Towards Reducing Alarm Fatigue: Peripheral Light Pattern Design for Critical Care Alarms

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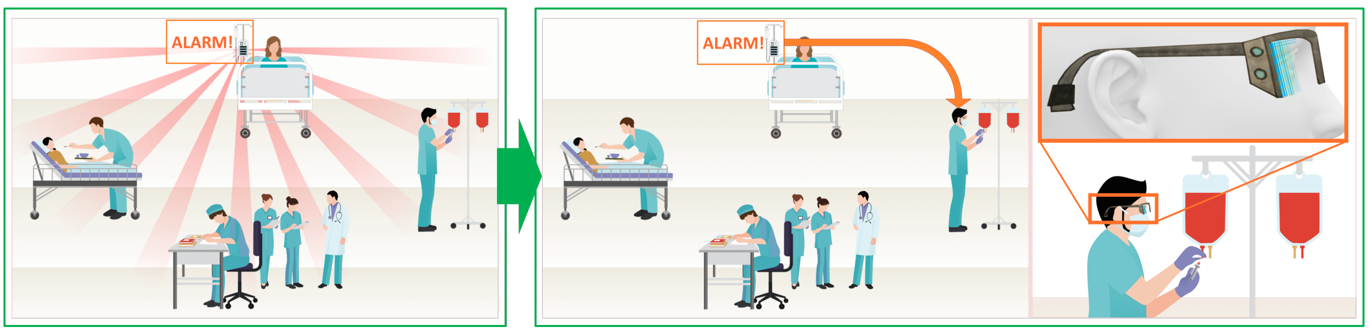

Figure 1: From ubiquitously audible to personal alerting

ABSTRACT

Everyone who has visited a patient in an intensive care unit will still remember the constant noise emitted from a number of highly sophisticated technical systems. For critical care nurses this creates a working environment in which about 350 alarms per patient are issued and each care taker is responsible for several patients at the same time. Alarm fatigue is a known effect in this demanding working environment which means a desensitization as well as a delayed response time for alarms. This can have severe consequences not only for the patients, but finally also for the care takers. To counteract the acoustic load on intensive care units, we explored light as a stimulus modality to display alarms in the user's peripheral vision using a head-mounted display. In a participatory design study, we developed several light patterns to represent three urgency categories. Under task conditions that mimic the load of care tasks, we evaluated the perceptibility and suitability of light alarm patterns. Our results show that peripheral light alarms are a promising approach to alert the user and our patterns can convey different levels of urgency.

Author Keywords

head-mounted display; critical care; wearable alarm system; safety-critical systems; human-centered design;

ACM Classification Keywords

H.5.2 User Interfaces: User-centered design; J.3 Life and Medical Science: Medical information systems

INTRODUCTION

Intensive care units (ICU) are equipped with a number of highly sophisticated technical systems and devices for patient monitoring, respiratory and cardiac support, pain management, emergency resuscitation devices, and other life support equipment. Patients in an ICU have life threatening illnesses and injuries or have undergone a major surgical procedure and need to be monitored 24 hours a day. The different medical devices issue visual and acoustic alarms for different reasons.

They might indicate that an important vital signal is above or below a certain threshold but also that a sensor is losing its signal because it has been displaced. To get an impression of the extent of these alarm systems, it is estimated, that the uninterrupted monitoring of vital body functions triggers up

NordiCHI'18, September 29-October 3, 2018, Oslo, Norway

ISBN 978-1-4503-6437-9/18/09...$15.00

DOI: https://doi.org/10.1145/3240167.3240218

to 350 alarm per patient and day [17]. As these alarms can be caused by technical problems or critical situations, each alarm has to be evaluated and acknowledged by a responsible nurse or physician. The alarms are commonly spatially distributed but ubiquitous which leads to a high level of noise pollution in ICUs. This does not only constitute a problem for nurses but also for the recovery of the patients [9].

The amount of alarms and also the noise level of all alarms in an ICU has a severe effect on the work conditions of a critical care nurse. Depending on the size of the unit, localizing an alarm and evaluating its importance can be very challenging. Furthermore, it distracts nurses from performing demanding tasks which should not be interrupted, e.g., refilling syringes or mobilizing patients. In this demanding environment, so called alarm fatigue is a severe and underrated condition which occurs when one is desensitized by the exposure to excessive alarm signals. It causes a delayed or inadequate response to alarms and effects in particular people working in safety critical environments, such as in an ICU [17].

Many interventions with the aim to reduce alarm fatigue have been evaluated so far. Literature has shown that interventions like e.g., alarm suppression algorithms, alarm or notification delays and alarm customization showed positive results in decreasing the number of alarms[22].
However, the remaining alarms are still ubiquitous and thus, obtrusive and audible for every person in the ICU. In our ongoing research, we aim to solve this issue by sending a patient's alarm directly to their responsible nurse. To reduce the acoustic alarm load for healthcare providers, we want to explore whether the personalized alarms can be delivered by other sensory modalities, starting with light (see Fig. 1).

Prior work in several domains has shown success in alerting users with peripheral light cues [1, 5, 20]. We assume that light is also a suitable stimulus in the safety critical context. To deliver the light alarms to nurses, we developed a head-mounted display (HMD). HMDs fulfill several safety and hygienic requirements that are common for systems in local hospitals, e.g., keeping the forearms free and enable hands-free interaction. Moreover, they can be easily integrated in the nursing workflow which includes a frequent moving between patient rooms, as they display information directly in the user's vision.

In this paper, we present the results of a feasibility study for peripheral notifications on an HMD during cognitively and physically demanding tasks as well as a participatory design study and evaluation for peripheral light alarms for critical care.
We showed that light is a feasible stimulus to represent alarms on an HMD during physically and cognitively demanding tasks. Moreover, we propose a set of peripheral light patterns to represent patient monitoring alarms on an HMD. Finally, our light patterns turned out to be an appropriate approach to present different urgent alarms in the peripheral vision of the user.

BACKGROUND

Most ICUs foster an ubiquitously audible alarm distribution. This means, the patient alarms of every patient sound from a central working and monitoring station and, depending on the local alarm policy within the hospital, also from the concerned patient room – audible for every person in the ICU and hard to localize its source [3]. To facilitate the evaluation of an alarm, common patient monitoring systems differentiate alarms into three categories: 1. high priority alarms (red alarms) for potentially life threatening situations, 2. lower priority alarms (yellow alarms) for exceeded alarm limits (e.g., blood pressure too high), 3. technical alarms (blue alarms) for situations in which the monitor cannot measure alarm conditions reliably (e.g., a removed electrode). Each alarm has an individual sound, which pitch and frequency of the beeps increases with the priority of the alarm. The colors red, yellow and blue highlight the source of the alarm (e.g., the relevant vital parameter) on the information display.
In hospitals, especially ICUs, the high number of alarms is a well-known problem. Due to the common spatial distribution, alarms are loud, hard to localize and distracting. 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. With vibrotactile and audible cues, a pager notifies nurses and especially physicians about relevant changes in the health status of their patients.
Maria M. Cvach et al. [8] tested a novel alarm escalation algorithm by using pagers as a secondary alarm notification system for six months on two surgical progressive care units. The algorithm distinguishes between crisis and non-crisis condition of high priority alarms. Both conditions run over two escalation steps. If the first nurse does not react to an alarm in a certain period of time, a second nurse will receive the alarm. If he or she does not react within 60 seconds, the charge nurse will be notified. For a non-crisis alarm, the algorithm starts delayed with a longer time period for the first escalation step. This approach decreased the mean alarm frequency and duration on the participating units significantly and shows the importance of a distributed alerting.Although portable devices like pagers can improve the distribution of alarms in hospitals, they have the disadvantage that they have to be put inside pockets. As nursing tasks are often stressful and physically demanding, the vibrotactile signal may go undetected [6]. This makes the usage of an additional audible signal for reliable alerting with mobile alarm systems unavoidable. Moreover, vibration may cause a condition called phantom vibration syndrome. This means, the user perceives that a device is vibrating, when, in fact, it is not. Studies illuminated that 68% of medical staff are affected, caused by having mobile phones or pagers in their pockets [2, 16]. For that reason it might be recommendable to use that modality carefully. We assume that light is a feasible alternative to represent notifications or even alarms. For that reason, we design light alarm patterns for the mentioned personalized alarm distribution.

In the following section, we present i.a. prior research that has shown success in using light for information representation in several domains.

RELATED WORK

In this section we present related work that shaped our design solution, focusing on information representation with light and head-mounted displays.

Information Representation With Light

Former research showed that peripheral light is a suitable modality to represent information within ambient systems. Ying-Ju Chang et al. investigated the usage of a noise-sensor light alarm in a newborn ICU [5]. The device in form of a flower was installed on a central wall of the ICU. It lights up when the noise level exceeds 65dBA. 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. [13]. This ambient display is placed on the back of a monitor 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 popups).

Andrii Matviienko et al. [11] developed guidelines to map information to light patterns in 2015. They 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, they 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 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. This work deduces 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.

Head-mounted Displays

Already in 2000, the anaesthesiologist Matt Weinger had the vision of a light weight head-mounted display to improve the work flow in hospitals [18]. Since then, the technology for smart glasses developed rapidly. Natalia Wrzesińska gave an overview of the usage of smart glasses in healthcare in 2015 [23]. She points out that the majority of the current studies used *Google Glass*. One example is the work of Wolfgang Vorraber et al. [21]. Via a Google Glass application, they monitored patient vital data to a participant during radiological interventions. The results showed that using smart glasses improved the efficiency and awareness on the task in hand by reducing head and neck movements toward the patient monitor. Wrzesińska assumes that wearables, especially smart glasses, have the potential to improve effectiveness of healthcare and education, although there is still a need for more investigations. Tilo Mentler et al. [12] sum up actual use cases for HMDs in healthcare and the usability challenges which arise for researchers and developers: Interaction design, information visualization, context of use. Moreover, they suggest to include all stakeholders during the development. This work encouraged us to display peripheral light alarms using an HMD.
Researchers investigated the usage of peripheral light on HMDs already for different domains. In 2012, Benjamin Poppinga et al. [15] 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.

One HMD aiming at the reduction of noise from mobile phones was engineered by Enrico Constanza et al. in 2006 [7]. 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. [14] 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.

The mentioned works show that an HMD is a promising device to improve patient care but also has potential to be improved. Our vision is to augment smart glasses with a peripheral light display that alerts healthcare providers with light alarms. The following section presents our first studies to explore light for redesigning critical care alarms.

EXPERIMENT

There are several safety regulations which keep us from testing in the field. For that reason we conduct our experiments in a lab setting with cognitively, physically and precision demanding tasks [10, 19, 24]. Those tasks shall mimic common loads during a nursing shift, like the patient handover, carrying portable medical devices or giving injections.

Due to the 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 we are 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.

Our experiment consists of two conditions with a between-subject design. We evaluated the perception of notification light patterns (based on the work of Matviienko et al. [11]) on an HMD during cognitively and physically demanding tasks first. The results led us to redesign the notification patterns.

Therefore, we conducted a participatory design study for three types of alarms: High priority, low priority and technical alarms. In doing so, we wanted to find at least one suitable light pattern for each alarm category. To avoid a confusion in final evaluations with the target group, we used commonly mapped colors to those alarms: red, yellow and blue. Finally, we evaluated the designed patterns regarding the subjectively perceived urgency, distraction and comfort. In the following, we describe the apparatus, the procedure and results of our studies.

Apparatus

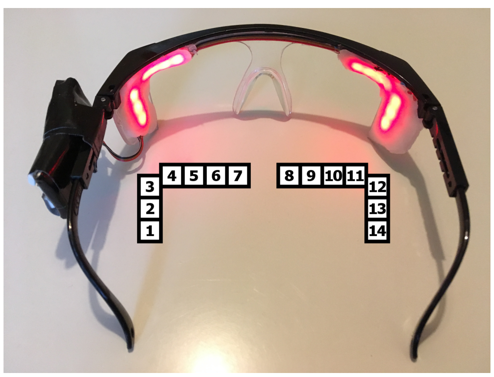

Figure 2: Head-mounted display and the numeration of LEDs

Nursing tasks include moving between patient rooms and other locations frequently, coupled with physically demanding tasks (like mobilizing patients). Therefore, we aim at developing a pervasive wearable alarm system that also allows hands-free interaction – like a head-mounted display.

To design and evaluate peripheral light cues, we developed an HMD, based on safety glasses. 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 final prototype is shown in Fig. 2.

Study 1: Feasibility Study

Methodology

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 [11], we implemented verified light patterns matching the information category "notification" using a blinking in red, yellow, and blue (see Fig. 3). The patterns differ in the blinkin frequency in terms of priority. The brightness values were adapted due to former pretests.

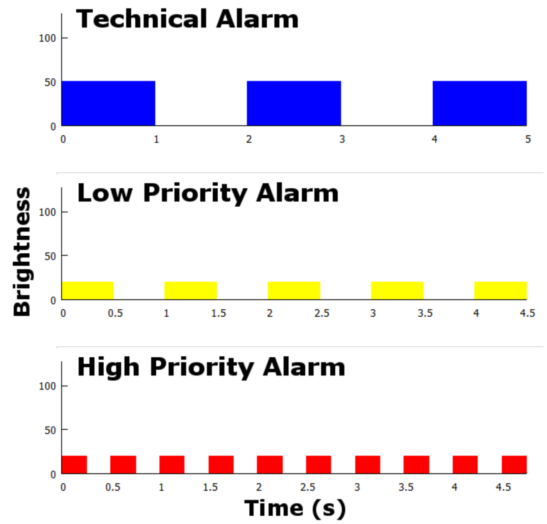

Figure 3: Patterns used in the feasibility study

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. 2). 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 [19] 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 [4]. The order of the subtasks 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.

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 4.3%. 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 th errors were missed patterns. For the remaining 12% no type of pattern was stated. This only affects the pattern *Low Priority Alarm*.

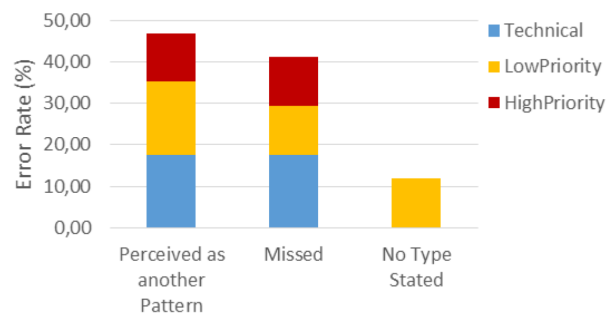

Figure 4: Errors in detail

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. 5). 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.

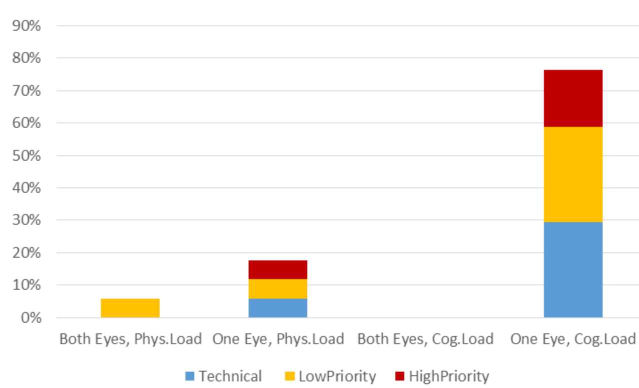

Figure 5: Percentage distribution per condition

Subjective Pattern Evaluation

The subjective rating of the perceptibility and distraction can be seen in Table 1. The diagram in Fig. 6 shows the following

	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 1: Summary of the rating results

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). 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).

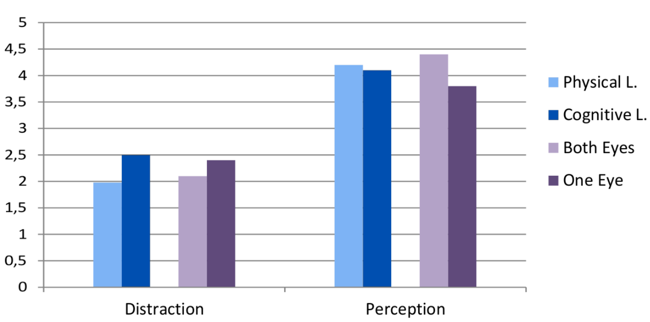

Figure 6: Perceived Distraction (left), Perceivability (right)

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 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 favourite 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.

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.

Study 2: Participatory Design Study

Methodology

Even though our first study revealed that the general usage of light patterns on HMDs is feasible for notifications in cognitively and physically demanding tasks, there was a critically high error rate for the safety critical domain. For that reason we conducted a user study to design alarm cues for the alarm categories "high priority alarm", "low priority alarm" and "technical alarm".

In doing so, we wanted to decrease the lack of distinguishability and hence the error rate of the notification patterns. We divided our study into two conditions, a design and an evaluation study. For the design study, we invited ten participants (6 female), aged between 18 and 33 years old. 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 as well as two less urgent light patterns for the colors yellow and blue. Therefore, 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 which 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 which 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 corrected, if necessary. The participants were asked to think aloud during the design process and to justify their design solutions afterwards. In the end they had to chose for each color, which pattern they prefer.

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 usage of each parameter is shown in Table 2, the number in brackets states the frequency of the used parameter within the preferred patterns.

	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)

Table 2: Used parameters within all designed light patterns

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 usage of different LED positions like a chasing light or just 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 frequencies as more urgent, 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.

Derived Light Patterns

Deriving from the results, we implemented five light patterns for each color which are also shown in Fig. 7.

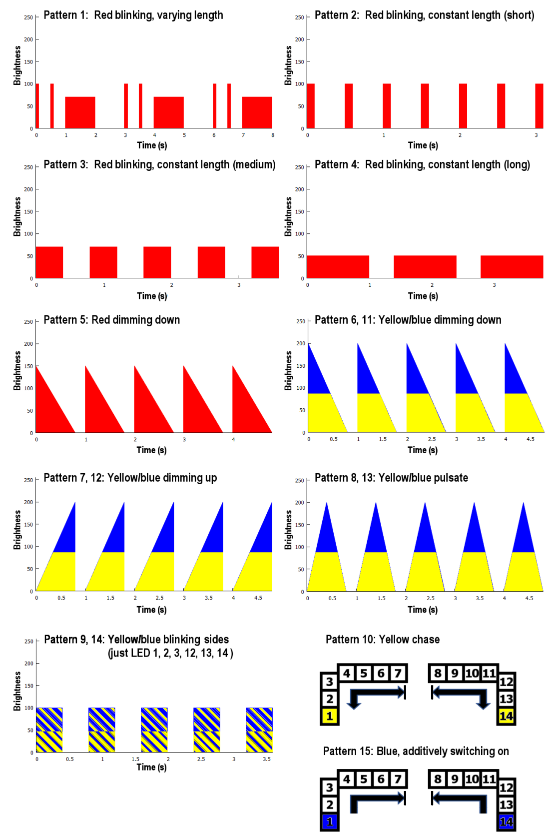

Figure 7: Overview of the implemented light patterns

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 usage of stepwise transitions for high priority alarms confirms the guidelines for urgent notifications of Matviienko et al. [11]. Therefore, we designed four light patterns, using a 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 similar urgent, we implemented similar patterns. Three of them include a combination of stepwise and smooth transition, one is a pulsing, one is a chasing light. Durations and brightness values are based on former pretests.

Evaluation of the Light Patterns

Methodology

In a further study, we wanted to evaluate, which of the shown patterns is suited best for representing three different types of alarms. Moreover, we wanted to find out whether blue light patterns appears generally, independent from the design of the pattern, less urgent than red or yellow. This study served for evaluating the implemented light patterns (see Fig. 7) 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), aged 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 Fig. 7) were shown to the participants on the HMD in intervals of one minute. Each pattern was repeated three times, the order of the patterns was randomized. To prevent the participants from getting tired or irritated we split the study into three conditions with different precision demanding tasks [10, 24]. 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. 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, where 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 Fig. 8). In the third task, the participants had to refill syringes with exact predefined

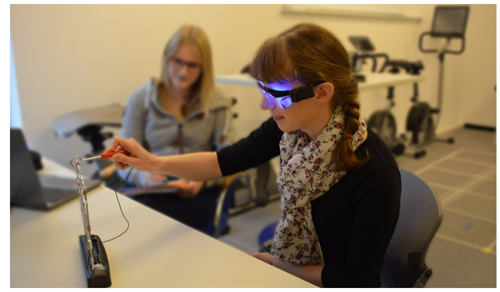

Figure 8: Participant doing a precision task wearing the protoype.

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, which appears urgent for the user but not distracting from the actual task. Since the HMD should be worn during a whole shift, we paid also attention for 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 given space for further annotations.

Results

Quantitative Results

In the following, we use *LP1 - LP15* for Pattern 1 - Pattern 15. We regard patterns rated with an average score higher as 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 which was 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 $p < 0.01$).

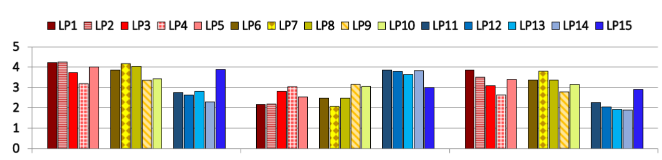

Figure 9: Overview of the results for each pattern

Neither one of the red nor one of the yellow light patterns were perceives 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 Fig. 9.

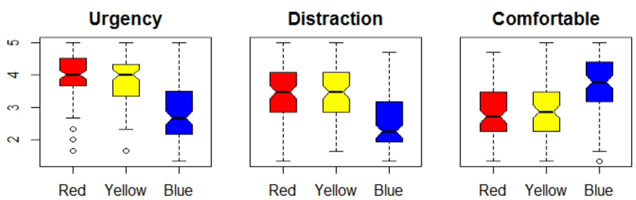

Figure 10: Summary of the perception between colors

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 none 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 Fig. 10).
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, 18 participants LP1 and 15 LP5 with alarms. LP3, the constantly medium long blinking patter, 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 for 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" 9 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 which was mentioned 62 times was "pleasant". This was related to all blue patterns except LP15. This pattern was called "too long" or "hectic" 17 times.

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 may indicate that a sensor does not measure the data reliably, ignoring a blue alarm due to a 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 and should be expended by another sensory stimulus.
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. As an alternative we consider LP5, the down-dimming pattern, which lies in the middle regarding all factors but is still perceived as urgent. For the low priority alarm, we consider LP9, the constantly blinking lateral LEDs. As low priority 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 technical alarm, we consider the constantly pulsating pattern, LP13, which is the second most urgent and also the second most comfortable and distracting pattern.

However, our study results are limited, since they were not verified by healthcare providers thus far. Moreover, there are several safety regulationswhich keep us from testing our patterns in the field. For that reason we are planning to conduct further experiments with nurses in intensive care simulation labs to evaluate the general usability of our prototype and the light patterns for nurses.

CONCLUSION AND FUTURE WORK

In this paper we presented an ongoing approach to reduce alarm fatigue in ICUs. We showed a conceptual personalized alarm distribution and multimodal signaling model. In a participatory design process we developed and evaluated alarm light patterns on a self made head-mounted display. Our results showed that an HMD is a feasible medium to present information with light in the user's peripheral vision. Moreover, we provide a set of evaluated light patterns that represent different levels of urgency on an HMD. These light patterns can signalize patient alarms during nursing tasks. We admit that we cannot generalize our results for nurses working in the ICU, yet. However, we made a first step towards deriving peripheral light alarms that may reduce alarm fatigue. Our next step will be the design and evaluation of vibrotactile patterns for technical alarms on an HMD. In our ongoing research, we will focus on the integration of our multimodal alarm concept into smart glasses and an associated interaction design. Finally, we will evaluate the peripheral head-mounted alarm display with healthcare providers (especially nurses) in a realistic lab environment.

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