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Research-Based Design and Usability Guidelines for Electronic Charting Systems (ECS) in Yachting and Boating☆

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Abstract

Electronic Charting systems (ECS) in yachting and boating are the non-professional counterparts to ECDIS in commercial shipping. In the absence of legal regulations on design and use, a wide variety of products have developed. Their usability is not only safety critical but often even determines whether navigation functions like route building or track recording are used at all. With two empirical studies employing standard usability methods from human factors research, we assessed the usability of a variety of current ECSs on a sailing yacht. In study 1, nine usability experts conducted multimethod analyses while sailing in typical cruising areas on sea. Building on the results, a standardized user test was designed and carried out with 12 prototypical users plus 3 usability experts in inland waters (study 2). Finally, a set of 38 design and usability guidelines were formulated. The guidelines may not only help boat owners and charter companies in selecting a current market product but also aid manufacturers in designing their future products.

Contributions: David Jung (study 1) and Martin Müller (study 2) conducted the studies and formulated the guidelines. Gisela Müller-Plath designed and managed the research project ANeMoS (*A*nalysing Use and Impact of *N*ew *M*edia *o*n *S*ailboats) which the present work is part of, commanded the sailing yacht, and wrote the paper.

Keywords: Electronic Charting System (ECS), Usability, Boating, Yachting, Chartplotter, GPS.

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1. Introduction

Most modern sailing or motor yachts are equipped with an Electronic Charting System (ECS). Although an ECS on a pleasure craft usually does not qualify as an Electronic Chart Display and Information System (ECDIS) and thus, according to SOLAS V, the craft is required to have nautical paper charts on board, electronic navigation is increasingly on the rise.

For example, in a 2015 survey among 112 German sailing yachts on the Baltic coast (Müller-Plath, 2016, 2018), 83 % were equipped with at least one ECS: 73 % had a chartplotter as part of a multifunction display (MFD) on board, 44 % a laptop with a navigational chart application, and 30 % a tablet computer. However, 60 % of the ECS owners refrained from interacting with their device, i.e., they neither set up waypoints or routes nor did they record tracks, and 10 % did not even switch it on. On charter boats, these portions were even higher. Since the ability and willingness of navigating "old school", i.e. with paper chart and magnetic compass, is constantly decreasing, the high proportion of non- or passive ECS users constitutes an alarming safety issue.

According to the latest annual review of the European Maritime Safety Agency, casualties and incidents involving recreational sailboats with auxiliary motor and motor boats have more than doubled between 2012 and 2016 (EMSA, 2018, p. 30). For sailboats, most incidents involved collision and grounding/stranding (p. 106), and the vast majority of all pleasure craft incidents occurred in coastal waters (p. 110). All these types of incidents might possibly be reduced by proper use of a reliable and well-designed ECS.

In our own survey on German sailing yachts in Baltic coastal waters (Müller-Plath 2016, 2018, see above), 66 % of the interviewed shipmasters reported that their ECS caused a serious navigational problem or incident at least once. For example, boat masters reported that sometimes a nearby lateral buoy was charted on the starboard side of the ship but appeared on the port side. They attributed this to a chart error without considering that the GPS position of the ship might have been inaccurate by several meters. In another incident, an essential cardinal buoy indicating a shoal was displayed only in the highest zoom level of a vector map. The famous crash of the offshore racing yacht *Vestas Wind* on a remote reef in the 2014 Volvo Ocean Race demonstrates that even highly experienced navigators are overstrained with this feature of many vector charts (Oxenbould et al., 2015, p. 33). Such phenomena of "over-reliance in familiar signs" is a well-known cognitive failure in human-computer interaction (Rasmussen, 1986), and should thus be counteracted by the design of the system.

Asked about the general advantages and drawbacks of electronic navigation in yachting, the boatmasters praised the fast and precise GPS positioning, in particular in bad weather and at night, but criticized the diversity of devices, the abundance of functions, and the complicated operation of the human-computer interface, e.g. the structure of menus (Müller-Plath, 2016, 2018).

Whereas human factors research has been dealing a long time with the usability and human-centred design of web pages and many other domains of computer interaction, recently even in the realm of commercial shipping (e.g. Grech & Lützhöft, 2016), maritime ECSs on pleasure crafts were disregarded so far. The present work intends to fill this gap: Based on two usability studies on coastal and inland waters, a set of usability guidelines were formulated.

2. Theory

2.1. Electronic Charting Systems (ECSs) on Pleasure Crafts

A variety of terms and abbreviations have been established for systems and their components, which will be briefly outlined in the following as far as relevant for this paper (for details see e.g. the Boat Crew Handbook from the United States Coast Guard, 2017).

An **electronic charting system (ECS)** consists of a CPU-based unit with electronic charts, a Global Navigation Satellite System (GNSS) receiver, a display, and an input device. For pleasure crafts, there exist specially designed stationary systems, the Multifunction Displays (MFDs), which include some more components and are connected to the power system of the boat, as well as mobile devices like tablet computers with specific apps, which are battery dependent. Figure 1 shows three different ECS types.

The first component, the **electronic chart,** is of either vector or of raster type. Vector charts consist of data that represent real world objects. Since each object is separate, it allows the user to query the chart for more information than can be displayed. It also allows the ECS to test each object for grounding or height alarms. Based on zoom level and operator preference, the ECS hides or displays certain objects, for example a certain percentage of buoyage. Raster charts (RNC) are digital images of paper charts, referenced to geographic coordinates. A GPS position can be displayed upon the raster chart, but accuracy depends upon many factors, including the type of projection (e.g. Mercator) and the reference system (e.g. WGS-84) used in the original chart. Users cannot query raster chart data for more information or base alarms on them. On the other hand, the entire information of the paper chart is always visible, and the image becoming pixelated when zooming too high may warn the user against an over-reliance on GPS accuracy.

The second component, the **GNSS receiver,** is an electronic device that receives and digitally processes the signals from a satellite constellation and ground-based correction transmitters (DGPS) in order to provide position, time, speed, and course over ground. It supports signals from GPS, GLONASS, Galileo, and other regional systems, as well as DGPS sources, and is either built into the ECS or an interfaced external antenna.

Thirdly, the **display** is either a chartplotter, mounted stationary to the ship, or a mobile device like a tablet computer. It displays the GNSS signal as a boat icon on the electronic chart so that position, heading, and historic track of the boat can be visualized. A chartplotter is usually not only interfaced with the GNSS receiver but also with a variety of other signal transmitters, e.g. depth sounder, radar, AIS, anemometer (on sailing boats), sonar (on fishing boats), and motor unit (on power boats). Whereas on commercial ships, data are displayed on several screens located on the ship's bridge, on pleasure crafts they are assembled in one single device, the multifunction display (MFD), which is mounted outside, usually close to the helm. The display needs to be robust and visible in harsh weather as well as direct sunlight. The different data screens can be displayed either in alternation by command or in a split-screen mode.

Finally, the **input device** is either simply the touchscreen, or a set of rotary and push buttons, or a so-called "hybrid touch" providing both. With the latter, the navigator might, for example, shift the map, zoom in, and set waypoints via touch which is quick and easy but often inaccurate, or via rotary/push buttons which is more cumbersome but more precise, especially in rough sea or bad weather (see Figure 1, left panel).

Figure 1: Three ECS types for pleasure crafts as used in the first study.
Left: Multifunction Display (MFD) with hybrid touch as input device and vector chart (Raymarine eS75, Navionics chart).
Centre: MFD with touchscreen as input device and navigational vector chart (Garmin GPSmap 721xs).
Right: Seaworthy tablet with touchscreen as input device and navigational app (Neptune nep 7, app DK yacht navigator).

Now, what is the difference between ECS and ECDIS? In short, an ECS might qualify as an ECDIS if it fulfils the chart carriage requirements set up by the IMO in SOLAS regulations V/18 and V/19 (IMO, 2014). Therefore, it must be type-approved, it must use the official and up-to-date Electronic Navigation Charts (ENCs, i.e. no raster charts and no vector charts produced by a private company), it must be maintained so as to be compatible with the latest IHO standards, and it must have adequate, independent back-up arrangements in place (IMO, 2017a). Performance standards for ECDISs have long been defined by the IMO, the IHO, and the IALA, and are constantly being worked on. For technical, legal, or usage details, the interested reader is referred to the elaborate book by Weintritt (2009). Also, a standard mode (s-mode) of operation, activated by button press, has intensely been discussed (e.g., Conley, 2018) and is now being developed (IMO, 2017b). For pleasure craft ECSs, in contrast, legal regulations on design and use are lacking, and the market has produced a wide variety of products. Our usability guidelines provide a first step towards quality assurance and unification in this realm.

2.2. Usability and Usability Evaluation

Intuitively, everyone knows what usability is, at least when lacking. The International Organization for Standardization (ISO) in its standard 9241-11 defines usability in human-system interaction as “the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specific context of use” (ISO, 1998, 2018). Bevan et al. (2016) spell out how these concepts are understood and thereby extended in the new version of the standard: **Effectiveness** comprises “accuracy, completeness, and lack of negative consequences with which users achieved specified goals”. Both objective and perceived success are necessary. In an ECS on a sailing yacht, grounding as a consequence of not displaying a shoal and/or a cardinal buoy is an example of lacking effectiveness (negative consequence, and fallacy in spite of perceived success in setting up a safe route). **Efficiency** means how much effort (mostly measured in time) users require for achieving the goal. For example, an ECS is inefficient if in order to change a waypoint underway when the user, who on a sailing yacht is usually the helmsman, has to go through several levels of a complicated menu on the chartplotter. **Satisfaction** meant originally only what users think about a product’s ease of use, but has been redefined in the new version to refer to user experience (UX) in the modern understanding, thereby comprising “positive attitudes, emotion and/or comfort resulting from use”. All unintended effects from operations reduce satisfaction, like setting a waypoint on a touchscreen when trying to shift the map. Further, the new version clarifies that not only regular use but also learning how to use the system, accessing it from different levels of capability, and maintaining it should be effective, efficient, and satisfactory. Part 110 of standard ISO 9241 (ISO 9241-110, 2008) relates specifically to the usability of interactive systems. It formulates seven principles that are necessary for usable interactive software dialogues: suitability for the task, self-descriptiveness, controllability, conformity with user expectations, error tolerance, suitability for individualization, and suitability for learning.

Whereas with web-pages and other human-computer interfaces, a high degree of usability only adds to customer satisfaction and thereby sell numbers, in the domain of yachting and boating, where there is little legal regulation of how to perform the navigation task, the usability of an ECS is safety-critical, either directly by the system being ineffective, or indirectly, when efficiency and satisfaction determine whether the user uses the device and/or specific functions at all.

Since it is not trivial to detect even severe usability issues, a variety of evaluation methods have been developed in human factors research, comprising analytical procedures for usability experts as well as user tests and questionnaires for domain experts (for a detailed overview, see, e.g. standard ISO/TR 16982 (2002). Although usability evaluation has been a standard in human-system interaction since 1998 (ISO 9241-11, 1998; ISO/TR 16982, 2002) and ECS/ECDIS are being used for ship navigation at least since then, human factors research is still rare in this realm. For example, Grech and Horberry (2002, cited in Grech & Lützhöft 2016, p. 96) described a relationship between increasing technological levels and loss of situation awareness. With regard to ECDIS, Grech and Lützhöft (2016) found that the navigational aids with their multitude of modes often overstrain the average user. When usability is lacking, the crew may be trapped into so-called design induced errors. These and other works (e.g., Brooks & Lützhöft, 2015; Lee et al., 2015) laid the foundation for the “Guideline on Software Quality Assurance and Human Centred Design for e-Navigation” issued by the IMO in 2015. To date, very few usability studies have been published for commercial craft ECDISs (e.g. Wang & Zheng, 2014; Nakagawa et al., 2016) and none for pleasure craft ECSs.

Having been alert to serious usability problems of ECSs on pleasure crafts through our own survey (Müller-Plath, 2016, 2018), we decided to conduct the first. Since human-centered design (formative usability evaluation) is out of reach for human factors researchers at a university, we were left with assessing usability issues on current market products (summative evaluation). Our purpose was not to test and assess the devices competitively but to publish general principles on ECS design and usability in the format of guidelines, which will hopefully affect consumers' present purchase decisions and manufacturers' future product developments.

We conducted two studies on sailing yachts cruising coastal and inland waters. Participants ranged from usability experts with basic knowledge of sailing and navigation to prototype users, i.e. experienced yacht masters. A variety of usability evaluation methods according to standard ISO/TR 16982 (2002) and the IMO guideline (2015) were applied, as set out as follows.

3. Materials and Methods

Our usability evaluation on current market products corresponded to IMO guideline stage 4 "integration and testing" and activity 4 "evaluate the design against usability criteria" in the cycle of user-centered design (2015, p.5, p. 13). We applied methods of all types recommended in the IMO guideline for this stage: expert evaluation (observation of scenario/task performance), questionnaires, interviews, walk-throughs, task-based user testing, and observations. Table 1 gives an overview.

Table 1: Overview of methods, material, participants, and settings in the three usability evaluation studies

Methods	ECS / Chart	Participants	Setting: Craft; Place
	Study 1		
Think-aloud Questionnaires: ISONORM 9241, AttrakDiff 2 Walk-through: Keystroke Level-Model (KLM)	1. MFD Raymarine eS 75 / Vector chart Navionics Platinum 2. MFD Garmin GPSmap 721 xs / Vector chart Garmin BlueChart 3. Tablet neptune nep 7 / Raster chart App DK yacht navigator	Usability experts with decent knowledge in sailing and navigation (n = 9)	Sailing yacht „Mary Read" (32 ft); Baltic coastal waters between Germany, Poland, and Denmark
	Study 2		
Standardized task-based user test	1. MFD Raymarine eS 75 / Software Lighthouse 2, Vector hart Navionics Platinum 2. MFD Garmin GPSmap 721 xs / Vector chart Garmin BlueChart 3. Tablet neptune nep 7 / Raster chart App DK yacht navigator 4. Tablet Apple iPad Air2 / Raster chart App DK yacht navigator 5. Tablet Apple iPad Air2 / Vector chart App Navionics Boating HD 6. * Tablet Samsung Galaxy Tab3 / Raster chart App NV-charts 7. * MFD Standard Horizon CP 300i / Raster chart NV-chart	Prototypical users, i.e. yacht sailors (n = 12): Age: 32-82 years Nautical miles sailed: 1.000 – 100.000 Navigation experience with ECS/with paper only: n = 10 / n = 2	Different sailing yachts (see text); inland waters: lake of Wannsee and Havel, Berlin, Germany
Supplemental standardized task-based user test	8. MFD Garmin GPSmap 820 / Vector Chart Garmin BlueChart 9. MFD B & G Zeus / Vector chart NV-chart 10. MFD Furuno TZTL-12F / Vector chart MM3 MaxSea	Usability experts (authors of the study with good knowledge in sailing and navigation / technician with basic knowledge (n = 2 / n = 1)	Not on craft but on MFDs displayed in a shop; Hamburg, Germany

* Device on participant's own yacht.

3.1. Study 1: Expert Evaluation

3.1.1. Participants, ECSs, and Setting

Nine students of the master program Human Factors at Berlin Institute of Technology with a major in cognitive ergonomics and some boating experience participated as usability experts. Although familiar with usability standards in human-computer interaction and GPS navigation devices, none of them had any experience with maritime ECSs. In preparation for the present study, they received training in maritime paper chart navigation sufficient to pass the German recreational marine vessel license test. Afterwards, they went in threesomes on board the 32 feet sailing vessel "Mary Read", which was equipped with three ECSs (two MFDs and one tablet, see Figure 1 and Table 1). One was mounted close to the helm, the other next to the companionway, and the tablet was handheld. Usability was evaluated during three one-week sailing trips leading through popular yachting areas in the Baltic and providing different challenges to coastal navigation: numerous isles and islets in the first, open sea crossings through major shipping lanes and traffic separation schemes in the second, and narrow channels, fairways and extended shoals in the third.

3.1.2. Procedure, Task, and Methods

On each sailing trip, each participant was assigned one of the three ECSs for navigation and usability testing. (Thus, each ECS was independently tested by three experts in different area and weather conditions.) The first two days of the trip allowed the participants to become familiarized with the boat, maritime navigation, and the functionality of the individual ECS. On days 3-5, the three participants served as navigator on one leg each with his/her ECS in order to empirically test its usability. On days 6-7, each participant assessed his/her device analytically with a cognitive walk-through. Day 7 also served as a spare day. The lengths of the test legs varied between 18 and 48 nautical miles. For safety reasons, all legs were sailed in daylight. The weather varied between clear weather, rain, and haze, so that the sight was between about 10 and 0.5 nautical miles.

For the usability test, the navigator accomplished two tasks with his/her ECS, route planning and navigation. The tasks were carried out on the chart display of the device with according data windows and menus, but not including radar, AIS or sonar overlay.

Route planning comprised the following goals:

- Set several waypoints on the electronic chart,
- connect them to a route,
- consider all hazardous points and areas underway,
- store the route for subsequent use.

During the task, the navigator was asked to think aloud (Duncker, 1926; Nielsen, 1994), with another participant recording all verbalized and observed usability issues. Subsequently, the navigator completed two standardized questionnaires, the "ISONORM 9241-10", which assesses the seven dialogue principles that are requested for interactive software dialogues in ISO 9241 part 10 (see section 2.2 of this paper), and thereby focuses on the concepts effectiveness and efficiency in the usability definition (ISO, 1998, 2018), and the "AttrakDif" which focuses on the concept "satisfaction" in the usability definition, i.e. user experience (UX; ISO, 2018).

On the other day, the navigator used his/her ECS for navigation underway by advising the helmsman in sailing the route. This task comprised the following goals:

- Display the stored route on the chart,
- display additional navigational information like soundings, bearings, ETAs, etc.,
- zoom in and out where necessary,
- check XTE and read bearings,
- quit waypoints when reached,
- at each waypoint: announce new heading to the helmsman, landmark for steering when available (e.g. buoy), and possible dangers (e.g. shoals),
- start, stop and store track recording.

During this task, the navigator was again asked to think aloud and to complete the two questionnaires.

For the analytical usability evaluation, the Keystroke Level Model (KLM, Card et al., 1980, El Batran & Dunlop, 2014) was applied. Based on assumed time durations for typical operations like button press, swipe, or zoom, it predicts how long it will take an expert user to accomplish a task without errors with the ECS. The KLM thus constitutes an objective measure of efficiency. Each participant had to accomplish the following six typical tasks:

- Place a new waypoint at a rough position (a buoy),
- delete an existing waypoint,
- build a route between two existing waypoints,
- build a route with two new waypoints,
- during navigation, display the bearing between two subsequent waypoints,

- insert a new waypoint into an existing route,
- start track recording.

In each, the number and type of operations for optimal task solution were recorded.

3.1.3. Data Analysis and Results

Since it was not our aim to evaluate the three ECS devices competitively but to formulate general design principles, the positive and negative usability issues from the 18 (2 tasks x 3 devices x 3 participants) think-aloud protocols were rated in seriousness and classified into a 10 x 7 matrix (10 functional areas, 7 dialogue principles according to ISO 9241-110, 2008). Data from the subjective usability questionnaires as well as the objective efficiency estimates from the KLM method were accumulated across the three participants testing the same device and also entered into the matrix. Based on the matrix, a preliminary version of design and usability guidelines was formulated with 27 items, organized into eight sections and rated according to their relative importance in five levels. For details of study 1, the reader is referred to the master thesis by Jung (2016, in German).

3.2. Study 2

3.2.1. Participants, ECSs, and Setting

Twelve experienced yacht sailors volunteered for conducting a standardized user test. Regarding age, sex, level of experience in yachting and in electronic navigation, their distribution (Table 1) resembled as closely as possible that of our above cited survey sample (112 German sailing yachts on the Baltic coast, Müller-Plath, 2016, 2018). The user tests took place on an inland sailing area of approximately 12 km length and 2-4 km width with several arms, islets, harbours, and a buoyed fairway. In every user test, three persons were on board: The participating sailor, the investigator, and the yacht skipper. Ten sailors participated on our boat "Mary Read" and tested one of the ECSs no. 1–5 in Table 1, which took about 3 - 3.5 hours each. Two sailors participated with their own boat and conducted the user test twice, first with their own, familiar ECS (no. 6-7 in Table 1) and afterwards with one of our mobile ECSs (no. 4-5 in Table 1), which took about 4 – 4.5 hours.

As a supplement, three usability experts (two authors of this paper and the technician of the department) tested three other renowned ECSs in a shop on land.

3.2.2. Procedure, Task, and Methods

Each participant performed the standardized user test on the boat, filled out a checklist, and gave an interview. The user test was organized into three procedural sections: User settings, route building, and navigation. Whereas the first mainly reflects the initial interaction with a new device (e.g. when buying a new device or taking over a charter boat), the two others should be routine procedures on every sailing day. The tasks were:

Section 1: User settings (boat moored in harbour):

- Set the waypoint arrival distance which triggers the waypoint arrival alarm to 0.1 nm = 185 m.
- Set sound level and tone of waypoint arrival alarm according to your own preferences.
- Set the depth at which the shallow water contour and colour is displayed to 3 m.
- Configure the input devices so that the chart is operated only via buttons and the menu only via touch.
- Set up data boxes in corners and/or at top of chart screen that display the following information during navigation: position (lat/lon), COG, SOG, distance to next waypoint.

Section 2: Route building (boat moored in harbour):

- Build a route of three waypoints (WP) according to a sketch on a paper chart: Place WP 1 so that a direct course to WP 2 is possible, WP 2 by entering a specific position (lat/lon), and WP 3 close to a specific buoy.
- Store the route for later use.

Section 3: Navigation (boat moored in harbour)

- Activate a stored route consisting of five WPs.
- Report the following route data: total length, number of waypoints, starting time, estimated time of arrival (ETA), route display on the chart.
- Start navigation mode in order to follow the route.

(Boat casts off and sails are set if possible)

(En route between WP 1 and 2)

- Move WP 3 from one buoy to another.

(En route between WP 4 and 5)

- Extract information about a specific lighthouse from the chart.
- Find a specific lock on the chart and determine its rise.
- Determine distance and bearing from WP 5 to this lock.

The participant was asked to complete each task as fast as possible or to find that the function was not available. He/she was allowed three minutes of trial-and-error before being offered assistance. Solving time and levels of assistance were recorded, as well as the behaviour and oral comments. Immediately after each section of tasks, the participant completed the associated part of a checklist, reflecting the items of the preliminary usability guidelines, which in turn were derived from the result matrix of Study 1 (see above). Back in the harbour, the test ended with an interview on the tested system.

The supplemental user test in a shop on land was identical in all parts except that the navigation mode could not be started and GPS accuracy not be assessed. Moreover, the tasks lacked the realistic and demanding characteristic of operating the device while sailing the boat.

3.2.3. Data Analysis and Results

First, the usability of each device for each task was assessed quantitatively: The levels of assistance the participants needed, the solving time, and the rating of whether the participant would use it himself for a sailing trip served as measures of the usability components effectiveness, efficiency, and satisfaction (see Section 2.2). Moreover, usability was assessed qualitatively by the users' comments, interviews, and behavioural observations. For detailed results, the interested reader is referred to the master thesis by Müller (2016, in German).

Based on these results, we revised the preliminary usability guidelines. In sum, the participants of study 2, who were in contrast to the young usability experts of study 1, yacht sailors of typical age and experience, confirmed in large parts the preliminary version: 22 items were confirmed, 1 item cancelled, 5 items split up into two or three items, and 7 new items were added. We also reassessed the relative importance ratings of the items.

4. General Results

Based on two standardized studies on a sailing yacht, one performed by 9 usability experts on 3 different ECSs on sea, the other carried out by 12 prototypical users plus 3 experts on 10 different ECSs in inland waters and a shop on land, a set of 38 design and usability guidelines was formulated, consisting of nine sections.

The first section concerns the input device. Both usability studies showed that a touchscreen as the only input device lacks effectiveness: It's neither operated precisely in swell nor with gloves. We thus recommend a second input device (1.2). Moreover, a touchscreen should not respond to rain or spray (1.1) and allow effective zooming in landscape mode (1.3).

With regard to touchscreen operation (section 2), almost all analysed devices needed to be improved. The main problem was unintentional setting of waypoints when the user tried to trigger some other function on the chart. This could easily be resolved if a long tap for waypoint setting was implemented instead of a short one. In general, gestures (2.1) and symbols (2.2) should comply with conventions familiar from other touch applications. Moreover, hit areas must be large enough (2.3) and located so that the finger of the user does not cover necessary chart information (2.5). Since a frequent operation is moving a waypoint in a route, this should be possible directly on the chart and not only through a menu several levels away (2.4).

Section 3 concerns the chart. Although vector and raster charts each have their own advantages and disadvantages (see above section 2.1, p. 2), users preferred vector charts. However, the associated opportunities are currently not yet exhausted (3.3, 3.4, 8.1), and the dangers not effectively addressed: As illustrated in the introduction, the majority of users felt insecure with the vector chart arbitrarily leaving out navigational information at higher zoom levels (3.1) and with too many zoom levels (3.2). Some charts were difficult to perceptually conceive because of choice of colours (3.6).

Section 4 deals with navigational information (waypoints, routes, status information) displayed on and interacted with on the chart screen. Most users wished a summary of the route before starting it (4.1). All users considered it essential that an informative list of waypoints be optionally displayed next to the chart (4.2, 4.4) and linked with the chart (4.3), as well as some data boxes with status information (4.5). Currently, only one system provided an effective, efficient, and satisfactory solution. Another requirement was that chart objects (e.g. buoys, lights) be always displayed in priority to waypoint and route symbols (4.6), which none of the systems fulfilled.

The structure of the menu (section 5) needed improvement, particularly in one of the systems. Not only did it require long sequences of operations to carry out related functions (5.2), but also the buttons were located far from each other (5.1) and termed in unfamiliar words (5.3). All this hinders efficient interaction.

Section 6: In software design, recurring workflows must be identified and implemented rather than single functions in order to interact effectively and efficiently with the system. In our studies, the system with the shortest processing paths was rated most usable by the experts in study 1. However, it failed the user test in study 2 because of hidden and/or unfamiliar symbols to trigger them. Thus, recurring workflows (building a route, inserting a waypoint into a route, etc.) should require short processing paths (6.1) which are easily accessible (6.2). Most users wished an undo function (6.3).

Section 7 concerns transparency. According to standard ISO 9241-110 (2008), any system must inform the user about its current status. Most safety-critical is the accuracy of the GPS position (7.1) and loss of connectivity with a data source (7.4). Users also wished information about loading times (7.2) and processes being automatically carried out in the background (7.3).

Customization of functions is demanded in section 8. Since not only users differ (in digital experience, language, etc.) but also situations, any possibility to individually configure the system was appreciated by the users (8.1-8.5). Also, users wish an easy mode with a reduced functionality (8.6). Particularly for charter boats, an s-mode (see ch. 2 for ECDIS) might be a good idea.

The final section 9 regards user support. Mainly the users in study 2 wished an interactive tutorial (9.1) and a built-in and easily accessible help-function (9.2) when confronted with a new system or task.

The format of the guidelines was oriented at the well-known "Research-Based Web Design and Usability Guidelines" published by the U.S. government (Leavitt & Shneiderman, 2007). For each guideline, the relative importance was rated, and the empirical support from the present and additional research is given. The guidelines in full length with comments and illustrations are provided in the appendix.

5. Conclusions

Resulting from two usability studies with experts and prototypical users, a set of 38 design and usability guidelines were formulated in order to improve effective, efficient, and satisfactory use of ECSs in yachting and boating. The guidelines may not only help boat owners and charter companies in selecting a market product but also aid manufacturers in designing their future products.

The studies and the guidelines focused on standard maritime navigation tasks at daylight. Other popular functions and components of MFDs were not analysed (e.g. sailing or fishing functions, AIS, radar, see p. 3). The guidelines are limited to ECS application for day trip navigation in inland or coastal waters and do not cover offshore, professional, or regatta applications.

Although some of these limitations seem negligible in the light of the statistics reporting that the vast majority of casualties and incidents on pleasure crafts occur in coastal waters (see above, p. 2), future work should extend the guidelines to collision prevention functions like AIS and radar. The guidelines need to be revised at regular intervals as technological development moves on.

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Appendix: Research-based Design and Usability Guidelines for ECS in Yachting and Boating

Remark: The guidelines mainly refer to navigation tasks in daylight without AIS or radar overlay.

1. Input Device

1.1 The touchscreen must be insensitive to rain or spray.

Comment: Water drops must not set unwanted waypoints or trigger functions.

Relative Importance: 4 – very important

Research Support: 1 system, 1 expert in study 1 (Jung, 2016, p. 65)

1.2 There should be two input devices for using menus and applications, a touchscreen and a physical device.

Comment: Input via touch is quick and easy, whereas input via keys and/or buttons is more precise. In hard weather conditions or with gloves, the user may not be able to operate the device via touch. An example of a hybrid touch is shown in Figure A.1.

Relative Importance: 3 –important

Research Support: 1 system, 2 experts in study 1 (Jung, 2016, pp. 48, 61); 1 system, 3 experts in study 2 (Müller, 2016, p. 62).

Figure A.1. Positive example of guideline 1.2.: This hybrid touch device can be operated alternatively via the touchscreen, or via one rotary and seven push buttons on the right-hand side.

1.3 On the touchscreen, the sensitivity to the pinch gesture for zooming should match the vertical screen extent.

Comment: If the vertical extent of the screen is altered, e.g. by switching from portrait to landscape, or by using a split-screen mode, the sensitivity of pinch should be adjusted accordingly to allow effective zooming.

Relative Importance: 2 –moderately important

Research Support: 1 system, 1 expert in study 1 (Jung, 2016, p. 50); 1 system, 3 experts in study 2 (Müller, 2016, p. 64).

2. Operation

2.1 Gestures for touchscreen operation should comply with common navigation applications.

Comment: Touchscreen gestures should be as follows: short tap on the chart activates the indicated function, closes an open menu, and centres the chart; long tap on the chart sets a waypoint; swipe shifts the chart; pinch zooms in or out. In particular, if a short tap on the chart sets a waypoint, frequently unwanted waypoints are set.

Relative Importance: 5 – compulsory

Research Support: 3 systems, 6 experts in study 1 (Jung, 2016, pp. 46, 49-50, 53); 2 systems, 4 users / 3 experts in study 2 (Müller, 2016, p. 57, 63).

Additional evidence: ISO 9241-110 (2008; conformity with user expectations, error tolerance).

2.2 Symbols indicating touchscreen operations should comply with common conventions.

Comment: Symbols indicating operations need to be unequivocal, e.g. a button marked with a symbol that indicates operation via swipe on other common systems should also be operated via swipe on the ECS screen (Figure A.1 no. 1).

Relative Importance: 3 – important

Research Support: 2 systems, 3 experts in study 1 (Jung, 2016, pp. 51, 53); 4 systems, 6 users / 3 experts in study 2 (Müller (2016, p. 56, 60, 62-63).

Additional evidence: ISO 9241-110 (2008; conformity with user expectations); Nielsen (1995, 2nd heuristic).

2.3 Touchscreen hit areas should be large enough.

Comment: Hit areas, i.e. areas of the screen the user touches to activate something, require adequate space for the user to accurately (and confidently) press (Figure A.2, no. 2). The average fingertip is between one to two centimetres wide, which roughly correlates to somewhere between 44px and 57px on a standard touchscreen.

Relative Importance: 3 – important

Research Support: 2 systems, 1 user / 3 experts in study 2 (Müller, 2016, p. 57, 63).

Additional Evidence: Nielsen & Budiu (2013).

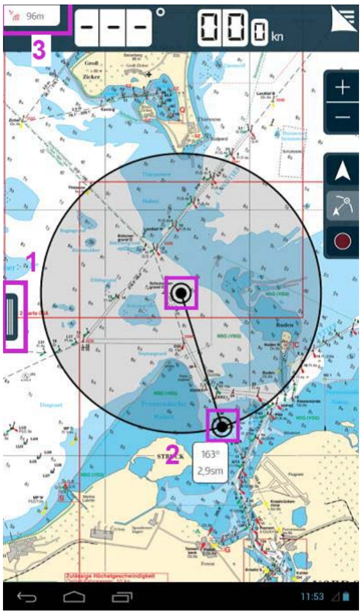

Figure A.2. No. 1: Violation of operation guideline 2.2. The symbol at the left hand side of the screen conventionally implies to be operated by swipe but actually requires a short tap in order to open the waypoint list, thereby violating guideline 2.5. **No. 2: Violation of operation guidelines 2.3, 2.5.** The magenta coloured squares denote the hit areas for operating the divider tool which measures distance and bearing between two points. However, they are so small that they are hard to activate (guideline 2.3), and when being moved, the user's fingertip covers the chart object of interest (guideline 2.5). **No. 3: Example of transparency guideline 7.1.** In the upper left corner of the screen, the accuracy of the GPS position is always visible as digits (here: 96 m, which is too inaccurate for coastal navigation). See Figure A.5 for a better solution.

2.4 Waypoints (WPs) need to be moved directly on the chart.

Comment: There should be three ways for moving a waypoint on the chart: (a) selecting the WP with a long tap and moving it via swipe, (b) selecting the WP with a long tap and selecting its new position with another long tap, (c) selecting the WP with a long tap and entering its new GPS coordinates.

Relative Importance: 5 – compulsory

Research Support: 3 systems, 5 experts in study 1 (Jung, 2016, pp. 46, 50, 53); 1 system, 3 experts in study 2 (Müller (2016, p. 63).

2.5 The user's finger should not cover chart information.

Comment: If a chart element (e.g. a waypoint, the divider tool) is to be positioned precisely on some point on the chart via swipe, then the area for activating the element has to be large. Otherwise the finger of the user covers just that detail of the map (e.g. buoy) that is necessary for precise positioning (see Figure A.2, no. 2).

Relative Importance: 5 – compulsory

Research Support: 1 system, 2 experts in study 1 (Jung, 2016, pp. 52, 64); 1 system, 1 expert in study 1 (Müller, 2016, p. 63).

3. Chart features

3.1 In vector charts, navigation-relevant information must be visible all the time.

Comment: Navigation-relevant information like shallows, rocks or buoys must be visible at every zoom level. The symbols need to be chosen so that the chart stays clear at all zoom levels. If the hiding of some information cannot be avoided for reasons of clarity, the user should be informed that information is hidden, e.g. with a text "not all information visible" or an unequivocal symbol.

Relative Importance: 5 – compulsory

Research Support: 2 systems, 5 experts in study 1 (Jung, 2016, pp. 47, 50, 59); 4 systems, 1 user / 3 experts in study 2 (Müller, 2016, p. 59, 62-63).

Additional evidence: ISO 9241-110 (2008; suitability for the task); Lavie & Oron-Gillad (2013).

3.2 The number of zoom levels should be limited.

Comment: With too many zoom levels, users may lose the overview of the navigated area. In particular, a zoom level that exceeds GPS accuracy may induce overreliance on digital technology.

Relative Importance: 2 – moderately important

Research Support: 1 system, 2 experts in study 1 (Jung, 2016, pp. 47, 60).

3.3 The vector chart should provide additional information on chart objects.

Comment: Additional information like opening times, signals, VHF channels, moorings or buoy names/numbers should be available for chart objects like bridges, locks, harbours, lighthouses, buoys etc.

Relative Importance: 3 – important

Research Support: 3 systems, 3 experts in study 1 (Jung, 2016, pp. 48, 52, 54), 8 systems, 12 users / 3 experts in study 2 (Müller, 2016, p. 58-60, 62).

Additional evidence: ISO 9241-110 (2008; suitability for the task, suitability for individualization).

3.4 All chart and menu entries should be displayed in the pre-set system language.

Comment: The system must not mix languages.

Relative Importance: 3 – important

Research Support: 2 systems, 2 experts in study 1 (Jung, 2016, pp. 51, 60); 3 systems, 1 user / 3 experts in study 2 (Müller (2016, p. 61-63).

Additional evidence: ISO 9241-110 (2008; suitability for individualization).

3.5 Categories of chart objects should be contrasted from the background and each other by colour.

Comment: This is necessary in order to find information at a single glance (Figure A.3).

Research Support: 2 systems, 5 experts in study 1 (Jung, 2016, pp. 47, 50, 59); 1 system, 1 user in study 2 (Müller, 2016, p. 61).

Additional evidence: ISO 9241-110 (2008; suitability for the task); Treisman (1985).

Figure A.3: Violation of chart guideline 3.5. Too much information is displayed in magenta and therefore difficult to perceptually segregate in one glance.

4. Navigation (routes, waypoints, and data)

4.1 Before starting a route, a brief summary should be displayed.

Comment: The total distance, number of waypoints, duration or starting time and estimated time of arrival (ETA), and graphical presentation on the chart should be given (see Figure A.4, No. 1).

Relative Importance: 4 – very important

Research Support: 2 systems, 2 experts in study 1 (Jung, 2016, p. 51, 55); 2 systems, 1 user / 3 experts in study 2 (Müller, 2016, p. 59, 62).

4.2 The list of waypoints should be optionally displayable next to the chart.

Comment: The user should be able to view the graphical route display and the list of waypoints simultaneously (Figure A.4, no. 1).

Relative Importance: 4 – very important

Research Support: 1 system, 1 expert in study 1 (Jung, 2016, p. 55).

Additional evidence: ISO 9241-110 (2008; suitability for the task).

Figure A.4. No. 1: Positive example of navigation guidelines 4.1–4.4: The list of waypoints next to the route contains the necessary information for every waypoint, is linked with the route, and can be optionally shown and hidden. **No. 2: Violation of navigation guideline 4.6.** The waypoint symbol hides the light sectors of the beacon almost completely.

4.3 The list of waypoints should be linked with the route.

Comment: When a user selects a waypoint from the list, the chart should display it simultaneously, and vice versa in order to comfortably interact with it.

Relative Importance: 4 – very important

Research Support: 1 system, 1 expert in study 1 (Jung, 2016, p. 55).

Additional evidence: ISO 9241-110 (2008; suitability for the task).

4.4 For every waypoint, the list should show either the change of course or the new course, making it unequivocally clear which one is shown (Figure, A.4, No. 1).

Comment: The helmsman needs this information in order to anticipate steering actions.

Relative Importance: 4 – very important

Research Support: 1 system, 2 experts in study 1 (Jung, 2016, p. 61).

Additional evidence: ISO 9241-110 (2008; suitability for the task).

4.5 Navigation information in data boxes and fields should always be visible, easy to understand and configurable by the user.

Comment: On most devices, data boxes and fields are provided, that show status information of the boat and the course, e.g. lat/lon position, speed over ground (SOG), course over ground (COG), depth, time, distance to go etc.

Relative Importance: 3 – important

Research Support: 2 systems, 3 experts in study 1 (Jung, 2016, pp. 58-60, 62-63); 5 systems, 4 users / 3 experts in study 2 (Müller, 2016, p. 58, 61, 62-63).

Additional evidence: ISO 9241-110 (2008; suitability for the task, self-descriptiveness, suitability for individualization).

4.6 Display of chart objects should be prioritized.

Comment: Navigational chart objects like buoys, depth information etc. must not be hidden by graphical elements set by the user, e.g. waypoint symbols or route names (Figure A.3, no. 2); these are better displayed in empty spaces on the display or semi-transparently.

Relative Importance: 5 – compulsory

Research Support: 1 system, 1 expert in study 1 (Jung, 2016, p. 53); 1 system, 1 user in study 2 (Müller, 2016, p. 60).

Additional evidence: ISO 9241-110 (2008; suitability for the task).

5. Menu structure

5.1 Buttons for related functions should be located close to each other.

Comment: Buttons for functions that are commonly activated in succession (e.g. setting waypoints and connecting them to a route) are operated more easily when located adjacently. Likewise, buttons for opposing functions (e.g. deleting a waypoint and inserting a waypoint) should be located far from each other. See Figure A.5 and section 6. "Workflows")

Relative Importance: 4 – very important

Research Support: 2 systems, 6 experts in study 1 (Jung, 2016, pp. 49-50, 53); 1 system, 1 user in study 2 (Müller (2016, p. 59).

Additional evidence: Chang et al. (2002).

Figure A.5: Violation of menu guidelines 5.1 and 5.2. In order to build a route, the user first sets waypoints via "Charts" (1) and then connects them to a route via "Nav Info" (2). Not only are the two buttons located far from each other (guideline 5.1) but also many taps are necessary to navigate from one related screen to the other (guideline 5.2), implying high memory load.

5.2 The structure of the menu should be comprehensible.

Comment: Categories and sub-categories of the menu should be organized so that they are easily found, and the user's memory load is minimized (for a negative example, see Figure A.4).

Relative Importance: 5 – compulsory

Research Support: 3 systems, 8 experts in study 1 (Jung, 2016, pp. 46, 49, 53, 58-59, 62, 66); 6 systems, 8 users / 3 experts in study 2 (Müller, 2016, p. 58-62).

Additional evidence: ISO 9241-110 (2008; suitability for learning); Nielsen (1995); Shneiderman & Plaisant (2009).

5.3 The system should speak the user's language.

Comment: For status displays, menu entries, and chart labels, familiar terms and correct nautical language should be used in order to avoid uncertainty (e.g. "speed over ground (SOG)" instead of "velocity" in the status display, or "save route" instead of "finish build" in route building; also, abbreviations like RTE or RNG are not familiar to everybody).

Relative Importance: 5 – compulsory

Research Support: 3 systems, 5 experts in study 1 (Jung, 2016, pp. 46, 59, 61, 62); 7 systems, 5 users / 3 experts in study 2 (Müller (2016, p. 58-63).

Additional evidence: ISO 9241-110 (2008; self-descriptiveness, conformity with user expectations); Nielsen (1995).

5.4 The menu should not be cluttered by needless functions or options.

Comment: Functions or options relating to data sources not connected (e.g. radar, AIS) are unnecessary and should be left out or at least greyed out in order to relieve the user's working memory.

Relative Importance: 2 – moderately important

Research Support: 1 system, 1 expert in study 1 (Jung (2016, p. 59).

Additional evidence: Shneiderman & Plaisant (2009).

6. Workflows

6.1 The software needs to be designed so that frequent workflows are carried out efficiently.

Comment: Instead of functions, frequently used workflows should be designed. They should require as few steps as possible and end with the presentation of the changed or requested information. Frequently used workflows are

- Setting a waypoint (WP)
- Deleting a WP
- Building a route
- Inserting a WP into a route
- Starting track recording
- Displaying actual position
- Displaying actual course
- Displaying course between two subsequent WPs
- Displaying change of course at a WP
- Skipping a WP
- Displaying bearing and distance to any point on the chart

Relative Importance: 5 – compulsory

Research Support: 3 systems, 9 experts in study 1 (Jung, 2016, pp. 40-43, 49, 72-73; 3 systems, 5 users / 3 experts in study 2 (Müller (2016, p. 57-58, 60, 62, 64).

Additional evidence: ISO 9241-110 (2008, suitability for the task).

6.2 The first interaction of each workflow should be easily accessible.

Comment: The first interaction of the sequence of steps of each workflow needs to be placed visibly and denoted meaningfully in order to optimize accessibility.

Relative Importance: 4 – very important

Research Support: 3 systems, 8 experts in study 1 (Jung, 2016, pp. 46, 49, 53, 58, 62, 66).

Additional evidence: ISO 9241-110 (2008, conformity with user expectations, self-descriptiveness, suitability for learning).

6.3 The system should offer an undo-function.

Comment: The user should have the opportunity to easily undo the last interaction, e.g. an erroneous waypoint deletion.

Relative Importance: 1 – cosmetic

Research Support: 2 systems, 2 experts in study 1 (Jung, 2016, pp. 47, 54).

Additional evidence: ISO 9241-110 (2008, error tolerance).

7. Transparency

7.1 The user should always be kept informed about the accuracy of the current GPS position of the boat.

Comment: In order to prevent over-reliance on technology, the user should not only see the vessel's location on the chart but also its accuracy according to the GPS status. This could be implemented as digits (Figure A.2 (3)) or preferably as a circle around the boat icon, as in some applications for navigation on land: The smaller the circle, the more certain the app is about your location. (Figure A.6).

Relative Importance: 5 – compulsory

Research Support: 2 systems, 2 experts in study 1 (Jung, 2016, pp. 58, 62); 1 system, 2 users in study 2 (Müller, 2016, p. 57).

Additional evidence: Nielsen (1995).

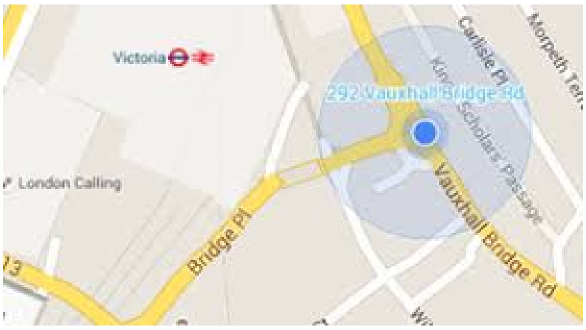

Figure A.6: Menu guideline 7.1., idea from an application for land navigation. The user is informed about GPS position accuracy by the radius of the blue circle around the blue dot, indicating that the current position is somewhere inside the circle.

7.2 The user should be informed about system loading times.

Comment: When starting the system and in case of a delay, the user should be informed that the system is still working, e.g. by a progress bar.

Relative Importance: 2 – moderately important

Research Support: 1 system, 1 expert in study 1 (Jung, 2016, p. 53).

Additional evidence: Nielsen (1995), Shneiderman & Plaisant (2009).

7.3 The user should be informed about procedures the system is carrying out automatically.

Comment: When the system carries out a procedure without interacting with the user, e.g. automatically saving a route built by the user, the user is uncertain about this unless informed.

Relative Importance: 3 –important

Research Support: 2 systems, 5 experts in study 1 (Jung, 2016, pp. 47, 51); 4 systems, 7 users in study 2 (Müller, 2016, p. 57-60).

7.4 The user must be informed about any changes in the status of the system.

Comment: If the system loses connectivity with a data source, e.g. the GPS, or a data source does not transmit properly, e.g. the echo sounder, it is safety-critical for the user to know that the displayed data is no longer up-to-date.

Relative Importance: 5 –compulsory

Research Support: 1 system, 1 user in study 1 (Müller, 2016, p. 57).

8. Customization

8.1 The depth at which the shallow water contour and colour is displayed should be configurable according to the draught of the individual vessel.

Relative Importance: 3 – important

Research Support: 1 systems, 1 expert in study 1 (Jung, 2016, pp. 61).

Additional evidence: ISO 9241-110 (2008; suitability for individualization).

8.2 Alarm: Alarm sounds should be configurable according to the user's preferences.

Comment: Some users perceive the waypoint arrival alarm as unpleasant or wish to assign different alarm sounds to different functions.

Relative Importance: 3 – important

Research Support: 2 systems, 2 experts in study 1 (Jung, 2016, pp. 60, 62-63).

Additional evidence: ISO 9241-110 (2008; suitability for individualization).

8.3 Waypoint arrival distance: The distance that triggers the waypoint arrival alarm should be configurable individually and separately for different waypoints.

Comment: The default waypoint arrival radius is too large for narrow fairways, and too small for open waters, in particular when beating to windward.

Relative Importance: 3 – important

Research Support: 2 systems, 2 experts in study 1 (Jung, 2016, pp. 63, 67); 1 system, 1 expert in study 2 (Müller, 2016, p. 63).

Additional evidence: ISO 9241-110 (2008; suitability for individualization).

8.4 Setting waypoints: Besides setting waypoints directly on the chart, the system must also allow them to be entered as lat/lon coordinates.

Comment: Precise waypoints can only be set by lat/lon coordinates. Moreover, only this input method allows transferring waypoints from paper charts or nautical books.

Relative Importance: 5 – important

Research Support: 3 systems, 5 users in study 2 (Müller, 2016, p. 57, 60-61).

Additional evidence: ISO 9241-110 (2008; suitability for the task).

8.5 Snapping (i.e. selecting a touchscreen object by tapping in its proximity): A snapping function for object selection should be available as an option that can be activated or de-activated.

Comment: Snapping is perceived as useful by some users but as inconvenient by others.

Relative Importance: 3 – important

Research Support: 2 systems, 2 experts in study 1 (Jung, 2016, pp. 47, 50).

Additional evidence: ISO 9241-110 (2008; suitability for individualization).

8.6 Easy mode: In a system with a wide range of functions, the user should be able to choose between an expert and easy mode for operating the device.

Comment: Some users favour an easy mode with a reduced scope of functions, whereas others prefer the full functional range. Even superior, particularly for charter boats, might be a standardized mode (s-mode) as discussed for commercial ship ECDIS.

Relative Importance: 2 – moderately important

Research Support: 3 systems, 1 user / 3 experts in study 2 (Müller (2016, p. 57, 63).

Additional evidence: ISO 9241-110 (2008; suitability for individualization, suitability for learning).

9. User support

9.1 There should be an interactive tutorial for instructing first-time users.

Comment: With an interactive tutorial, novice users are introduced to the structure of the menu and how to operate the device, including building an example route. The user should be able to repeat or skip the tutorial.

Relative Importance: 3 –important

Research Support: 1 system, 1 expert in study 1 (Jung, 2016, p. 62); 1 system, 1 user in study 2 (Müller, 2016, p. 59).

Additional evidence: ISO 9241-110 (2008; suitability for learning).

9.2 An easily accessible help function should be implemented in the system.

Comment: Some users prefer an integrated help function.

Relative Importance: 2 –moderately important

Research Support: 2 systems, 2 experts in study 1 (Jung, 2016, pp. 55, 62); 2 systems, 3 users / 3 experts in study 2 (Müller, 2016, p. 60, 62).

Additional evidence: ISO 9241-110 (2008; suitability for learning).