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Simulation and education

Comparative usability of manual defibrillators – A human factors study

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Abstract

Background: A manual defibrillator represents key equipment for resuscitation of cardiac arrest scenario. Improper or slow operation of a defibrillator may adversely affect acute care. A self-explanatory interface facilitates handling and decreases the risk of operating errors. Therefore, we evaluated the usability of four commercially available defibrillators.

Methods: 31 medical students executed 15 consecutive tasks on each defibrillator (Physio-Control Lifepak 20e, Schiller Defigard Touch 7, Corpuls 3 and Zoll X-Series). The operators' gaze was measured via eye-tracking and frequencies of required assistances and task completion times were recorded. Additionally, subjective perception of usability was assessed by a standardized questionnaire.

Results: Least assistances (16) were required when operating the Lifepak 20e and most (63) when operating the X-Series. Cumulative task completion times were shortest in the Lifepak 20e (124 ± 31 s), followed by the Corpuls 3 (220 ± 69 s), the Defigard Touch 7 (225 ± 81 s) and the X-Series (289 ± 85 s; $p < 0.001$). Completion times of specific tasks differed considerably between the devices. Eye-tracking revealed associated interface issues that impeded the operators' performance. Overall standardized usability was rated best for the Lifepak 20e (81 ± 15) and worst for the X-Series (44 ± 20).

Conclusions: The usability of defibrillators differs considerably and task specifically between devices. Interface issues of tasks impaired the operators' efficiency specifically. The perceived usability and the perceived stress-level after operating the devices corresponded with objective measures of usability. Eliminating specific usability issues may improve the operator's performance and, as a consequence patient outcome.

Keywords: Manual defibrillation, Operator performance, Task completion time, Eye-tracking, User interface

Introduction

Operating a defibrillator in a clinical setting is a complex task that involves the patient, the operator, and the device.[1] The individual strengths and weaknesses of a defibrillator's user interface may influence the operator's performance.[2] With increasing functionality of defibrillators, operational complexity has increased, and usability has become an increasingly important consideration.[3] Simple and self-explanatory designs of medical devices can significantly increase patient safety.[3–5] This appears particularly true for manual defibrillators, which are always used in an emergency situation when quick and accurate operation undoubtedly influence patients' outcome. In this study, we hypothesized that commercially available manual defibrillators differ in usability, based on the design of their user interfaces. Therefore, we asked individuals with a medical background but no experience in defibrillation to perform a series of tasks representing typical interactions with a defibrillator, to assess the usability of the human–machine interfaces. We measured task completion times and determined the frequency of requested assistances. Furthermore, we measured the operators' visual focuses via eye-tracking, and

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assessed their perception of device usability using a standardized questionnaire.

Methods

Defibrillators under test

The usability of four commercially available defibrillators from different manufacturers was studied: Lifepak 20e (Lifepak; Physio-Control Inc., Redmond, WA), Defigard Touch 7 (Defigard; Schiller, Baar, Switzerland), Corpuls 3 (Corpuls; GS Elektromedizinische Geräte, Kaufering, Germany) and X-Series (X-Series; Zoll, Chelmsford, MA). The four defibrillators were chosen based on comparable functionality and on assumed relevant prevalence in the European clinical environment.

Operators

The study was approved by the Ethics Committee of the University of Freiburg (EK-17/16) and written informed consent was provided by each subject.

Third-year medical students were screened for the study. Only persons who had no relevant experience with defibrillators were included to avoid biasing our results by habituation or coping strategies of experienced users. Furthermore, with respect to the psychophysical design of the study, persons were excluded when they had indicated last night's sleep of less than 5 hours, alcohol or drug intake within the last 12 hours. Moreover, to ensure comparability, the operators' reaction times were assessed as average from 30 rounds at a validated reaction test (ReactionCheck, DocCheck, Cologne, Germany).

Study protocol

To standardize prior knowledge of all subjects, a 4 min training video (slide presentation with recorded text) was shown before the start of the experiments providing basic theoretical knowledge about the use of defibrillators. The training video included an explanation of all tasks that had to be performed. To prevent from providing operational knowledge on a particular model, the defibrillator was presented herein in form of a simplified schematic drawing (rectangular box) without any model-specific characteristics. Items for operating (e.g. buttons or scales) were also presented in generalized form and location.

Operators were instructed to execute the tasks quickly but with due diligence, and they were informed that they could get assistance with the tasks, if needed. Within the first sixty seconds, they had to actively ask for assistance. After 60 seconds, a first assistance was provided by the experimenter without being prompted. After 120 seconds, a second assistance was given. First and second assistances included indication of the respective operating item to use, suggesting submenu search, or pointing out the necessity of additional activation/confirmation. If after 180 seconds the task had not been solved, the experimenter showed the control element required to complete the task.

All devices were placed in separate cabins to achieve comparable and quiet test conditions. At the beginning of the experiments, the initially covered device under test was uncovered and the operator was allowed to visually inspect the device for one minute. Thereafter, the operator was asked to perform 15 tasks. Tasks represented typical operating procedures of a manual defibrillator (Table1). Four tasks were not applicable with the Defigard, as this device did not include pacemaker mode and an ECG printer.

Table 1 – Faithful translations of the task instructions.

1	Switch the device on
2	Connect the therapy cable
3	Connect the ECG cable
4	Set defibrillation energy to 150 Joule*
5	Deliver shock
6	Set defibrillation energy to 200 Joule*
7	Discharge defibrillation energy
8	Activate synchronized defibrillation
9	Activate pacemaker mode
10	Set pacemaker rate to 80 beats/min§
11	Set pacemaker current to 40 milliampere
12	Activate AED mode
13	Print an ECG strip
14	Show state of charge
15	Switch the device off

Numbers are given exemplarily.

* Defibrillation energy to set ranged from 100 to 360 Joule, depending on the defibrillator.

§ Pacemaker rate to set ranged from 80 to 110 beats/min and current to set ranged from 40 to 100 milliamperes, respectively.

Task instructions were given orally to the operator by the experimenter (author KF) standing to his side. All task instructions were read aloud word-by-word as given in Table 1, identically for each model (except of the tasks not applicable with the Defigard). The operator was allowed to start rendering the task at his/her own discretion.

Measurement of task completion time (TCT) began with vocalization of the task and ended once the task was completed at the experimenter's decision. Completion of a task was confirmed by the experimenter and thereafter the next task was given.

Each operator performed the tasks with each investigated defibrillator in randomized order. The order of tasks did not change between devices. In tasks including setting values, the values varied between devices to avoid execution of the respective task ahead of time.

Assuming that in the typical clinical situation cables are connected, a theoretical device related time to first shock was estimated as the sum of TCTs to switch the device on, set defibrillation energy and deliver shock.

Eye-tracking analysis

The eye-tracking device (Tobii Pro Glasses 2, Tobii AB, Stockholm, Sweden) was adjusted individually and calibrated according to the manufacturer's instructions.

Eye movements were continuously measured during the execution of the tasks. In offline analyses gaze points were manually mapped onto a snapshot image displaying a two-dimensional view of the respective defibrillator's interface using dedicated software (Tobii Pro Glasses Analyzer 1.34, Tobii AB).

For automated analysis of the eye-tracking data, areas of interest (AOI) were defined to indicate the target display item for solving a task. Time to First Fixation (TFF) was calculated from the start of vocalizing the task until the operator's first fixation within the respective AOI. If a task required multiple operating steps or the respective AOI lay within a submenu, multiple snapshots were used to map the successive operating steps and times were added up.

Heat maps were generated from fixations and superimposed onto the snapshots. Therefore a two dimensional convolution of the fixation points and a Gaussian curve with radius 1.2° was calculated. For the purposes of this paper, eye-tracking data are presented for selected tasks that showed significantly different TCT between the tested devices.

Usability evaluation

In order to determine the global acceptance of the devices we used a standardized usability questionnaire.[6,7] The System Usability Scale (SUS) includes a 1 to 5 points Likert scale, to state agreement or disagreement to 10 items which cover aspects of system usability, such as the need for support, training, and complexity (Table S1). After the operators had executed all tasks in a particular defibrillator, they were asked to record their immediate response to each item of the questionnaire, without thinking longer about it. The SUS score ranges from 0 to 100, with larger scores indicating better usability.[6] Scores of individual items are, however, not meaningful on their own.[6]

Operators' remarks

Having rendered all tasks at a device, operators were allowed to express personal free-text remarks. The operators' remarks were clustered and the three most frequent remarks are given for each device, respectively.

Statistics

Due to the lack of pre-existing data, a sample size calculation based on empirical values could not be performed. In accordance with suggestions for qualitative usability assessment from literature[8] and regarding our aim to analyse quantitative results we aimed at a minimum sample size of 30 naïve operators.

Data are presented as mean and standard deviation if not indicated otherwise. Tasks not applicable to the Defigard were excluded from statistical analyses for all devices and are presented in descriptive form, if relevant.

Statistical tests were applied on quantitative study measures while descriptive statistics are provided for quantitative study results.

To compare frequencies of assistances, Chi Square tests were applied on a contingency table with four columns (indicating the defibrillators) and eleven rows (indicating tasks to compare),[9] followed by Fisher's exact test for post comparison of assistances (no assistance required vs. assistance required) for a respective task. One-way ANOVA was calculated to compare TCT and TFF for each task between the defibrillators (GraphPad PRISM, ver. 6.02, GraphPad Software Inc., La Jolla, California, USA). Friedman's test was applied to compare SUS scores between defibrillators, followed by Dunn's multiple comparison test, if applicable. A p-value <0.05 was considered significant.

Results

Of 37 included operators data from 31 (Median age 22 years, range 20–30 years; 18 female, 13 male) were included in the final analyses. In 2 operators calibration of the eye tracking device failed, in 3 eye tracking data were incomplete due to discontinued wireless LAN connection of the eye-tracking device and in 1 subject the eye tracking glasses slipped several times resulting in unusable measurements.

The reaction times of the operators were between 0.32 and 0.48 seconds (median 0.39 seconds).

Quantitative results

Assistances

Out of a total of 1736 tasks, in 163, one or more assistances were given (9.4%). In 120 cases a single assistance was sufficient to successfully render the task. In 31 cases two, and in 12 cases three assistances were given, respectively. The frequencies of 1st assistances differed considerably between devices and tasks (Fig. 1; both $p < 0.001$). Assistances were given 63 times in the X-Series, 42 times in the Corpuls and 16 times in the Lifepak. A total of 42 assistances were given in the Defigard, disregarding tasks on the use of pacemaker and printer.

Task completion time

In specific tasks, TCT differed significantly between devices (Fig. 2). Cumulative TCT (excluding tasks on pacemaker and printer use) were shortest in the Lifepak (124 ± 31 s), followed by the Corpuls (220 ± 69 s), the Defigard (225 ± 81 s) and the X-Series (289 ± 85 s; $p < 0.001$).

Theoretical device related time to first shock was shortest in the X-Series (25 ± 11 s) followed by the Lifepak (33 ± 17 s), the Corpuls (43 ± 20 s), and the Defigard (59 ± 38; $p < 0.001$ s).

Eye-tracking analysis

TFF varied significantly between defibrillators for certain tasks (Table 2). Gaze distributions on devices with longer TFF were more scattered compared to devices with shorter TFF for the same tasks. (Fig. 3 and Supplemental file).

Qualitative results

Usability evaluation

Mean SUS scores differed significantly between defibrillators (Fig. 4). Subjects rated usability of the Lifepak better than all other devices.

Operators' three most frequent free remarks

For the Lifepak, 17 operators commented the button for discharging defibrillation energy as not obviously visible. 6 rated the sockets for the ECG and therapy cables clearly visible and 4 rated the button labelled as 'Stimulator' (German version) misleading with regard to the pacemaker function.

For the Defigard, 10 operators experienced dealing alternatingly with touchscreen and soft keys as confusing. 8 rated the sockets for the ECG and therapy cables difficult to identify and 5 rated the monitor's display too complex, requiring too much submenu search.

For the Corpuls, 9 operators rated the sockets for the ECG and therapy cables difficult to identify. 6 felt the turning knob for choosing functions and setting variables helpful and logical. 4 mentioned that they did not recognize the audio announcement 'start analysis' as a request to actively execute this function.

For the X-Series, 10 operators rated setting stimulation frequency and energy in the pacemaker module to be confusing. 9 rated the sockets for the ECG and therapy cables difficult to identify and 5 experienced the label "Analysis" on the button for initiating AED mode as misleading.

Specific usability deficiencies revealed with certain tasks

Setting up the devices

Connecting therapy cables was most time consuming in the Defigard, the Corpuls and the X-Series. TFFs and operators' subjective

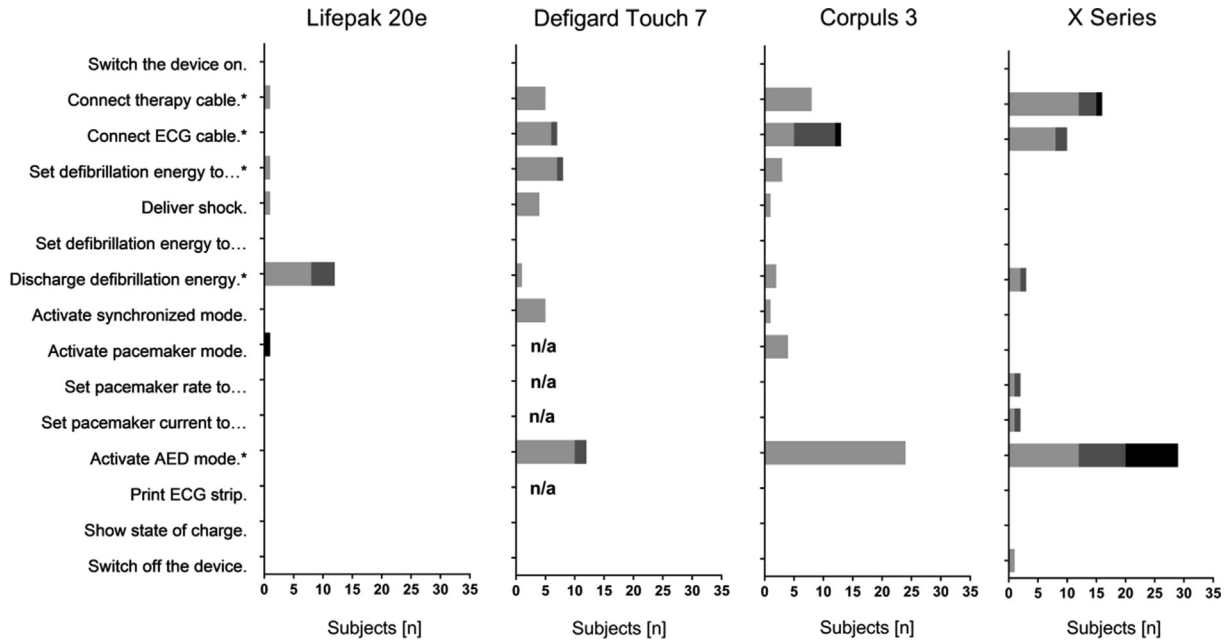


Fig. 1 – Frequencies of assistances claimed by the 31 operators given for the 4 defibrillators in the order in which tasks were tested (vertically top down). Light grey bars indicate 1st assistances; dark grey bars indicate two assistances; black bars indicate three assistances. n/a = tasks were not applicable in the device. Asterisks indicate device as significant factor for frequency of assistances ($p < 0.05$).

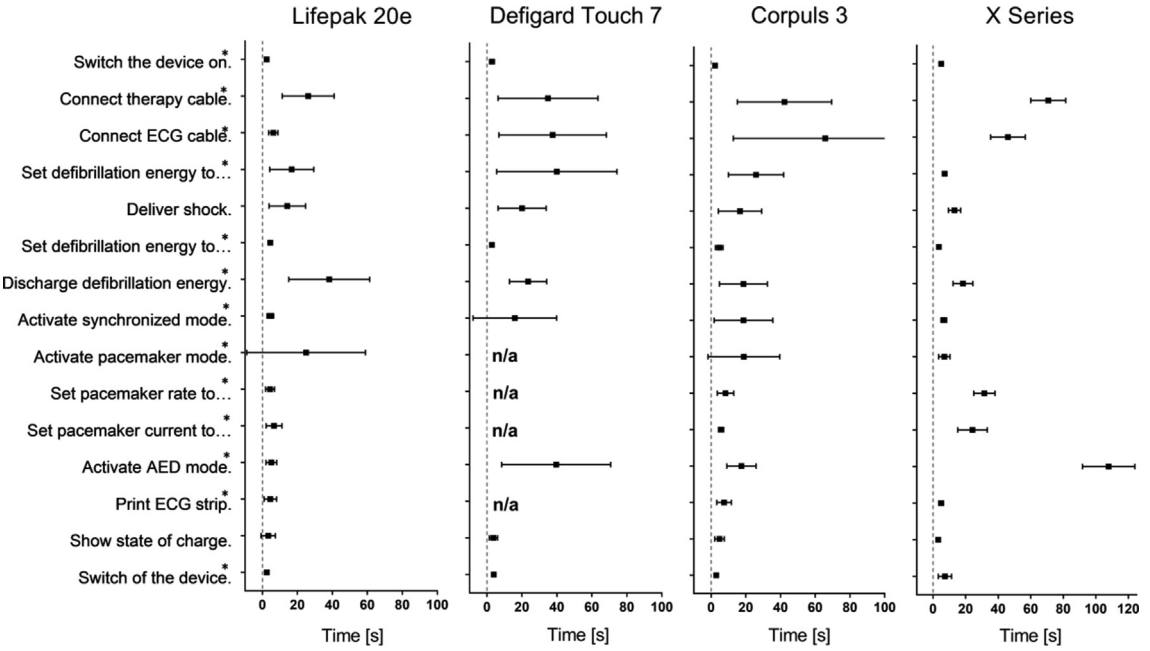


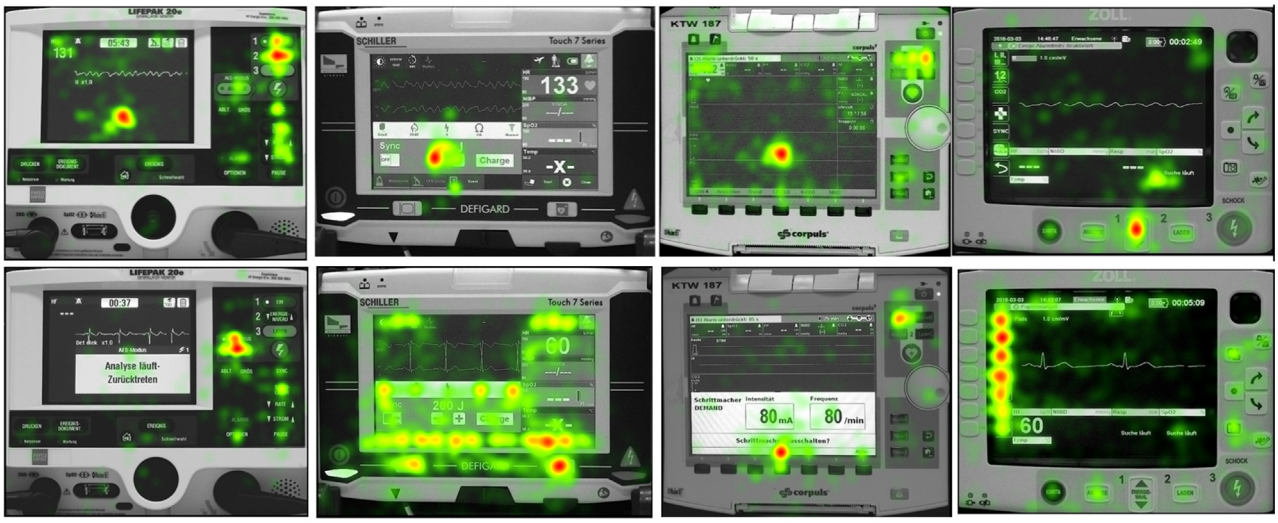
Fig. 2 – Task completion times (TCT) for the 4 defibrillators in the order in which tasks were tested (vertically top down). Bars indicate means ± standard deviation. n/a = these tasks were not applicable in the device. *$p < 0.05$ regarding at least one comparison of TCTs of the same task between different devices, calculated by one-way ANOVA. Asterisks indicate device as significant factor for TCT ($p < 0.05$).

ratings indicated difficulties with identifying the respective sockets. The operators' performance was not improved in the Defigard and the Corpuls during the subsequent task on connection of the ECG cables. By contrast, the Lifepak, cables were connected within fractions of the respective times with the Defigard and the Corpuls and the X-Series, and only one assistance was required.

Table 2 – Time to first fixation (TFF) based on eye-tracking metrics for tasks showing significant differences in task completion times between at least two comparisons of included devices.

	TFF [s]			
	Lifepak 20e	Defigard Touch 7	Corpuls 3	X-Series
Connect therapy cable	12.8 ± 9.4	16.0 ± 21.7	45.3 ± 34.2	43.4 ± 20.7
Connect ECG cable	1.8 ± 1.8	35.9 ± 33.1	57.0 ± 52.5	14.4 ± 16.5
Set defibrillation energy to…	3.7 ± 4.0	38.9 ± 34.4[#]	5.2 ± 6.3	2.4 ± 3.3
Deliver shock	5.5 ± 4.4	18.0 ± 16.0	7.9 ± 7.9	4.5 ± 4.3
Discharge defibrillation energy	20.3 ± 15.4	3.6 ± 3.8	12.9 ± 10.8	9.6 ± 8.6
Activate synchronized mode	3.3 ± 2.1	10.8 ± 18.7	5.8 ± 3.4	4.7 ± 4.9
Activate pacemaker mode	1.5 ± 1.1	n.a.	3.2 ± 1.6	3.5 ± 4.4
Activate AED mode	2.3 ± 2.4	11.3 ± 13.7	10.8 ± 7.2[#]	82.1 ± 32.7[#]

[#] Values include time required to open the submenu and until first fixation of the area of interest within the submenu, deliver shock includes charging.



Lifepak 20e | Defigard Touch 7 | Corpuls 3 | X-Series

Fig. 3 – Heat maps generated by eye-tracking based gaze analysis for selected tasks. Upper row: task "Set defibrillation energy to…". Lower row: task "Activate AED mode". Spatial distribution of fixations superimposed to snapshots. Fixations counts appear colored, red areas represent a high number of fixations.

Executing defibrillation

Setting the defibrillation energy required long TCT and frequent assistances in the Defigard. Shock delivery required long TCT, long TTF and frequent assistances with the Defigard. Discharging the defibrillation energy required most assistances and took longest with the Lifepak.

Pacemaker mode

Only small differences occurred in the performance with the equipped devices. With the Lifepak TFF was relatively short but TCT long. Setting pacemaker frequency and current took longest in the X-Series.

AED mode

Activating the AED mode caused long TCT and required several assistances in all devices but the Lifepak. In the X-Series activating the AED mode resulted in the highest number of requested assistances. Some operators even switched off and restarted the machine to activate the AED mode.

Discussion

The main result of our study is that there are considerable task specific differences in the usability of manual defibrillators. Assessment of the global performance indicated the highest user satisfaction with the Lifepak. Translating SUS values into adjective ratings,[10] its usability was '*excellent*', whereas the other devices ranged between '*poor*' and 'good'. Thereby, our objective measures reflected the experienced usability - Devices with higher evaluation scores were associated with lower TCT, TFF, device relate time to first shock and fewer assistances.

The reported specific usability deficiencies with regard to certain tasks are discussed in detail:

Setting up the devices

Manual defibrillators are usually assembled and ready for immediate use. Cable disconnection may, however, provide a source of fault. Noticeably, connecting therapy cables was most time consuming. TFFs and operators' subjective ratings indicated difficulties with iden-

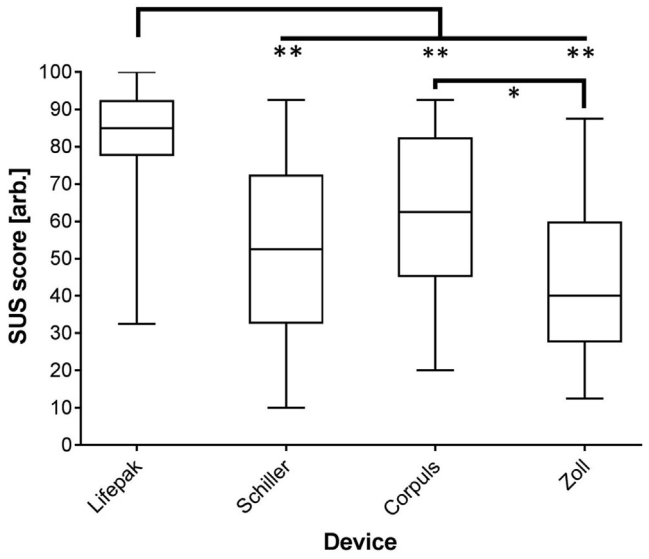


Fig. 4 – Scores calculated from the System Usability Scale (SUS; 6) evaluated by subjects for the 4 defibrillator devices. *$p < 0.05$, **$p < 0.01$, (Friedman test followed by Dunn's multiple comparison test).

tifying the respective sockets in the Defigard, the Corpuls and the X-Series. In the Defigard and the Corpuls, the sockets for therapy and ECG cables are located laterally and on the back of the device, and covered by bags. By contrast, the Lifepak provides easy to access sockets at its front side.

Executing defibrillation

Setting defibrillation energy in the Defigard, is a three-step process involving the touch screen's submenus. Concomitant long TFF and diffuse distribution of the operators' gaze revealed that operators struggled with identifying the primary step. However, with the later repetition, times to render this task clearly speed up in all devices and assistances were no longer required. This indicates a learning effect at this task. Shock delivery with the Defigard is executed via a hard key, whereas all preceding steps are rendered on the touchscreen. Associated long TTF indicated the operators' difficulties with switching between types of control-elements. Accordingly, operators rated such alternation as confusing in their free remarks.

With the Lifepak the energy could be immediately discharged by pressing the turning knob at the front side. In contrast to all other devices, however, no instruction on this function is displayed, resulting in frequent requests for assistance.

Pacemaker mode

This task demonstrated exemplarily how inconsistent labelling impedes operators' performance. In the German version of the Lifepak, the button to activate the pacemaker mode is labelled 'Stimulator'. Relatively short TFF demonstrate that this button attracted the operators' attention, however, the operators kept searching. Obviously, 'Stimulator' was not associated with the 'pacemaker' function (German: 'Schrittmacher') in contrast to the labels 'Schrittm.' on the X-Series or 'Pacer' on the Corpuls. For setting pacemaker frequency and current in the X-Series different buttons are to utilize than for setting defibrillation energy in the preceding tasks. Further, these show upwardly and downwardly curved arrows pointing to the right, which caused confusion in the operators.

AED mode

When the AED mode was requested, the pacemaker mode was still running on the Corpuls and the X-Series. Whereas pressing the AED button in the Lifepak immediately leads to the requested ECG analysis, the pacemaker mode has to be terminated first in the other devices. In the X-Series for example, when pressing the button to activate the AED mode the machine emits a beeping sound, without any further advice. This resulted in the highest number of requested assistances.

In the Corpuls elevated TCT may have resulted from the requirement of two operational steps to initiate ECG analysis. After activating the AED mode a voice prompt vocalizes 'start analysis'. Not expecting a second step, many operators waited for the analysis to begin automatically and eventually requested assistance. Respectively, confusion was expressed in the operators' remarks and previously identified as a potential source of hazard by another study.[11]

Notwithstanding moderate TFF, long TCT in the Defigard, diffuse gaze distribution indicated the operators' inability to identify the requested item at the display. The AED mode is activated by a fixed key at the bottom of the display and labelled with a pictogram instead of text, which was perceived as 'ambiguous'.

Few previous investigations aimed at comparing manual defibrillators by means of outcome related strengths of interface usability. In a multi-site study, Fidler and Johnson compared the usability of three different manual defibrillators involving experienced operators.[12] They investigated completion times and user satisfaction, thereby addressing more complex simulated resuscitation scenarios. This way they were able to identify strengths and shortcomings of defibrillators, provide insight into common user errors and into user preferences of practicing clinicians. Interestingly, even though the devices they tested lacked touchscreens, their experienced users expressed a preference for having touchscreen capabilities. By contrast, our operators were rather confused when functions were present in sub-menus or when the type of controlling was to switch during a task.

In our study, we followed a more detailed approach with the intention to identify task specific user interface issues. By putting into context TCT, gaze metrics, and operator ratings, we could identify shortcomings in user interface design in a highly specific fashion. By employing naïve operators we intensified the focus on user interface issues, as we would not expect that these would be able to work around a specific issue based on professional experience. Nearly all identified shortcomings were related to a specific device while on the other devices the operators were able to perform the same task quite well. In other words, there are design solutions for executing each task efficiently by users who are not specifically trained.

Our study may support user interface design but also training on the devices, including a focus on specific shortcomings. Awareness of these during training may compensate for issues, avoid user errors, and improve operator's safety and patient outcome.

Limitations of the study

The bench test situation by nature disregards distractions by the patient's condition, clinical environment or other tasks performed at the same time. However, this approach allows for highly reproducible

conditions and for testing in naïve operators. To further investigate potential effects of the detected shortcomings on patient safety, studies in full-scale simulation representing the complex working environment and high stress situations are required.

Naïve test persons are not in charge to operate a manual defibrillator. Generally, staff is only allowed to operate medical equipment after training according to manufacturer specifications and trainees do not use defibrillators unsupervised. However, inexperience with equipment and shortage of trained staff account for the largest share of critical incidents reported at an intensive care unit,[13] inappropriately followed manufacturer protocols caused up to 65% and 'user interface concerns' up to 12.5% of all human factor-related issues.[14] Moreover, defibrillation is not a task of planned clinical routine but rather always an exceptional situation. In such situation, intuitive use may be crucial. In this context, it has to be noted that the theoretical device related time to first shock depends clearly on a user's experience. Moreover this value does not include evaluation of the patient and time to place the electrodes on the patient. The latter, however can be assumed as independent from the device, due to comparable design of the electrodes.

The analysis of use errors is an important tool for identifying critical usability issues. Use errors did not occur in our study, potentially reasoned by the study design, requesting only smaller tasks and allowing for assistance requests.

Utilizing think-a-loud methods might have given additional insight into user actions and understanding. Our subjects were not instructed to utilize think-a-loud methods since this may have had an impact on TCTs and TFFs. Furthermore, we wanted to omit that subjects modulate their gaze, e.g. towards the experimenter, when speaking, e.g. towards the experimenter.

Offering assistances during the tasks may not reflect clinical practice. Some tasks demanded complex consecutive operating steps in certain devices. Beyond investigating the simple 'fail' or 'pass' of a task, assistances allowed for a more detailed evaluation of the specific operating steps.

Conclusions

With our study, we disclosed task-specific strengths and shortcomings in usability of modern manual defibrillators. We found distinct differences in usability between different defibrillators. Shortcomings in the user interfaces impaired the operators' performance by increasing task completion times and were related with the perception of poor usability. Eliminating the specific usability issues may improve the operator's performance and as a consequence patient outcome.

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CRediT authorship contribution statement

Stefan Schumann: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Axel Schmutz:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Kim Feger:** Writing – review & editing, Data curation, Conceptualization. **Johannes Spaeth:** Writing – original draft, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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