Boundary conditions for safe detection of clinical alarms: An observational study to identify the cognitive and perceptual demands in an Intensive Care Unit

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Abstract

Many medical devices found in intensive care units (ICUs) use alarms to inform the user of critical, potentially life-threatening conditions. Urgent information is typically indicated by auditory stimuli, because audition is regarded a sentinel sense particularly suited for alerting purposes. In contrast to this general assumption, however, empirical evidence from the laboratory shows that even apparently automatic perceptual processes (such as the detection of an alarm) depend on the availability and allocation of processing resources. Aim of the present study was to characterise the work conditions in a German ICU with respect to factors that influence the perceptual and cognitive load and that may, therefore, compromise alarm detection. Seven experienced intensive care nurses were shadowed during their morning shifts to identify the time consumption and occurrence rates of individual activities, proportions of multi-tasking, and the frequency of task-switching and disruptive events. Amounts of multi-tasking (24% of the time spent on manual tasks) and task-switching (on average every two minutes) were considerable. Moreover, nurses were interrupted (e.g. by an in-room alarm) about every 3 minutes. Based on findings such as these, further studies may systematically investigate in how far the work conditions in an ICU are suited for reliably detecting alarms.

Introduction

In clinical context, device alarms are used to inform care-givers of hazardous situations such as device malfunctions or critical changes of the patient's vital functions in order to trigger the necessary intervention. This goal can, however, only be achieved, when the care-giver detects the alarm, in the first place, and there is evidence from case reports that this may not always be the case. Notably, stimulus detection not only depends on physical features of the stimulus but also on the available processing resources. For instance, in a recent flight-simulator study, almost 40% of the participants did not report a landing gear alarm that sounded while they were dealing with a critical wind-shear situation (Dehais et al., 2014). This finding demonstrates that even salient stimuli may escape awareness when processing resources are strongly engaged otherwise (see also Simons & Chabris, 1999). This may be a serious problem in clinical work conditions like the intensive

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care unit (ICU), where nurses have to frequently rely on device alarms to keep track of the patients' vital status and failures to detect an alarm may have fatal consequences.

The degree to which stimulus awareness is compromised by an on-going task has been shown to be associated with the task's perceptual (e.g. Cartwright-Finch & Lavie, 2007; see also Konstantinou & Lavie, 2013) and cognitive demands (e.g. Fougnie & Marois, 2007; Simons & Chabris, 1999). Hence, the risk of missing an alarm on the ICU may depend on which other activity the nurse is currently performing. Moreover, cognitive load also depends on other factors, for instance on the necessity to deal with multiple tasks in a given time (task-switching; for reviews see Kiesel et al., 2010; Monsell, 2003). Clinical work is also described as highly fragmented - determined by frequent switches between tasks (and also multi-tasking) (e.g. Cornell et al., 2010, see also Berg, Ehrenberg, Florin, Östergren, & Göransson, 2011; Berg et al., 2013; Chisholm, Collison, Nelson, & Cordell, 2000; Kalisch & Aebersold, 2010; Tucker & Spear, 2006 ; Walter, Li, Dunsmuir, & Westbrook, 2014; Westbrook, 2014). This is typically discussed in the context of interruptions, which are assumed to contribute to medical errors because of their demands on prospective memory (for reviews Grundgeiger & Sanderson, 2009; Li, Magrabi, & Coiera, 2012).

Goal of the current study

To the best of our knowledge, it has not yet been investigated, whether and how the perceptual and/or cognitive demands that follow from working in a clinical environment impair the detection of device alarms. Answering this question is important, because conscious detection may be regarded a prerequisite for adequately responding to an alarm – and hence to the alarm's effectiveness. The present observational study was a first step to reaching this goal. It aimed at describing and quantifying the work conditions on an ICU (because alarms may be particularly relevant on an ICU) by recording nurses' locations and activities, as well as external distracters. These conditions shall be mimicked in future studies to investigate their impact on alarm detection (for a similar approach see Edworthy, Meredith, Hellier, & Rose, 2013).

Methods

Study setting

The study was conducted in the surgical ICU of the University Hospital Bonn. Seven different nurses were shadowed (five nurses twice, two nurses once) during their morning shifts (between 7.00-10.00 a.m. or 10.00 a.m.-1.00 p.m.). To minimize the potential impact of the observers, participating nurses were recruited only among nurses with a special training in intensive care and at least 1.5 years of experience as an intensive care nurse. The observation setting was a standard double patient room, consisting of two compartments, which could be separated by a sliding wall. Ethics approval was obtained from the ethics committee of the University Hospital Bonn before starting the study. For confidentiality reasons, neither audio- nor video-recordings were made. All participating nurses gave their written informed consent. Other nurses and the physicians of the ICU were informed by notices posted both in the nurses’ and the physicians’ station. Patient-related data were not recorded. When a patient was conscious, one of the observers explained the purpose of their presence and ensured that the patient was comfortable with the situation.

Data collection

In six of the twelve observation sessions, only a single nurse was present, who was responsible for two (5 sessions) or one (1 session) patients. In the remaining six sessions, the participating intensive care nurse was accompanied by another nurse, who underwent on-the-job training for qualification reasons. These dyads were always assigned two patients. The average duration of the individual observation sessions was 165 minutes, ranging from 151 to 192 minutes. Since the goal of the current study was to assess the demands imposed on intensive care nurses *while monitoring the patient with the help of alarms*, activities occurring while the monitoring task was delegated to a colleague were not recorded. These instances included: breaks, helping a colleague in a different room, abandoning the ward for an external emergency call, and transporting a patient to the operating theatre. Whenever any of these instances occurred, the recording was suspended until the nurse returned to the patients’ room. Correcting for these times yielded individual observation durations between 124 and 168 minutes (mean: 152 minutes, SD = 12).

Observational procedure and activity categories

Observational data were collected simultaneously by two of the authors, a psychologist (KL) and a medical engineer (MN). Prior to the study, the observers had visited the ICU several times (for approximately 20 hours in total) to acquaint themselves with the specific work environment. Starting with a list of nursing activities provided by the nurse management, activity categories were defined that could be identified by observable cues and that were regarded to be roughly homogeneous with respect to the involvement of perceptual, cognitive and motor processes. These categories were further refined during five pilot sessions (included in the pre-study visits to the ICU) and supplemented by additional categories for different kinds of disruptive events (i.e. alarms, telephone ringing, and being disrupted by a person). The final list of observation categories, together with the associated observable cues, is given in Table 1. For recording, a custom-made observation tool was used that was programmed as an Android application on a Samsung Galaxy tablet PC.

Table 8. Overview of observation categories and associated Kappa values

	Nurse's position	**Defining cue**	**Temporal characteristic**	**Kappa value (SD)**
		Manual activities		
Taking blood	patient room	at the patient, at IV line with syringe and sample tube	duration	0.88 (0.13)
Preparing drugs	patient room	at the medication preparation desk, handling drugs and infusion solution	duration	0.80 (0.08)
Managing lines, catheters, tubes	patient room	at the patient or device, manipulating or looking at catheters/lines or ventilation tube	duration	0.59 (0.23)
Operating a medical device via user interface (standard)	patient room	at the device, pressing buttons on user interface	duration	0.68 (0.10)
Stopping alarms	patient room	at the device, pressing buttons on user interface in response to an alarm	event	0.45 (0.21)
Other interactions with medical devices (non-standard, special devices)	patient room	at the device, involving interactions other than pressing buttons, may include additional equipment	duration	0.81 (0.10)
Fetching supplies	hall/othe r rooms	leaving the patient room and returning with supplies (medication, other)	duration	0.72 (0.21)
Blood gas analysis	hall	at specific device for blood gas analysis with blood sample	duration	0.90 (0.10)
Documenting	patient room	using patient data management system at specific terminal, using the PC	duration	0.90 (0.05)
Washing and changing dressings	patient room	at patient, using special equipment (wash mitt, dressing material)	duration	0.87 (0.09)
Bedding the patient and changing linens	patient room	at patient, together with a colleague; handling linens	duration	0.83 (0.13)
Tidying	patient room	anywhere in patient room, moving any kind of equipment	duration	0.57 (0.37)

Observing activity				
Observing the patient or a device	patient room	anywhere in patient room, looking at the patient or a device	duration	0.41 (0.14)
Oral activities				
Exchanging information with other nurse/physician	any location	other nurse(s) or physician(s) present, talking, listening and responding	duration	0.65 (0.14)
Teaching	any location	less experienced nurse(s) present, talking, listening and responding	duration	0.87 (0.15)
Talking to the patient	patient room	at patient, patient conscious, talking, listening and responding	duration	0.66 (0.25)
Disruptive events				
Direct interruption by a person	any location	other person entering and addressing nurse	event	0.43 (0.31)
Alarm in patient-room 1	any location	Alarm audible in current position of nurse, originating in patient room 1	event	0.74 (0.11)
Alarm in patient-room 2	any location	Alarm audible in current position of nurse, originating in patient room 2	event	0.72 (0.13)
Alarm in another patient room	any location	Alarm audible in current position of nurse, originating neither in patient room 1 nor 2	event	0.39 (0.14)
Telephone ringing	any location	Telephone ringing audible in current position of nurse	event	0.66 (0.13)

Activities were defined by location (e.g. at the patient's bed), the *effector* involved (hands, mouth, eyes) and the *tool or device that was handled*. To account for natural limitations to simultaneously performing several activities with the same effector, we grouped 'manual activities', 'oral activities', and 'observing' into separate groups and configured our observation tool to prevent the simultaneous coding of individual activities *within* these groups[1]. An active activity would automatically terminate when a new activity of the same group was started. Activities from other

[1] The only exception to this was "Stopping alarms", which could be performed one-handedly while performing a different task with the other hand, e.g. holding the patient or a syringe.

groups were not affected. For instance, when a nurse worked on the data entry terminal of the electronic patient data management system (PDMS), the manual activity “documenting” would be activated by the observer. When the nurse now read a value from a device while remaining at the PDMS terminal and then entered the value into the PDMS, “observing patient/device” would be coded simultaneously to “documenting”. By contrast, when the nurse moved to the device and pressed some buttons to extract a value, the manual activity “operating a medical device via user interface” would be coded. This would terminate “documenting”. When, in the latter case, the nurse entered the value into the PDMS system, this would trigger a second stint of “documenting”. These two examples would yield one versus two instances or occurrences of “documenting”, respectively.

Observer agreement

To obtain an estimate on the reliability, Kappa-values (Bortz & Lienert, 2008) were calculated for individual categories across 60 s time windows (see also Table 1). Most Kappa values were well above .60, indicating substantial or better observer agreement (e.g. Landis & Koch, 1977). Observer agreement was somewhat poorer for “Checking on and manipulating catheters/lines and tubes”, “Tidying”, “observing patient/device” as well as for “Stopping alarms” and “Interruptions by person”, most likely due to the elusive nature of these categories, i.e. these events may more easily be missed by at least one of the observers.

Data pre-processing

The coded activity categories, together with their start and stop times, were saved to an Excel-file. Subsequent to each observation session, the following processing steps were performed on these raw data. Firstly, each observer went through the records individually to correct entries marked as erroneous during observation. Secondly, individual recordings of observers 1 and 2 were compared. Gross deviations in the selected categories were discussed until agreeing on a common solution. The individual observation files were then changed accordingly. From these raw data, information concerning the duration of activities, the occurrence rate of activities and disruptive events, simultaneous activities and switching were extracted as detailed below.

Results

Time consumption, typical durations, and occurrence rates of activities

For each observation file, individual instances of activities were counted (i.e. each time an activity was started was counted a new instance of this activity). For each observation session, event counts were converted to hourly rates of occurrence, separately for each activity. Additionally, the total time share of each activity was calculated by summing the durations of individual instances and dividing by the observation time. For each observation session, the final values of total durations and occurrence rates were computed by averaging across the values obtained for the two observers. To obtain the most typical duration for individual occurrences of each activity, the individual instances were assigned to one of the following duration categories: 10 s or shorter, 11-30 s, 31-60 s, 61-120 s, 121-240 s, 241-360 s, 360 s or longer. Relative proportions of instances in the individual duration categories were determined and averaged across observers (see Tables 2 and 3).

The most time-consuming activities were “Information exchange”, followed by “Washing/Dressings”, “Documenting”, “Preparing drugs”, and “Linens/bedding” (Table 2). As to the most typical duration of individual instances of activities, this was less than 10 or 11 to 30 s for activities like “Lines/tubes”, “Device (standard)” or “Observing”. Other activities were typically performed for somewhat longer durations, e.g. “Documenting” or “Preparing drugs” (11- 60 s), “Linens/bedding” (31-120 s), or “Washing/dressings” (61 s-240 s). Notably, substantial proportions instances longer than 240 s were only found for “Linens/bedding”, “Washing/dressings” and “Information exchange” (Table 2).

Table 9. Mean percentages of observation time consumed by the different manual and non-manual activities (N = 12) and percentage distributions of individual instances of the activities over duration categories

	Mean (%)	SD	≤ 10 s	11-30 s	31-60 s	61-120 s	121-240 s	241-360 s	> 360 s
Information exchange	19.72	7.70	25.19	26.12	18.09	17.41	7.40	2.44	3.36
Washing/ dressings	15.77	8.92	6.35	17.52	17.31	23.54	18.65	6.53	10.09
Documenting	9.55	2.99	10.53	30.31	25.04	24.12	9.10	0.90	0.00
Preparing drugs	9.05	4.43	15.35	24.18	29.02	18.64	11.75	0.82	0.24
Linens/bedding	8.26	5.97	14.80	18.55	23.83	20.30	8.15	7.54	6.83
Talking to patient	7.09	7.63	40.56	21.13	18.09	11.81	4.56	2.73	1.13
Device (nonstandard)	5.38	3.59	3.35	22.94	24.47	36.28	10.77	1.85	0.34
Fetching supplies	5.16	4.44	25.97	24.94	24.95	15.93	4.96	2.73	0.52
Teaching	4.98	7.63	12.97	39.90	21.29	7.15	13.98	2.75	1.96
Lines/tubes	4.67	1.98	33.79	38.49	20.43	6.76	0.54	0.00	0.00
Device (standard)	3.81	1.77	49.93	29.87	15.00	3.26	1.93	0.00	0.00
Observing	3.72	1.84	61.33	26.52	8.32	2.30	1.53	0.00	0.00
Taking blood	1.93	1.48	14.53	15.67	32.84	23.10	9.32	4.55	0.00
Blood gas analysis	1.90	1.11	12.38	9.50	13.49	51.72	12.92	0.00	0.00
Tidying	1.21	1.07	32.85	41.62	14.04	11.49	0.00	0.00	0.00

The most frequent activities were “Information exchange”, “Observing”, “Device (standard)”, “Lines/tubes”, “Documenting”, and “Preparing drugs” (Table 3). Notably, the particularly frequent activities “Observing”, “Operating (standard)” and

“Lines/tubes” did not rank highly in overall time-consumption – these activities typically took only around 10 seconds. By contrast, “Washing/dressings” and “Linens/bedding”, which were relatively time-consuming in total, were restricted to fewer, but longer occurrences within a shift.

Table 10. Mean numbers of occurrences/hour for the different manual and non-manual activities (N = 12)

	occurrences/hour	SD	Min	Max
Information exchange	12	6	4	21
Observing	8	4	5	15
Lines/tubes	7	2	3	11
Device (standard)	7	4	4	18
Documenting	6	2	3	11
Preparing drugs	6	3	2	9
Talking to patient	5	6	0	18
Fetching Supplies	4	2	2	7
Washing/Dressings	4	2	0	7
Device (nonstandard)	3	2	0	6
Linens/bedding	3	2	1	7
Stopping alarms	3	4	1	17
Teaching	3	4	0	10
Tidying	2	1	0	4
Taking blood	1	1	0	2
Blood gas analysis	1	1	0	3

Performing activities simultaneously

For each manual activity the percentage of time was determined that this activity was performed in parallel to observation and the communication activities, respectively. In 24% of the time spent on any of the manual tasks, observing or any form of communication was additionally performed. However, there were differences between activities (Table 4). The activities with the highest percentages of time shared with observing (patient or device) were managing lines/tubes and standard interactions with a device. Information exchange with a colleague occurred for almost one third of the time spent changing linens/bedding the patient and was also frequent while operating the blood gas analyser, managing lines/tubes or documenting. Finally, while changing linens/bedding and while washing, nurse often talked to the patient.

To determine the fragmentation of the work on the ICU counted the number of switches between the different manual activities was counted. A switch from activity A to activity B was defined, if *stopping* activity A was followed by *starting* activity B within 30 s. Otherwise a switch to “nothing” was coded (these were not further considered in the analyses). Numbers of switches were first counted separately for each observer and then averaged across observers. To determine switching rates, total numbers of switches were summed across activities and divided by the observation time, separately for each observation session. It showed that nurses switched between manual activities rather frequently: On average once every 110 s (SD = 35; between once every 53 s and once every 167 s).

Table 11. Mean percentages of time the manual activity presented on the left (rows) was accompanied by observing, information exchange with a colleague, teaching, or talking to the patient (the standard deviation is presented in parentheses).

	observing	information exchange	teaching	talking to patient	sum
Taking blood	1.32 (3.11)	7.50 (14.90)	5.96 (19.78)	4.55 (8.12)	19.33
Lines/tubes	5.60 (5.52)	15.91 (17.52)	2.92 (5.41)	5.79 (6.37)	30.22
Device (standard)	7.46 (7.17)	11.70 (10.58)	5.36 (8.63)	3.64 (5.20)	28.17
Device (nonstandard)	1.80 (3.83)	13.60 (15.20)	7.25 (15.06)	7.38 (9.46)	30.02
Fetching supplies	0.02 (0.06)	10.75 (10.14)	1.80 (5.26)	0.14 (0.25)	12.70
Documenting	3.11 (2.46)	15.61 (14.87)	1.39 (3.94)	0.98 (1.74)	21.08
Washing/ Dressings	0.30 (0.34)	10.74 (12.43)	4.77 (13.41)	12.27 (16.11)	28.08
Linens/ bedding	2.45 (4.27)	29.54 (25.74)	5.33 (14.39)	15.81 (19.00)	53.12
Preparing drugs	1.52 (1.79)	8.44 (9.00)	3.95 (6.41)	3.23 (5.23)	17.14
Blood gas analysis	0.21 (0.67)	16.30 (16.83)	0.18 (0.58)	0.00 (0.00)	16.70
Tidying	0.55 (0.95)	3.11 (5.15)	0.51 (1.75)	1.77 (3.36)	5.93

Task-Switching: Overall frequencies and individual transition probabilities

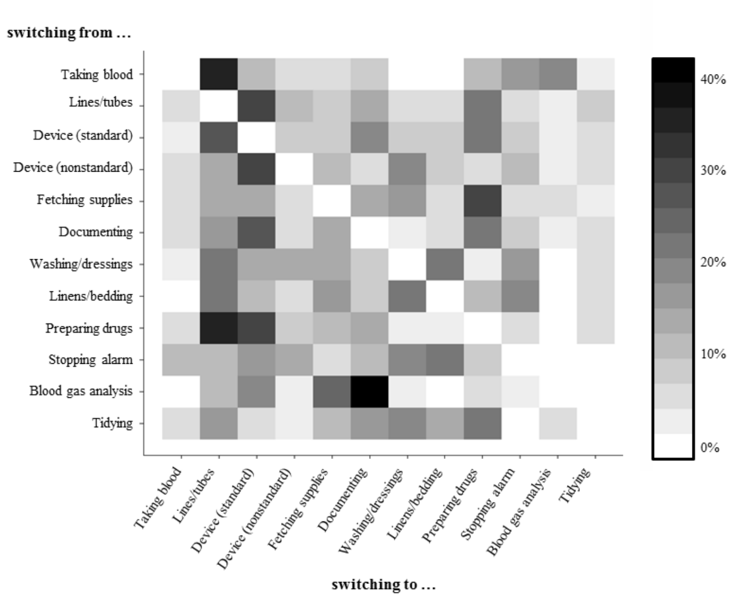

Figure 1. Distribution of switches from individual manual activities (y-axis) to any other manual activity (x-axis). Values are shown as percentages relative to the total number of switches from the activity plottet on the y-axis.

Switching from one activity to another was not arbitrary (see Figure 1, which shows the percentage of switches from any activity depicted on the y-axis that was directed to any of the activities presented on the x-axis, relative to all the switches originating from the activity on the y-axis). For instance, when the current activity was “preparing drugs”, nurses most likely switched to “managing lines/tubes”. Likewise, “Managing lines/tubes” was followed in most instances by a “standard interaction with a device”. Assuming that particularly frequent transitions between activities reflect their procedural relatedness, an additional switching rate was computed that accounted for switches between highly related activities (i.e. with more than 15% of the switches from activity A directed at activity B). The resulting values showed that a switch occurred on average every 225 s (SD = 84), with a minimum of one switch every 91 s and a maximum of one switch every 417 s.

Disruptive events

Finally, direct interruptions by colleagues, alarms from within the double patient’s room, alarms from other rooms and telephone ringing were counted. Direct interruptions by a colleague and alarms from within the double patient room were regarded “task relevant” disruptive events, because the shadowed nurse was the addressee. Alarms from other rooms and the ringing of the telephone were primarily addressed at other members of staff, hence “task irrelevant” for the observed nurse.

During observation, not every single sound was transcribed to the observation tool, but a note was taken whenever an alarm was interpreted as a new event. For describing the load associated with disruptive events, the observation time was divided into 60 s time-epochs and the proportion of time-epochs that contained at least one disruptive event was counted. At least one task-relevant disruptive event occurred in 36% of the 60-second time windows (SD = 9, range between 20% and 47% across observation sessions). Task-irrelevant disruptive events were even more frequent: These occurred in 47% of the time windows, on average (SD = 14, range between 22% and 70%).

Discussion

The present observational study was aimed at identifying exemplary work conditions on an ICU with respect to factors that may – from a theoretical perspective - impact on perceptual and cognitive load. This includes the time share of the different nursing activities, as well as their distribution over time and the presence of potentially distracting events.

Most of the activities performed by nurses may be assumed to draw on perceptual and cognitive functions (documenting, preparing drugs, device – standard and nonstandard, fetching supplies, lines/tubes, observing, taking blood, blood gas analysis). Overall, nurses spent almost half of their time on these activities. Predominantly motor tasks (washing/dressings, linens/beddings, tidying) accounted for almost 25% of the time. In about one third of the time (often overlapping the manual activities), nurses verbally communicated with colleagues or with the patient – which should also tax perceptual and cognitive processes (see also Klink, 2012), particularly in noisy environments such as the ICU (for review see Konkani & Oakley, 2012). Interestingly, although the observation categories and the coding scheme were not identical, the present findings resemble those obtained for an English ICU by Edworthy and colleagues (2013) with respect to the occurrence rates of individual activities: These authors found “Observation”, “Staff talking” and “Preparing and administering drugs” to be among the most frequent activities.

Arguably, the *individual* tasks alone may not usually exploit the nurses’ perceptual and cognitive resources to a degree that endangers alarm detection. However, the need to coordinate several tasks simultaneously (multitasking) or sequentially (task-switching) may considerably increase cognitive load. In the present study considerable degrees of multitasking and task switching were observed. Multitasking occurred in 24% of the time spent on the manual tasks - up to 30% of the tasks with perceptual and cognitive components and up to 53% of the predominantly motoric manual tasks. Moreover, nurses switched frequently between activities - between approximately once every minute and once every three minutes (see also Cornell et al., 2010). Performance decrements are to be expected for multitasking conditions, because processing resources have to be divided between tasks – even though there may be differences depending on the overlap between, for instance, processes or modalities involved (e.g. Wickens, 2008). Task-switching in clinical settings is mostly discussed as a consequence of interruptions (e.g. Chisholm et al., 2000; Chisholm, Dornfeld, Nelson, & Cordell, 2001; Grundgeiger, Sanderson, MacDougall, & Venkatesh, 2010; Li et al., 2012; Walter et al., 2014; Westbrook, Duffield, Li, & Creswick, 2011). Here, turning to a new task is assumed to load on working memory, because the intention to complete the interrupted task (together with the steps already performed) must be kept active (e.g. Parker & Coiera, 2000; see also Grundgeiger & Sanderson, 2009). However, switching from one task to another may be regarded demanding even if there is no need to resume a previous activity (e.g. when two activities are part of the same overall task), in part because of the constant need to (re-) activate current cues and task-rules (Cornell et al., 2010; see also Kiesel et al., 2010). Similar demands on cognitive control may result from the fact that attention was frequently drawn by approaching colleagues and relevant alarms (at least once every 3 minutes), while at the same time irrelevant alarms and other noise distracters had to be filtered out (more than once every 2 minutes). Note that the study did not aim at determining whether an alarm elicited an intervention, so as to get an impression on the number of potentially undetected alarms. Because of the temporal delay between individual alarms and the associated responses, this should be impossible to infer from observational data, alone.

To summarize, the present study provides examples of naturally occurring durations and frequencies of individual tasks, proportions of multitasking between individual tasks, typical switching rates and rates of task-relevant and task-irrelevant disruptive events on a German ICU. These factors may be assumed to contribute to the nurses' perceptual and cognitive load. This information may be used to more closely match conditions in future laboratory studies to those in the field in order to investigate the risk of failing to detect an alarm under controlled conditions (for a similar approach see Edworthy et al., 2013). Insights into the cognitive restrictions to alarm detection under maximally realistic situations would provide important information with regard to the implementation of medical devices in the field.

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