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# How Does Digital Navigation on Sailboats Affect Spatial Abilities at Sea?

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ABSTRACT: Although SOLAS still requires nautical paper charts on pleasure crafts, more and more sailors prefer navigating digitally. What are the impacts on their spatial abilities? We conducted a field experiment at the Baltic coast and two simulator experiments with altogether 40 sailors. Participants plotted and/or piloted routes either in the classic manner on paper charts or digitally on an ECS. We assessed the situation awareness, the cognitive map, and (for the simulator only) the wayfinding with and without the navigation media. We found that digital navigation significantly impaired the cognitive map. Its impact on situation awareness, however, depended on previous navigation habits: Only sailors who used their paper charts regularly and actively benefitted from the ECS. We concluded that ECS navigation with its high level of automation lastingly alters spatial perception at sea and impairs orienting. With the vulnerable electricity supply on sailboats, this is a safety issue for shipping.

## 1 INTRODUCTION

Most modern sailing or motor yachts are equipped with an Electronic Charting System (ECS), the non-professional counterpart to the Electronic Chart Display and Information System (ECDIS) in commercial shipping. Since an ECS on a pleasure craft generally does not meet the chart carriage requirements set up by the IMO in SOLAS regulations V/18 and V/19 (IMO, 2014, 2017), the craft is required to have nautical paper charts on board. Nevertheless, electronic navigation continues to increase in this domain. For example, in a survey among 112 German sailing yachts on the Baltic coast (Müller-Plath, 2018), 83 % were equipped with at least one ECS: 73 % had a chartplotter as part of a multifunction display (MFD) on board, and 30 % a tablet computer with a navigational chart application. Users appreciate the continuous GNSS positioning, the integration of data from other signal transmitters like a depth sounder, radar, AIS, anemometer (on sailing boats), sonar (on fishing boats), and motor unit (on power boats), and the time-saving route-building functions. But how does using the small and variable digital chart (display size of usually 7 - 12 inches) with its high level of automation affect the spatial abilities of the sailor? This is most interesting in coastal waters where most pleasure craft traffic takes place and the danger of grounding and stranding is highest.

The most relevant spatial abilities at sea are orienting and wayfinding. Orienting is the ability to relate one's own position within the environment. It includes re-orienting, the ability to re-establish one's bearings after having lost them. Wayfinding refers to moving towards a destination. Both rely on spatial knowledge, the so-called cognitive map (Tolman, 1948). According to current psychological theory (e.g. Waller & Nadel, 2013), it comprises three aspects: Landmark knowledge, route knowledge, and geometric knowledge (overview knowledge). In the present research we investigated how navigating with an ECS affects cognitive maps, orienting, wayfinding, and the interplay of these three in a sailor.

Our hypotheses build on the following considerations: We start with the cognitive map. The ability to construct them is regarded innate to animals and humans, but a specific cognitive map is acquired by active exploration of an environment. Humans also use secondary means like pictures, words, or symbols on different media. Information from multiple sources needs to be weaved together (Nadel, 2013, p. 158). How is cognitive map acquisition affected by using digital GNSS devices? In road traffic, pedestrians using a GPS device acquired less accurate spatial representations (Ishikawa et al., 2008). For car drivers, digital GNSS navigation facilitated wayfinding but hindered the acquisition of a cognitive map (Burnett & Lee, 2005; Münzer et al., 2012). Since not only the tasks (navigating a two-dimensional plane instead of one-dimensional roads) but also the devices for maritime navigation differ from those in road traffic (e.g. no speech output), research results are not directly transferable. In sailing, we thus hypothesized that classic navigation supports the acquisition of a cognitive map: In plotting routes with course triangles and dividers on large paper charts, fixing positions via dead reckoning at open sea or cross bearing in coastal waters, and wayfinding by constantly looking out in order to match chart and environment while underway, an accurate and detailed cognitive map builds up. With the GNSS and the high level of automation in ECSs, however, this is not the case.

Secondly, spatial orienting in sailing is closely related to the concept of situation awareness. The concept originally stems from aviation and denotes the correct perception of elements of a situation, the comprehension of their meaning, and the projection of future states and events (Endsley, 1995a) in order to safely guide actions in a complex and rapidly changing environment, for example when the sailboat gets into a current in a narrow fairway. In addition to spatial orienting, attention plays a crucial role because information processing is selective and depends on action plans. Since situation awareness does not only refer to spatial elements of a situation but also for example to the wind, the depth of the water, or the speed of the boat, we will use the term "route awareness" in the remainder of the paper when we refer to the route-related spatial elements of the situation. It is synonymous to spatial orienting when sailing pre-planned routes, because you need to know from an egocentric perspective where you are coming from, where you are heading, and where you next have to change course. Obviously, digital GNSS-supported navigation has two opposing influences on situation awareness in general and route awareness in particular: improved availability of situational data but reduced attention to and cognitive processing of them. Whether this will result in improved or diminished situational awareness is open to investigation. The literature is unequivocal and does not include small recreational vessels: Asyali (2012) proposed that ECDIS navigation in commercial shipping improves the situation awareness of the navigator. However, the results were based on subjective assessments of ship officers in questionnaires, not on objective behavioural studies. Grech & Horberry (2002) on the other hand found a generally positive relationship between increasing technological levels and loss of situation awareness in shipping. For the present study, we could thus not deduce any specific hypothesis.

Thirdly, wayfinding is directly supported by ECSs. It should thus benefit from digital navigation as long as the medium is available but should break down when the sailor has to rely on his own cognitive map and orienting (route awareness).

Finally, the three spatial abilities (orientation/route awareness, wayfinding, and cognitive map) develop in close interplay with each other and with the medium used for navigation. ECS navigation with its small and variable digital chart and its high level of automation might weaken this association and thereby even lastingly alter perceptual processing at sea.

We investigated the hypotheses with a field experiment in coastal waters at the Baltic Sea and two simulator experiments in our lab (see Figures 1-3 for an overview). In all three studies, we experimentally varied the navigation media (classic vs. digital), and included previous habits of using navigation media as additional predictors. In the field experiment, we assessed as outcomes the situational awareness underway (including route awareness) and the cognitive map after sailing. The wayfinding could not be examined because of safety reasons. In the simulator experiments, the navigation media (classic vs. digital) were also varied but taken away at different points: In the first experiment they were used for route plotting and for piloting a segment of the route but then "lost", in the second for course plotting only. As outcomes, we assessed the wayfinding with and without the navigation media, the route awareness underway, and the cognitive map after sailing. In experiment 2, we analysed in addition how the navigation media, the route awareness, the wayfinding, and the cognitive map related to each other, and how these relations were influenced by previous navigation habits. The simulator with its highly standardized conditions allowed the more sophisticated and more reliable statistical analyses required for such an analysis. It also allowed more valid conclusions regarding causes and effects. The field experiment, on the other hand, was ecologically more valid. The two types of experiments thus complemented each other.

## 2 FIELD EXPERIMENT ON THE BALTIC

### 2.1 *Method*

Twelve sailors from different parts of Germany and Switzerland participated. With regard to age (33 - 68 years), sex (1 woman, 11 men), and level of experience (500 - 30,000 nautical miles sailed), the sample was typical of the population of German-speaking yacht sailors on the Baltic coast (Müller-Plath, 2018). All possessed a recreational marine vessel license and thereby sound navigation skills. It was particularly important for our study that the participants differed in their personal preferences of navigation media: In paper chart navigation, they reported 0 - 40 years of experience, with eight participants currently using their paper charts actively, i.e. making entries of courses and/or positions into the chart.

In digital navigation, their experience was 0 - 12 years, with five participants currently using an ECS actively, i.e. entering waypoints and/or routes. Our study took place in the coastal waters around the island of Rügen. None of our participants had ever been there. The test tracks were 7 - 19 nautical miles long. The weather varied from sun to rain, with wind from calm to strong with gusts. Seven of the twelve test tracks were run under sail, five under engine.

Each crew consisted of a skipper, two students as experimenters, and two participants as navigators, and sailed on one of the two participating yachts, a Hornet 32 and a Bavaria 46. Figure 1 depicts the procedure: On the first day, one of the two participants navigated classically, the other digitally. On the second day, classic and digital media were exchanged. Thus, 12 test tracks were sailed altogether, with each of the participants navigating twice. Tools for classic navigation were marine paper charts, protractor triangles, dividers, pencil, eraser, sharpener, calculator, and a handheld bearing compass. Tools for digital navigation was either an MFD (Raymarine 75eS with Lighthouse 2 software and vector chart Navionics Platinum, display diameter 7 inches, mounted next to the helm of the Hornet 32), or a tablet computer (Tablet Apple iPad Air 2 with the vector chart application Navionics Boating HD, display diameter 9.7 inches, used mobile on the Bavaria 46). The navigation task was standardised and consisted of two parts, route plotting and navigation underway (piloting): Plotting in the classic condition consisted of drawing courses on the paper chart, writing course and distance next to each course line, and writing the estimated time of arrival (ETA) next to each point of course change. Correcting the course for magnetic deviation, variation, wind, or current was not part of the task. Plotting in the digital condition consisted of building and storing a route from start to destination. Four participants each built the route by setting waypoints on the chartplotter of the MFD, by setting waypoints on the tablet computer, and by automatic routing on the chartplotter with carefully checking afterwards. For piloting, both navigators, each from his own medium, announced to the helmsman the courses and course changes, and in the case of a contradiction the skipper decided. Moreover, each navigator had to do a position fix once underway: the classic navigator via cross bearing and the digital navigator by reading latitude and longitude from the digital device.

The cognitive map was tested after the boat moored in the harbour by asking the participants to draw a sketch map of the navigated area on a blank piece of A4 paper (Burnett & Lee, 2005). The sketch had to include the following components: (1) adjacent coast lines, (2) port of departure, of destination, and alternative harbours, (3) shallow waters and other dangers to navigation, (4) navigation aids (buoys, lighthouses), and (5) planned route and sailed track.

The situation awareness of the two participants was assessed twice along on each test track with the freeze technique (Endsley, 1995b): Unannounced, the two participants were invited below deck and had to answer in writing and independently of each other nine questions about the current situation, grouped into the four domains position, wind, boat movement, and route. Since situation awareness means the correct perception of a situation in order to guide actions, the participants should not just reproduce naked numbers but give their answers in a meaningful and action-related format:

1 Position
– Indicate our position by a cross on a paper chart. (The chart style was different from the chart used for classic navigation.)

2 Wind
– Indicate the apparent wind angle (AWA) by an arrow at a boat icon.
– Indicate the true wind angle (TWA) by an arrow at the position indicating cross on the above paper chart.

3 Course
– Indicate the speed over ground (SOG).
– Indicate the course over ground (COG) by an arrow at the position indicating cross on the above paper chart.

4 Route (= spatial orienting, see the introduction)
– Indicate the bearing of the destination port by an arrow at a boat icon.
– Indicate the bearing of the port of departure by an arrow at a boat icon.
– Indicate the distance to the next course change.
– Indicate how many degrees to port or starboard the boat has to turn there.

On each test day, the entire procedure was practised in the morning, a port or an anchorage was called for lunch break, and the actual test track was sailed in the afternoon.

### 2.2 *Predictions*

According to the hypotheses stated in the introduction, we predicted that the cognitive map should be impaired after digital compared to classic navigation. This should more be the case the longer a participant had used digital media for navigation in the past. For the situation awareness we had no specific predictions because we hypothesized two contradictory influences of digital navigation (improved availability of situational data but reduced cognitive processing of them).

### 2.3 *Data analysis, results, and discussion*

#### 2.3.1 *Cognitive map*

The two freehand drawings in Figure 4 show in an exemplary way that the classically navigating participant has acquired a much better cognitive map than the digitally navigating one. For statistical evaluation, the 24 drawn sketch maps were rated by four independent experts who were blind to the condition.

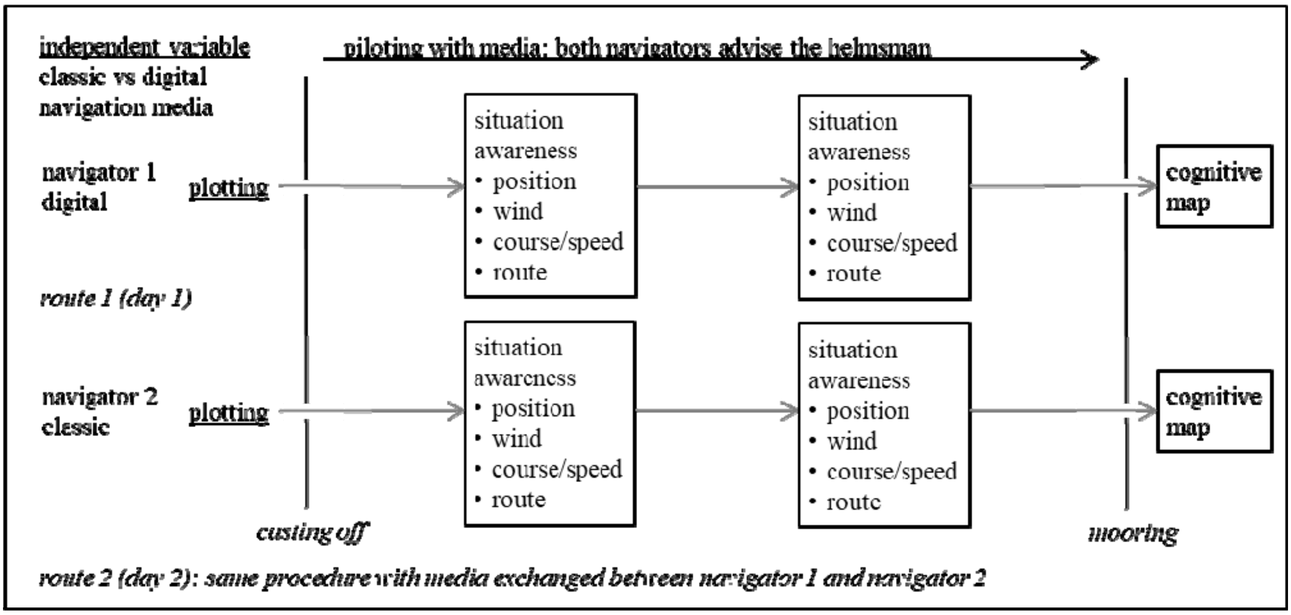


Figure 1. Field experiment: Procedure and dependent variables (framed). Within-person variation of independent variable.

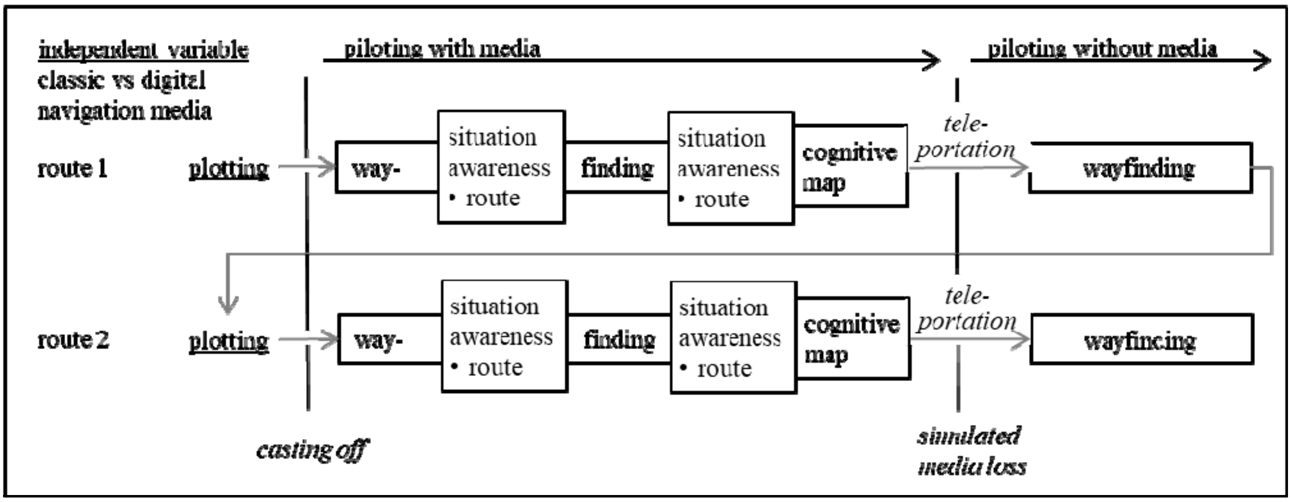


Figure 2. Simulator experiment 1: Procedure and dependent variables (framed). Within-person variation of independent variable.

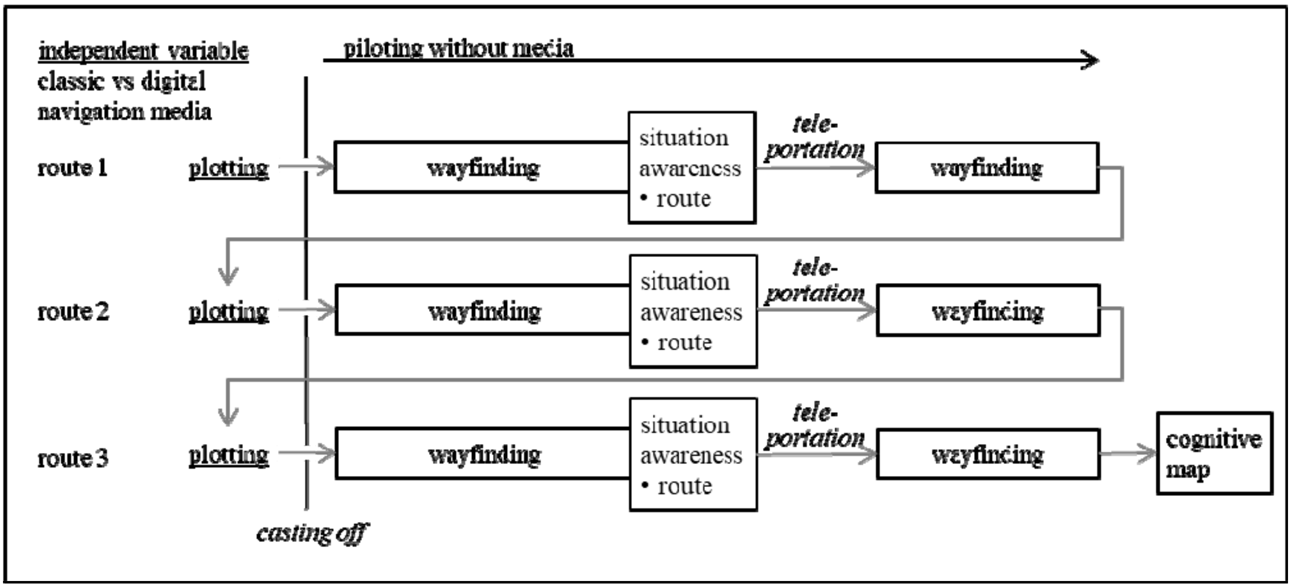


Figure 3. Simulator experiment 2: Procedure and dependent variables (framed). Between-person variation of independent variable.

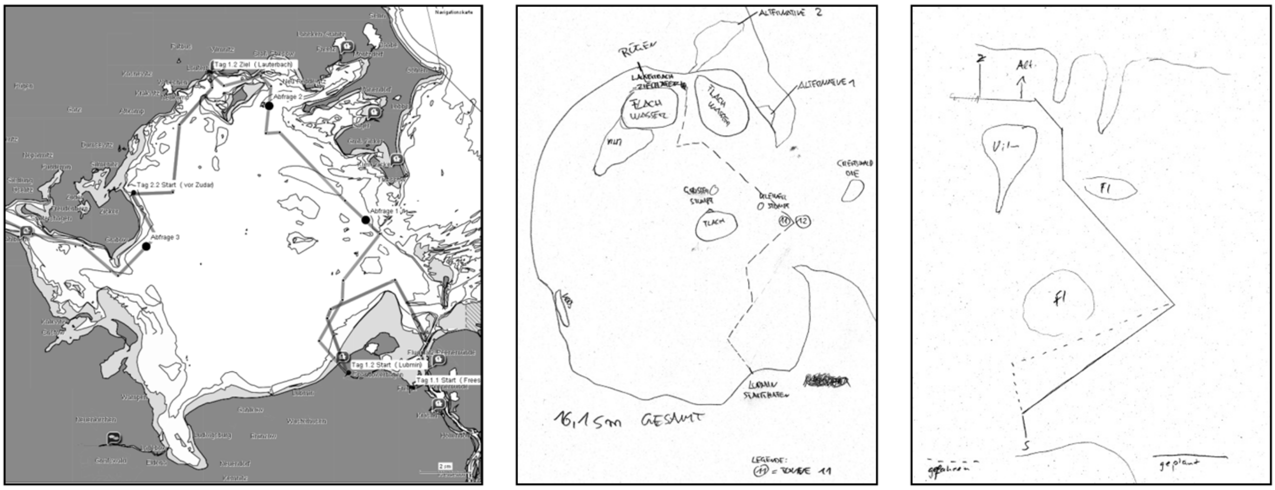


Figure 4. Left: Record of the test track from Lubmin to Lauterbach (the black dots mark the two queries on situational awareness). Middle: Freehand drawing of the classically navigating participant. It contains the coastline, shallow water areas, two buoys, port of departure, of destination, and alternative ports, as well as the route traveled. Right: Drawing of the digitally navigating participant. Coastline, shallow water areas, buoys, and ports are missing or wrong, only the route is correct.

They scored the accuracy of the five required components (see Methods section and Table 1) with a maximum of 100 points each. The total score for the cognitive map was the average of the five component scores. We then compared the drawing of each participant after navigating classically with that after navigating digitally (at another day on a different route; intra-person-comparison) and statistically assessed the difference scores with one-sample t-tests. All statistical analyses in this paper were conducted with R (R Core Team, 2018). Table 1 shows the results: The cognitive maps were significantly worse after digital navigation than after classic navigation not only in the total score but also in every component, except one: The routes/tracks were equally well represented in both conditions. On the other hand, the mental representations of navigation aids (buoys etc.) and of shallow waters/dangers were most severely impaired after digital navigation.

Further linear model analyses showed that the three manners of digital navigation (waypoint routing on the chartplotter, on the tablet, and autorouting on the chartplotter) impaired the cognitive map likewise: Mean costs were almost identical. Moreover, neither could the familiarity with the navigation tool account for the results nor differences between classic and digital route planning time.

With the help of multiple linear regression models we then explored which characteristics of the person (as linear predictors of the intra-person digital cost/benefit) moderated the effect of the navigation medium on the cognitive map. From all assessed person characteristics, which comprised age, nautical miles sailed, orienting abilities according to self-assessment, interest in electronic devices, and habits of using navigation tools - in particular: years of using paper charts only, years of using an ECS, years of not using paper charts anymore, active use of an ECS on the last sailing trip, i.e. with making entries, active use of paper charts on the last sailing trip, i.e. with making entries -, we selected the best subset of predictors with the cross validation technique (Shao, 1997). The best linear model contained age, years of using an ECS, and active use of an ECS on the last sailing trip as moderators. The model explained $R^2$ = .71 of the variance of the digital costs ($F(3, 8) = 6.81$, $p$ = .0136). All three predictors were highly significant (all $p$'s < .01): Besides younger sailors experiencing larger digital costs, previous navigation habits also mattered: Both the years of using an ECS and active use of an ECS on the last sailing trip enhanced the digital costs in the present experiment.

Table 1. Quality of cognitive maps after classic and digital navigation, and digital cost (-) or benefit (+) with statistical intra-person comparison (one-sample-t-test) in the field experiment.

| | Classic | Digital | Cost/Benefit | | |
|---|---|---|---|---|---|
| Component | Mean score (n = 12) | | | t(11) | p |
| Total# | 73.4 | 55.4 | -18.0 | -4.88 | .000* |
| Coast lines | 77.8 | 58.7 | -19.1 | -2.98 | .013 * |
| Landmarks | 72.6 | 53.1 | -19.5 | -4.31 | .001* |
| Shallows/ Dangers | 68.8 | 45.5 | -23.3 | -2.74 | .019 * |
| Navigation aids | 77.8 | 51.7 | -26.1 | -3.67 | .004 * |
| Routes/Tracks | 70.1 | 68.2 | -1.9 | -0.26 | .803ns |

\# Average of the component scores, maximum 100
* Statistically significant at level $\alpha$ = .05
ns Statistically not significant at level $\alpha$ = .20

As predicted, the cognitive maps were significantly impaired by digital navigation. Personal navigation habits seem to be the strongest moderators of this impairment, which increased with the duration of digital media use.

### 2.3.2 *Situation awareness*

At each freeze test query (two per track), the real data of the situation with regard to the nine questions were recorded at the moment the participants left the situation. Dependent on the impact of errors for safe navigation, the accuracy of each answer was scored with 0 - 3 points, summed up within each domain, and rescaled to a range of 0 - 100 for comparability. Scores were then averaged across the two queries of each track. The statistical analysis of the data followed the procedure described in the above section.

Table 2 shows the results: In contrast to the cognitive map, digital navigation had no significant impact on situation awareness in any of the assessed domains. The total mean score was even identical in the classic and the digital condition although the individual scores were different. The identity of means occurred by chance. (One has to bear in mind that due to the restricted range of original scores, 0 – 3 per answer, the probability of identical means is not as small as it might appear on first glance.)

Table 2. Situation awareness regarding the four domains position, wind, course, and route after classic and digital navigation, and digital cost (-) or benefit (+) with statistical intra-person comparison (one-sample-t-test) in the field experiment.

| Domain | Classic | Digital | Cost/Benefit | | |
|---|---|---|---|---|---|
| | Mean score (n = 12) | | | t(11) | p |
| Total# | 73.6 | 73.6 | 0 | 0 | 1.00 ns |
| 1. Position | 70.8 | 72.2 | +1.4 | 0.22 | .830 ns |
| 2. Wind | 70.1 | 80.6 | +10.4 | 1.36 | .202 ns |
| 3. Course/ Speed | 80.6 | 77.8 | -2.8 | -0.63 | .540 ns |
| 4. Route | 72.6 | 68.4 | -4.2 | -0.86 | .410 ns |

# Average across all nine answers, maximum 100.
* Statistically significant at level $\alpha$ = .05
ns Statistically not significant at level $\alpha$ = .20

Again, we then applied exploratory multiple linear regression analyses in order to explore which person characteristics might moderate the effect of the navigation medium on the total situation awareness, even if it was non-existent overall. The set of predictors and the statistical procedure for best subset selection were as in the cognitive map section. Here, the best linear model contained the two predictors "years of using an ECS" and "active use of paper charts on the last sailing trip", thereby explaining $R^2$ = 0.58 of the variance of the digital cost/benefit ($F$(2, 9) = 5.70, $p$ = .025): Sailors who actively used paper charts for navigation on their last trip, i.e. made entries into them, benefitted from the digital device for their situational awareness, whereas sailors who did not experienced costs ($p$ = .012). Simultaneously, the longer that the sailors had previously used digital devices, the more they benefitted from them in the experiment (or the less cost they experienced; p = .036). According to the comparison of the two regression coefficients, waiving the active use of paper charts is statistically compensated only by about 10 years of ECS use.

In summary, the situation awareness in general was not affected by digital navigation. This corresponded to the hypothesized opposite influences: improved availability of situational data, but reduced attention to and cognitive processing of them (see Introduction). Possibly the two cancelled each other. Most interestingly, however, personal navigation habits seem to make a difference: Sailors who actively used paper charts but were also familiar with digital devices benefitted most from the information provided by the ECS in this experiment. The two media, paper and ECS, might thus complement each other in supporting situational awareness. However, this result is regarded as preliminary because it relied on an exploratory statistical method. It will be checked and verified in the simulator experiment 2.

## 3 SIMULATOR EXPERIMENTS

Experiment 1 (Fig. 2) largely replicated the field study in order to validate the simulator on the one hand and the results from the field study on the other. In three points, however, the procedure was modified: First, since this was now safely possible, the wayfinding was assessed in addition to the situation awareness and the cognitive map. Secondly, from the four domains of situation awareness only the route awareness was assessed. Thirdly, the replication of the field study comprised only the first segment of each route in the simulator. On a second segment, in order to examine the hypotheses for wayfinding, a loss of the navigation media was simulated, the boat was then teleported to a position further on the route, and the participant was asked to re-orient and to pilot the way from there on with wayfinding as the dependent variable.

Experiment 2 (Fig. 3) was conducted with a larger sample of sailors and routes in order to investigate not only the impact of the navigation media on wayfinding, route awareness, and the cognitive map, but furthermore, how these three variables relate to each other, and what role the previous navigation habits play. Since we were interested in the development of the three spatial abilities over the course of navigation, the navigation media were taken away even earlier in this experiment: They were available only for route plotting but not for piloting the route, which had to be accomplished completely from memory.

### 3.1 *Experiment 1*

#### 3.1.1 *Method*

The sea simulator was programmed in our lab with the open source driving simulator software OpenDS (Math et al., 2013). It simulated sailing from an egocentric perspective with a sailboat of 9.40 m length and 1.90 m draught (Fig. 5) on the Isefjord, a deeply branched arm of the Baltic Sea into the Danish island Zealand, about 18 nautical miles long and 8 nautical miles wide. The area to be navigated contained several harbours and marinas, isles and islets, a buoyed fairway, and some narrow anchorages. Water depth is on average 5 - 7 m, but shallow near the coast, in harbour entrances, and at some single spots which are marked with cardinal buoys. The water depths in the simulator corresponded exactly to those indicated in the chart with linear interpolation in between. Other navigation aids included buoys, harbour buildings with sailboat masts, and coastlines. The simulation contained exactly the information provided in a navigational paper chart (Delius Klasing boating charts set no. 5, charts no. 20/21). The simulation was displayed on a 2D-screen of 2 x 3 m, at the bottom of which some navigation relevant data were displayed on simulated instruments (e.g. the magnetic course on a compass, COG, SOG, depth, latitude, longitude, and time). The participant was seated at a distance of 3.5 m to the screen and operated the boat with a joystick. Although the boat carried sails in order to visualise a sailboat, it was operated as a power boat because sailing skills were not subject of the experiment. Maximum speed ahead or astern was 6 knots. In case the boat grounded or collided with an obstacle (buoy, harbour pier etc.), this was indicated by a red flash and a deep sound. By altering the propulsion direction the boat could be freed.

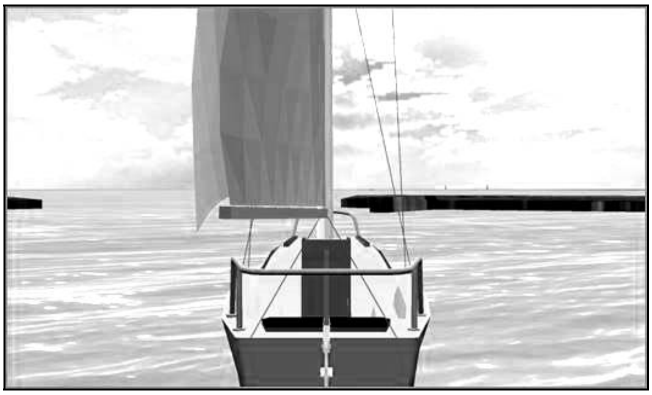

Figure 5. Sea simulator: Egocentric perspective when piloting the simulated sailboat on the "Isefjord".

The sample consisted of 8 sailors (1 woman and 7 men, age 26 – 76 years) with different levels of experience at sea (300 – 250,000 nautical miles sailed). All possessed a recreational marine vessel license and thereby sound navigation skills. As in the field experiment, they differed widely with regard to their habits of using navigation media: In paper chart navigation, they reported 0 - 45 years of experience, with five participants using them actively at present, i.e. making entries of courses and/or positions into the chart. In digital navigation, their experience was 0 - 12 years, with four participants using an ECS actively at present, i.e. entering waypoints and/or routes. None of the participants had ever been to the sailing area simulated in this experiment, and none had participated in the field experiment.

The procedure was as follows (Fig. 2): In order to provide a more standardised replication and to validate the simulator, the experimental design was in large parts matched to that of the field study: Every participant navigated two different routes (of 4 - 6 nautical miles length each), one classically and one digitally, in fixed order but with randomized assignment of media. The two routes were located in different parts of the Isefjord and plotted on different paper chart sheets so that the performance on one could not interfere with the other.

For classic route plotting, the participant was given a paper chart (the same Delius Klasing boating chart that the sea simulator was based on), course triangles, dividers, a calculator, a pencil, and white pieces of paper. In the digital condition, the participant received a 7-inch-tablet computer (Neptune Nep-Tab 7 Outdoor) with the navigation app Yacht Navigator (www.delius-klasing.de/yacht-navigator), which allows a user-friendly waypoint routing. The electronic chart in this app was a scanned image (raster chart) of the same Delius Klasing boating chart the simulator was based on and which in the classic condition was provided in paper. Thereby, effects of differences in chart information or layout were controlled. As in the field experiment, plotting in the classic condition consisted of drawing courses on the paper chart, writing course and distance next to each course line, and writing the estimated time of arrival (ETA) next to each point of course change. In the digital condition, it consisted of building up and storing a route by setting waypoints on the tablet computer with the help of the app.

The participants were tested individually. They started with planning (plotting) the first route on the paper chart or the tablet computer. Then he/she had to pilot the first segment of it on the simulator (about 1 nm, containing a harbour exit and two course changes) The navigation medium (paper or tablet with app) was available for piloting, with the GPS position on the tablet being simulated. Along this segment, three dependent measures were collected: The initial wayfinding was assessed and scored with up to 100 points, depending on the severity of errors (course error with self-correction, course error without self-correction, crossing shallow water, grounding). Secondly, the route awareness was tested twice on the segment (about 2 minutes after each course change) with the freeze technique (Endsley, 1995b): The participant had to stop the boat, turn away from the screen, and answer six questions about the current situation: bearing and distance of the port of departure, bearing and distance of the destination port, distance to the next course change, and where to and how much the course was to change there (resembling the questions in the domain "route" in the field experiment). The second route awareness test marked the end of segment 1. Thirdly, the cognitive map of the navigated area was collected here, with a sketch map drawing on a white piece of A4 paper. It contained the same components and was scored like in the field experiment. In order to investigate spatial re-orienting and wayfinding in case of a media loss, the boat was then teleported to a position in the second half of the planned route where a landmark or a navigation aid was in sight, and the participant was instructed: "Look, now we are already a little further on the route. Unfortunately, your tablet has crashed/your paper chart has fallen overboard. Please try to sail from here towards your destination from memory". The wayfinding on this segment, assessed as above, constituted the fourth dependent variable. After about 1.5 nm, the segment was stopped, and the participant went to the navigation desk in order to plot and pilot the second route in the same way as the first but with the other navigation medium. After completion of the two routes, confounding and possibly moderating variables were gathered with a questionnaire.

At the beginning there was a practice run in which the procedure was explained to the participants, in particular how to use the tablet app and to operate the "boat". Also, they were familiarised with the tasks and queries in the experiment.

### 3.1.2 *Predictions*

According to the hypotheses stated above and the results of the field study, we predicted that the route awareness would not be globally affected by one or the other navigation medium, whereas the cognitive map should be impaired after digital navigation. Regarding the wayfinding, we expected a benefit from the GPS-supported ECS as long as it is available but a cost when it is lost and the participant has to re-orient himself, due to the reduced cognitive map.

#### 3.1.3 *Data analyses, result, and discussion*

Table 3 shows the mean scores of the four dependent variables after classic and digital navigation, the mean cost or benefit from digital vs. classic navigation, and the statistical results of the intra-person-comparison.

Table 3. Initial wayfinding, route awareness, cognitive map with classic and digital navigation, later wayfinding after media loss, and digital cost (-) or benefit (+) with statistical intra-person comparison (one-sample-t-test of cost/benefit) in the simulator experiment 1.

| | Classic | Digital | Cost/Benefit | | |
|---|---|---|---|---|---|
| | Mean score (n = 8) | | | t(7) | p |
| Initial wayfinding | 81 | 98 | +17 | 2.65 | .033 * |
| Route awareness# | 67 | 65 | -2 | -.54 | .606ns |
| Cognitive map | 53 | 31 | -22 | -2.49 | .040 * |
| Later wayfinding | 83 | 73 | -10 | -0.60 | .565 ns |

# Average across the two queries on segment 1, maximum 100.
* Statistically significant at level $\alpha$ = .05
ns Statistically not significant at level $\alpha$ = .20

On the first segment of each route (plotting and piloting either classically or digitally, with two situation queries underway and a cognitive map sketch at the end), the simulator experiment closely resembled the field experiment. The results were alike as well: Whereas the navigation medium did not have a significant effect on the route awareness, digital navigation severely impaired the cognitive map. This was regarded a successful replication and a validation of the simulator.

Exceeding the possibilities of the field, the simulator also allowed assessing the wayfinding with and without the navigation medium. As predicted, the GPS-supported digital medium significantly bene fitted the wayfinding, almost to perfection, as long as it was available. After it was lost and the participant had to re-orient, the advantage vanished. In the sample, there was an average cost of 10 points after having navigated digitally, but contrary to the prediction this was not statistically significant. A closer look into the sample revealed large interindividual differences: Whereas two participants faced severe wayfinding problems after digital navigation (running into shallow waters and even grounding) but none after having navigated with paper - according to prediction -, two others benefitted from ECS use when required to find their way from memory. The other four were perfect or nearly perfect in both conditions. On the one hand, the route might have been too easy and too short to simulate a realistic situation (ceiling effect); on the other, the differences might be explained by person-specific characteristics, in particular previous navigation habits, which should affect perceptual processing at sea. The latter is the subject of the following experiment.

### 3.2 *Experiment 2*

#### 3.2.1 *Method*

The experiment was conducted with the same sea simulator as in experiment 1. The sample consisted of 20 sailors (2 women and 18 men, age 26 – 75 years) with different levels of experience at sea (100 – 100,000 nautical miles sailed). All possessed a recreational marine vessel license and thereby sound navigation skills. As in the previous studies, they differed widely with regard to their habits of using navigation media. In paper chart navigation, they reported 0 - 45 years of experience, with 13 participants currently using them actively. In digital navigation, their experience was 0 - 16 years, with 12 participants currently using an ECS actively. None of the participants had ever been to the sailing area simulated in this experiment, and none had participated in any of the other experiments.

The participants were randomized into two experimental conditions, classic and digital route planning, and tested individually. The overview of the procedure is depicted in Figure 3, placed further up in the paper in order to facilitate comparison with the other experiments. Three different routes of 4-6 nautical miles length each had to be plotted on the chart and piloted on the simulator. For piloting, however, the (paper or electronic) navigation medium was taken away. Since in this experiment we wanted to investigate the effects of using paper vs an ECS for *plotting* and for the subsequent development of route awareness and cognitive map, the participant had to pilot the routes from memory from the beginning. On each route, three dependent variables were collected. First, the initial wayfinding was assessed and scored with up to 100 points as in experiment 1. Secondly, after about 1.5 nm and at least one course change, the route knowledge was examined with the same technique and questions as in experiment 1. Thirdly, the boat was teleported to a position in the second half of the planned route where a landmark or a navigation aid was in sight, the participant was instructed "look, now we are already a little further on the route; please sail from here towards your destination port", and wayfinding on this segment was scored as initially for about 1.5 nm. The fourth dependent variable was the cognitive map of the entire navigated area, assessed after finishing all three routes. The three routes were located in different parts of the Isefjord and did not overlap. Finally, the same questionnaire was applied as above. There was also a practice run at the beginning.

#### 3.2.2 *Predictions*

When using digital navigation media only for plotting but not for piloting, we hypothesized that only their impairing influence on route awareness be effective (reduced cognitive processing of information during planning) but not the benefitting one (availability of situational data underway, see introduction). Moreover, we hypothesized in the introduction that previous navigation habits might lastingly have altered information processing at sea. We thus predicted the following effects of the route plotting medium and the previous navigation habits: First, the route awareness, i.e. the route related situation awareness, should be impaired after digital plotting compared to classic. Here, previous media use should be of no influence. Secondly, the cognitive map should be affected vice versa: No effect of the plotting medium (the cognitive map is hypothesized to build up during piloting where the two groups did not differ in navigation media), but an increased impairment with increasing duration of digital navigation in the past (altered information processing underway). Thirdly, the wayfinding should be impaired as far as it relies on route awareness and/or cognitive map. We expected positive associations between route awareness, wayfinding, and cognitive map. If these weaken with the duration of digital navigation in the past, this will be interpreted as an indicator of lastingly altered information processing at sea.

### 3.2.3 *Data analyses and results*

Table 4 shows how classic and digital route plotting affected the initial wayfinding, the route awareness, the later wayfinding, and the final cognitive map when piloting from memory.

Table 4. Initial wayfinding, situation awareness, later wayfinding, and cognitive map after classic and digital route plotting, and digital cost (-) or benefit (+) with statistical inter-group comparison (two-sample-t-test) in the simulator experiment 2.

| | Classic | Digital | Cost/Benefit## | | |
|---|---|---|---|---|---|
| | Mean score (n = 10##) | | | t(18) | p |
| Initial wayfinding# | 82 | 83 | +1 | 0.66 | .948 ns |
| Route awareness# | 77 | 65 | -12 | -2.81 | .012 * |
| Later wayfinding# | 89 | 66 | -23 | -2.46 | .024 * |
| Cognitive map | 58 | 63 | +5 | .44 | .666 ns |

# Average across the three routes, maximum 100
## Mean scores: n = 10 per group, cost/benefit between groups
* Statistically significant at level ◎ = .05
ns Statistically not significant at level ◎ = .20

The two groups did not statistically differ in age or experience, i.e. nautical miles sailed. Again, the time for route plotting could not explain the results.

After having assessed *if* the route plotting medium affected the route awareness, the wayfinding, and the cognitive map, we analysed *how* they did that, and what role previous navigation habits played. Therefore, we regarded each pair of variables that immediately succeeded each other in the experimental procedure (see Figure 2) as predictor and criterion in a regression model in which we included the previous navigation habits as moderating variables. In detail, we fitted the model equation (1) of moderated linear regression to the data, and tested the coefficients for significance.

$$E(Y_i)=\alpha+\beta x_i+\gamma m_i+\delta x_i m_i=(\alpha+\gamma m_i)+(\beta+\delta m_i)x_i \quad (1)$$

where $E(Y_i)$ denotes the expectation (theoretical mean) of the random variable $Y$ in person $i$ ($i$ = 1, ..., 20), modelling the criterion variable, $x_i$ the predictor variable $x$ in person $i$, $m_i$ the moderator variable m in person $i$, and $\alpha$, $\beta$, $\gamma$, $\delta$ the regression coefficients.

Based on the exploratory results of the field experiment, we examined the following navigation habits as moderators:

1 years of using an ECS,
2 years of not using paper charts anymore,
3 active use of an ECS on the last sailing trip, i.e. with making entries,
4 active use of paper charts on the last sailing trip, i.e. with making entries.

From the twelve moderated regression analyses (three pairs of predictor and criterion variables with four moderators each), only those with a significant global F-test are shown in Table 5.

Table 5. Moderated regressions: Coefficient estimates according to Equation (1) and significance of t-tests (df = 16). The horizontal sections of the table refer to the three pairs of predictor and criterion variables, denoted with the symbol =>

| Moderator | $\hat{\alpha}$ | $\hat{\beta}$ | $\hat{\gamma}$ | $\hat{\delta}$ |
|---|---|---|---|---|
| Plotting medium## => situation awareness (route knowledge)# | | | | |
| m1. Years ECS | 82* | -7.2 | -0.9* | -0.4 ns |
| Situation awareness (route knowledge)# => later wayfinding# | | | | |
| m1. Years ECS | -170* | 3.2* | 15 * | -0.2* |
| m2. Years no paper | -65 | 2.0* | 52* | -0.8* |
| m3. Active ECS use (0-1) | -80 | 2.1* | 94 | 0.2 |
| m4. Active paper use (0-1) | 42 | 0.5 ns | -108* | 1.5* |
| Later wayfinding# => cognitive map# | | | | |
| m1. Years ECS | 4.0 ns | 0.8* | 7.4* | -0.1* |

## Binary: 0 = classic, 1 = digital. # Metric: score 0-100
* Statistically significant at level $\alpha$ = .05
ns Statistically not significant at level $\alpha$ = .20

### 3.2.4 *Discussion*

To begin with, digital route plotting had no effect on the initial wayfinding (Table 4, first row). Because of the zero effect and the absence of any substantial correlations with the other dependent variables, we did not analyse this outcome any further.

For interpreting the results of the other dependent variables and the moderated regressions, one might want to envision that $\alpha + \gamma m$ is the intercept of the moderated regression equation (1), i.e. the predicted criterion value for predictor value 0. Herein, $\alpha$ denotes the criterion value for moderator value 0, and $\gamma$ its increase/decrease when the moderator increases by 1 unit (main effect of the moderator onto the criterion). Likewise, $\beta + \delta m$ is the slope of the moderated regression equation (1). Herein, $\beta$ denotes the effect of the predictor on the criterion for moderator value 0 (main effect of the moderator on the criterion). $\delta$ denotes how much this effect increases when the moderator increases by 1 unit (interaction of predictor and moderator).

With this notion in mind we will interpret the most interesting findings. First, according to Table 4, the digital route plotting reduced the route awareness underway on average by 12 points (or 16 %). According to the moderated regression in Table 5 top row, the only alternative predictor for this criterion was the duration of previous ECS use, reducing the regression intercept, i.e. the level of route awareness, by about 1 point per year. The conclusion is the same for both predictors: The digital plotting medium in the experiment as well as previous digital navigation impairs orienting at sea.

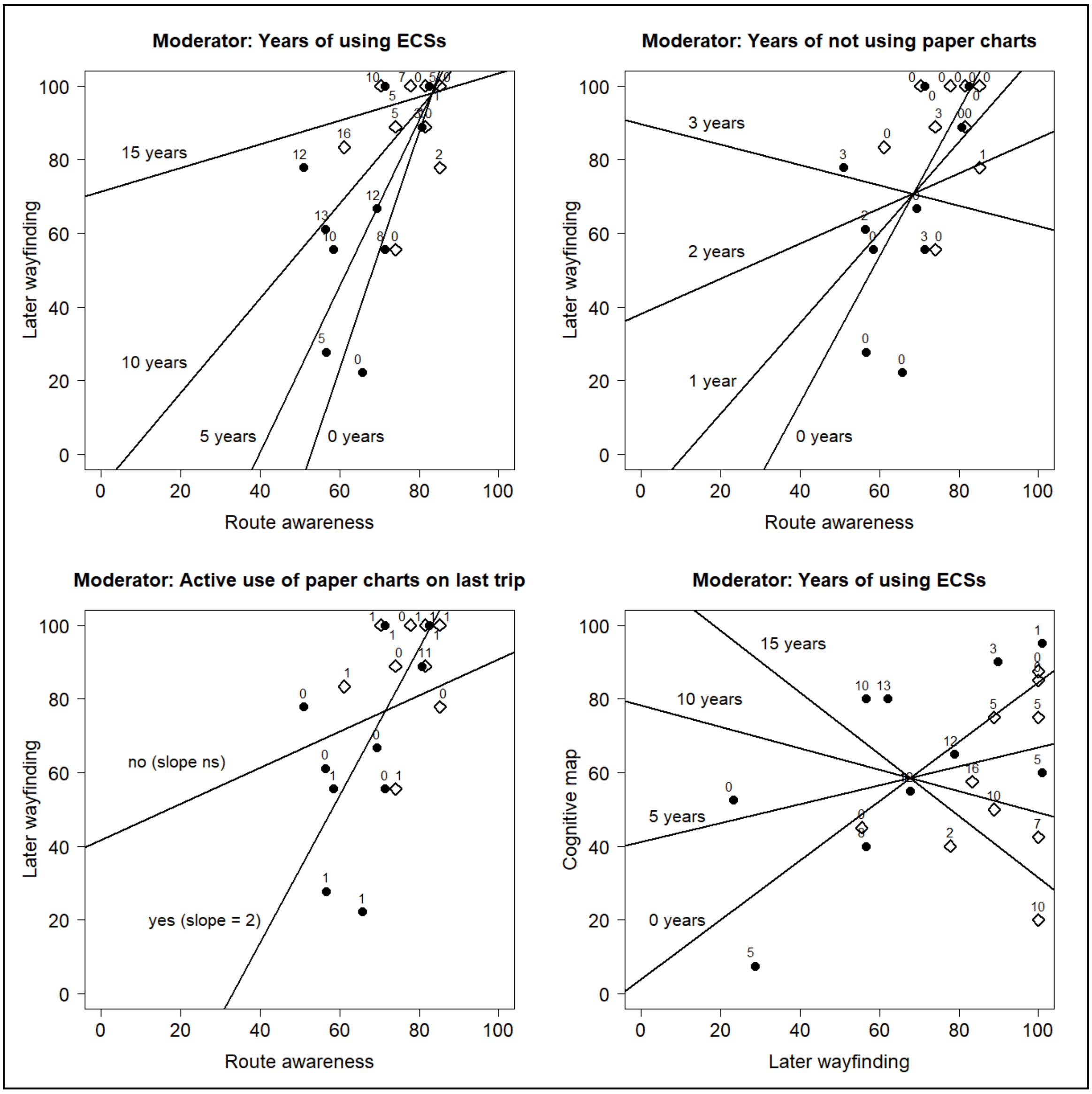


Figure 6. Four examples of how the relationship of every two successively collected variables in Experiment 2 (the former in the role of a predictor, shown on the x-axis, the later in the role of a criterion, shown on the y-axis), is influenced by previous navigation habits (as moderators, indicated by the numbers at the data points and the fitted regression lines). The four diagrams illustrate the results of the moderated regressions in the rows 2, 3, 5, and 6 of Table 5.

Moving on in the experimental procedure, Table 4 shows secondly that the wayfinding after being teleported to a later position on the route was even more strongly negatively impacted by digital route plotting than the route awareness, namely by 23 points (26 %). In addition, there was a positive association between the route awareness and the later wayfinding ($r = 0.59$), implying that the more accurate a sailor oriented himself on his route, the better he found his way later from a new location. According to the moderated regressions in Table 5, the previous navigation habits influenced this interplay in several ways: The intercept $\alpha + \gamma m$ is not interesting in this context, because a route awareness (predictor) value of 0 never occurs. Focusing thus on $\beta$ and $\delta$ in the four significant regression models (rows 2 - 5 in Table 5), we found the following: Without any previous ECS use, every additional point of route knowledge increases the wayfinding later on the route by 3.2 points. However, this positive relation is reduced by 0.2 points per year of ECS use, consequently (statistically) reduced to zero after 16 years (Table 5, row 2). This is illustrated in the upper left panel of Figure 6. The effect of the other moderators of this relationship are interpreted accordingly and depicted in the upper right and lower left panels.

The cognitive map was experimentally assessed after all three routes were plotted and navigated. In contrast to the other two experiments, in which the cognitive map suffered from digital navigation (Table 1, Table 3), there was no significant impact of the navigation media here (Table 4). The difference is obviously due to the fact that the chart medium was employed only for plotting but not for piloting in the present experiment, and suggests that the cognitive map indeed evolves underway. In support of this notion, we found a correlation between the later wayfinding and the quality of the cognitive maps ($r = 0.41$) in the present experiment. We thus analysed the role of previous navigation habits in this interplay, too (Table 5, row 6; lower right panel of Figure 6). We found that without any previous ECS use, every additional point in wayfinding increases the cognitive map by 0.8 points. This positive relation is reduced by

0.1 points per year of ECS use, and consequently (statistically) vanished after 8 years.

Taken together, all these results agreed with the prediction that long-lasting ECS use and abandonment of paper chart navigation weakens the association between the three spatial abilities investigated here (route awareness/orienting, wayfinding, and cognitive map). This supports our idea that solely digital navigation has a lasting effect on perception and information processing at sea.

## 4 GENERAL DISCUSSION

The results of the field experiment and the two simulator experiments can be summarized as follows.

As expected, an electronic charting system (ECS) supports wayfinding. Wayfinding accuracy was nearly perfect in our simulator experiment 1 in which a route in a coastal area was plotted on a tablet with a navigation app and piloted right after. With paper chart and magnetic compass, in comparison, the same sailors made some minor course errors or crossed shallow waters. This is undoubtedly a safety advantage of GNSS-supported digital navigation.

However, this advantage comes at a large cost. In all experiments, we assessed the situation awareness underway (only route awareness in the simulator but also other domains like position, wind, and course/speed in real sailing). When the route was plotted on a navigational chart but piloted without, after classic route plotting the route awareness was better than after digital. When the media were available underway, the situation awareness of the classically navigating sailors was still just as good although the ECS readily provided the data questioned in the test. The notion of Asyali (212) who proposed a better situational awareness in digital navigation on the basis of questionnaires, was thus not confirmed by our experiments. When taking previous navigation habits into account, we even have to agree with Grech & Horberry (2002) who proposed that technological progress is associated with a loss of situational awareness. In the field experiment, i.e. under realistic conditions, a sailor benefitted from the ECS only if he regularly and actively used paper charts for navigation in his own practice. On the other hand the longer a sailor had navigated digitally in the past, the worse was his situation/route awareness with the ECS in the experiment. We ascribe this interaction to a defective cognitive map (see below) and to permanently altered information processing at sea. Not only does the sailor pay too little attention to the data provided by the ECS but he also might lose the deeper understanding that is necessary to comprehend and correctly interpret them.

Orienting (route awareness) and wayfinding rely on spatial knowledge, the so-called cognitive map (Nadel, 2013). In both experiments in which the sailors used the navigation media for piloting, the cognitive maps were much poorer after digital compared to classic navigation. This finding is complemented by the correlation and regression analyses of the data of simulator experiment 2 in which the positive statistical associations between route knowledge and wayfinding, and between wayfinding and the cognitive map, were weakened by the duration of previous digital navigation, by not actively working with paper charts, or by waiving them completely. Taken together, these findings suggest the following mechanism: In classic times, after having plotted the courses on the paper chart, during piloting the sailboat navigator constantly had to match chart data with nature in order to find his way. By this he/she acquired the spatial knowledge, i.e. the cognitive map. With GNSS-supported digital navigation, this view into nature is not necessary anymore. Moreover, the electronic chart frequently varies its look (varying map detail by zooming in and out the vector chart, varying visible section of the map by dragging it on the small display). Both will result in spatial knowledge not being properly acquired and stored, thus a defective cognitive map and spatial orienting. As a result, the advantage of a more accurate wayfinding with the ECS turns to a disadvantage when the medium fails. This was empirically tested in the two simulator experiments in which the sailors were “teleported” to a spot later on their route where they had to re-orient themselves and find their way onwards without their (digital or paper) chart. Piloting from memory was more accurate after classic than after digital navigation. In practice, this finding is even more relevant because a media loss is much more likely with a digital device than with paper: Not only is electricity limited and vulnerable on the small and often old sailboats but also the software of pleasure craft ECSs is susceptible to breakdowns like any computer software nowadays. Especially in coastal areas with their typical hazards, a disoriented skipper is a safety issue not only on his own boat but also for commercial shipping.

Concerning generalisation of the experimental finding to realistic conditions, we assume that most effects might even be larger in practice, where procedures and tests are not known in advance, and where the navigational challenges are more difficult (longer and more complicated routes, multiple tasks, harsh weather, etc).

We will conclude with some ideas on technical and legal implications. As argued above, we cannot recommend doing without paper charts on pleasure crafts. An ECS should be used as a complement but not as a supplement. However, since it is time-consuming to prepare routes on two media in parallel before the boat can cast off, one might want to think about technical solutions that combine the advantages of both: Active interaction with a large and visually stable chart for route plotting and piloting on the one hand, and GNSS support with possible add-ons like AIS, radar overlays, weather data, etc. on the other. Moreover, today’s sailboat crews are often small, and no one wants to sit for hours below deck for navigation anymore if mobile solutions for outdoor use are available. One idea is to plot courses on paper (e.g. when the boat is moored in harbour) with a digitally trackable pencil that can afterwards transfer the data to the ECS for underway outside use through a bluetooth or WiFi connection. Also, in order not to permanently lose the ability to orient at sea, an “out-of-the-loop training”, in which pleasure craft skippers are forced to navigate old-school, should be exercised regularly, and probably even become a standard for maintaining the license.

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