, e.g. the respective patient, and the vital data causing the alarm, or sensors. Based on our findings, we suggest to use a transparent or semitransparent display to avoid the feeling of a restricted field of view. As common for wearables, the WAS should also be as lightweight as possible.

There are also other possibilities to design wearable alarm systems. Therefore, other requirements must be neglected. Vibrotactile turned out to be inappropriate and uncomfortable for the head. However, for other body locations, as a less detailed alarm display that serves to just notify nurses about changes in their patients' health status, we provide our evaluated vibration patterns. Our findings indicate that a vibrotactile system could be attached on the upper arms (see Fig. 9.3).

Other possible locations that would not influence the safety of patients or nurses would be the back, legs, or feet, but their recognizability and also their comfort need to be evaluated during nursing tasks.

A second way to use vibrotactile alarms for a detailed alarm system would be in combination with a HMD. However, this would neglect the requirement regarding an easily and quickly applicable one-device system.

For touchless interactions with wearable, but also stationary alarm systems, we suggest using feet as input methods to be well integrable into the nursing workflow. However, we explored only the edge of this field and the gestures need to be redesigned. We address this in the future work.

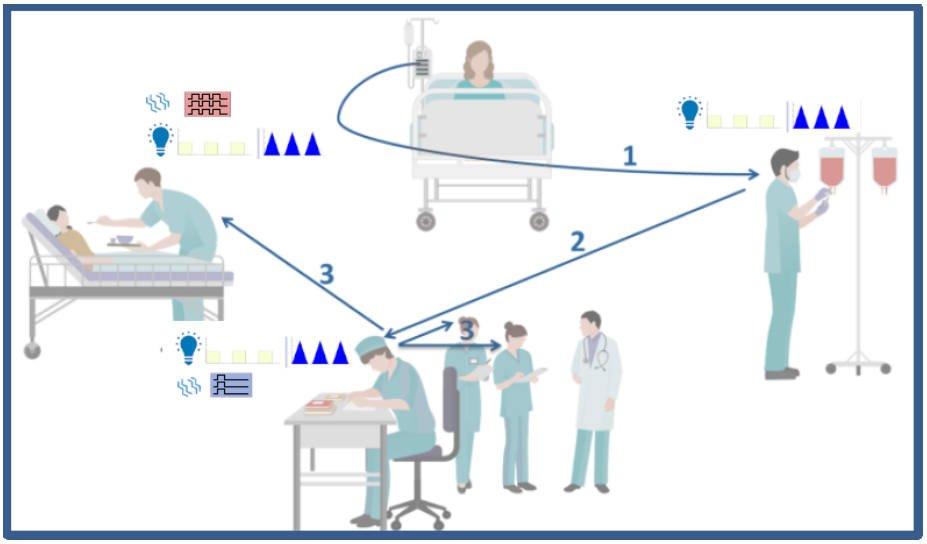


Figure 9.1: Integration of the proposed alarm design into our alarm distribution algorithm.

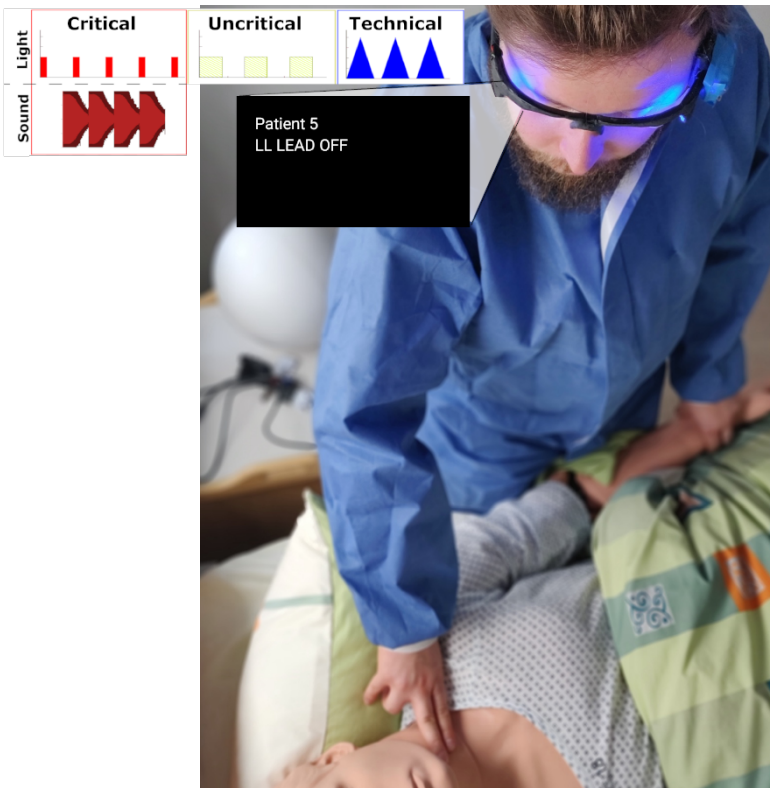


Figure 9.2: Possible application for a multimodal alarm system. [Cob19]

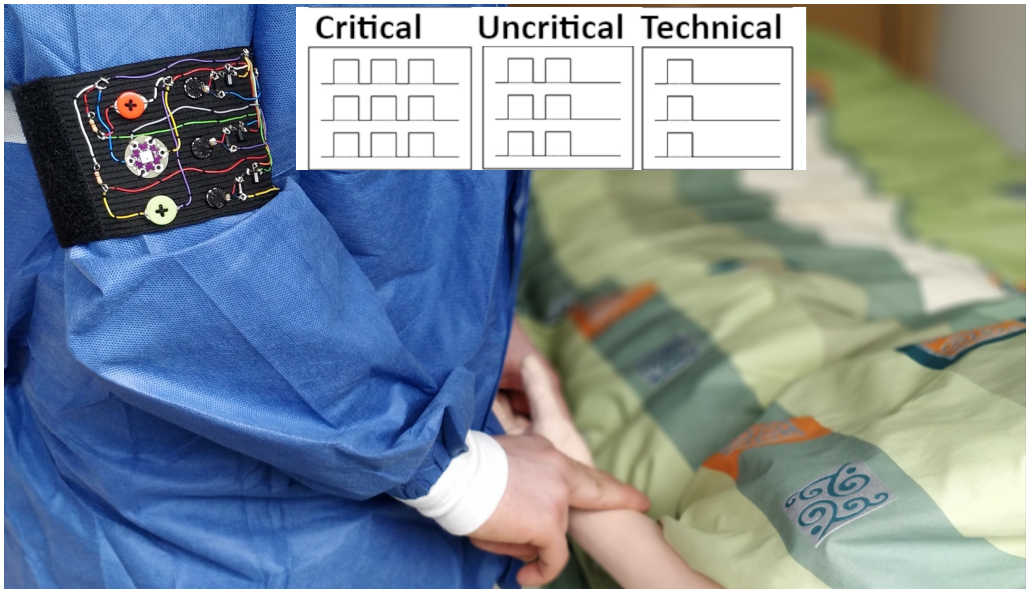


Figure 9.3: Possible application for vibrotactile alarms. [Cob19]

9.4 Limitations

Even though we followed a promising methodological approach to fulfill the user requirements, our work shows some limitations, that hinder us from generalizing our results.

9.4.1 Sample Size

To develop a multimodal alarm alarm distribution, we followed the HCD. Due to the current nursing shortage, the willingness of stressed and overworked nurses to participate in user studies which take longer than an hour is limited, despite financial compensation. For smaller studies, in which the expertise and specific knowledge of nurses is not necessarily required, we therefore invited participants outside the target group. Hence, our sample size in our studies is limited in the number of experts and variety of Hospitals. The nurses participating in our studies, were all employed in German ICUs. Subsequently, this hinder us from generalizing our results.

9.4.2 Field Studies

Another limitation shows our general study design. Due to several safety regulations, we were not allowed to test our findings in the field. Even though we tried to design our study set-up under realistic task and environmental conditions, we could not recreate the actual stress and loads of a typical ICU shift.

This applies also to the social acceptance of such a system. Due to the special circumstances, patients and relatives suffer from stress which could be increased by seeing HMDs, which are not established yet. We were not able to include this factor in our studies so far, but it should be addressed in future work.

9.4.2.1 Long-term Usage

The last limitation which need to be mentioned is the long term usage. As already mentioned, nurses as participants are a rare resource, and we are in a stage of development which cannot yet be integrated into the real environment, we could only evaluate the usage in a short term. Hence, we could also not evaluate a realistic number of alarms. This limitation is highly important, so we addressed this in our future work section.

9.5 Future Work

In our work, we investigated, how a wearable system should be designed to alert nurses for changes in their patients' health status. We did this as fundamental research, following a human-centered design approach. For the next iterations, to approach the development of a medical device, researchers and/or engineers should follow IEC 62366 [Com15], which involves in-depth inclusion of risk analysis processes.

In later stages, such a system can be evaluated in the field. Therefore, it could be used as a secondary alarm device as a first step, to evaluate the suitability in a long-term usage, and finally, to be introduced as part of the work clothing.

Another research field that should be considered is the social acceptance. As patients on ICUs are in a critical condition and relatives suffer from stress and fear, we would recommend to evaluate the acceptability in normal wards of a hospital.

Another field to be addressed is the interaction. As we mentioned in our limitations, we only investigated the edge of touchless interaction methods. We evaluated gestures via the head, shoulders, and feet as a proof of concept. However, the design space is broad to be explored in depth. E.g., speech or gaze input need to be designed and evaluated regarding their social acceptance.

Regarding our alarm design, we aim to encourage researchers to investigate other body locations to convey multimodal alarms. Hence, the hardware could be integrated within work clothing, as HMDs are not established yet. Further potential for research constitutes the integration of our light patterns into furniture, e.g., the frame of a patient bed, or the desk of a working place.

But also the transfer to other domains associated with a noisy work environment, or demand similar loads like nursing, e.g., hand-eye coordination and physical

loads, is worth exploring. For both, safety-critical areas, such as power plants, or chemical laboratories, but also in industrial production processes, the integration of wearable alarm or notification systems might be useful to improve working conditions.

Figures

Tables

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