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Simulated Navigation Performance with Marine Electronic Chart and Information Display Systems (ECDIS)[1]

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Licensed mariners carried out two simulated navigation studies testing electronic chart and information display systems (ECDIS) against paper chart navigation. In the first study, six mariners each completed approaches to Halifax, Nova Scotia, harbour with good and bad visibility and a range of wind and currents. Conditions included chart with radar, ECDIS with radar overlay and ECDIS with separate radar. ECDIS produced better performance and a smaller workload than paper charts and the radar overlay was slightly better than the separate radar display. In the second study, six new mariners completed exercises with low visibility and heavy or light radar traffic using ECDIS with radar overlay, ECDIS without overlay and ECDIS with optional overlay. Mariners preferred the optional overlay but all three conditions produced about equal performance. Based on mariners' performance and expressed preference, we recommend that ECDIS systems provide optional radar overlays.

KEY WORDS

1. ECDIS. 2. Paper chart. 3. Radar overlay.

1. INTRODUCTION.

The past century saw radical changes in marine navigation. The magnetic compass was succeeded by the gyrocompass, the sextant and chronometer by radio navigation and binoculars and telescopes by radar. The paper navigation chart now competes with electronic displays that can locate the ship on a chart in real time, display other ships' positions on the chart, superimpose radar information over the chart and suggest manoeuvres (Smeaton & Coenen, 1989; Baziw, 1996; Rolfe, 1996). Electronic chart display and information systems (ECDIS) are well on their way to completing the technical transformation of an ancient art.

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[1] The first study was carried out for the Canadian Hydrographic Service and reported to them by Mercer and Hong (1994). The second study was carried out under PWGSC contract no. W7711-9-7561A between Human Factors North Inc and the Defence and Civil Institute of Environmental Medicine (now Defence Research and Development – Toronto) and reported to them by Donderi (2001). Sharon McFadden was the contract manager, and we thank her for her help and encouragement.

Smith *et al*. (1994) studied simulated navigation performance by testing two ECDIS systems against conventional chart navigation while piloting a 207-metre containership into and out of New York and San Francisco harbours.[2] One ECDIS system allowed a complete radar plot to be superimposed over the display while the other allowed a selected ARPA target to be transferred from the radar to the display. Nine navigation scenarios were about equally difficult in navigation, collision avoidance and bridge management requirements. Six mariners carried out the scenarios in counterbalanced order to reduce influences based on increased familiarization with ECDIS during the study. Some scenarios required manual updating of the ECDIS position while others used automatic position updating. Two scenarios required conventional paper chart navigation. Records were kept of each mariner's use of ECDIS and conventional charts. Performance records included cross-track error, closest point of approach to collision or navigation hazards and omitted tasks and procedural errors. Each navigator completed the NASA Task Load index for navigation, collision avoidance and bridge navigation tasks after each session and a detailed post-scenario questionnaire recorded mariners' evaluations of ECDIS features.

ECDIS with automatic positioning updates reduced the measured workload of the navigation component of the task as well as decreasing the proportion of time spent on navigation, while it increased the amount of time spent on collision avoidance without changing the collision avoidance workload. Mariners made more navigation errors, as recorded by an expert mariner overseeing the exercise using video and audio records, when navigation workload was high. Smith *et al*. conclude that using ECDIS with automatic positioning increases safety by reducing navigation workload and errors and by increasing the proportion of time spent on visual collision avoidance.

We report two ECDIS navigation simulator studies. In the first, mariners navigated a Halifax, Nova Scotia, harbour approach under good and poor visibility conditions using either paper charts and radar, ECDIS with a separate radar display, or ECDIS with a radar overlay. In the second study, simulated heavy fog forced mariners to use ECDIS and radar information at minimum visibility under three conditions: separate radar and electronic chart, radar overlaid on chart, or free choice of separate or overlaid displays. The piloting scenarios included the St. Lawrence Seaway, Come-by-Chance, Newfoundland, and Halifax harbour. Our two studies confirm that ECDIS navigation is superior both objectively and subjectively to paper chart navigation and that the radar overlay, which under some conditions is better than a separate radar display, should be optional.

2. EXPERIMENT 1: ECDIS VERSUS PAPER CHART.

2.1. *Simulator*. The marine simulator at the Centre for Marine Simulation (CMS)[3] is a full ships' bridge installed on a six degrees-of-freedom motion platform, surrounded by a 360° visual projection screen and operated by a Norcontrol computer system. For this study, the wheelhouse was equipped with a Norcontrol DB 2000 ARPA radar console and an Offshore Systems Limited (OSL) ECPINS v.1.4 electronic chart display system. The OSL display system presents an electronic chart

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[2] Using the Computer-Aided Operations Research Facility (CAORF) of the National Maritime Research Center, Kings Point, NY.

[3] The Centre for Marine Simulation is an operational unit of the School of Maritime Studies of the Marine Institute, St. John's, Newfoundland.

Figure 1. Simulator wheelhouse.

oriented to and coordinated with the ships' position as displayed by an "own ship" mark on the chart. The user can vary the chart orientation and scale. The system allows the user to superimpose a transparent radar overlay at the same position, scale and orientation as the chart. The radar display remains oriented to the chart display as the ship moves.

The electronic chart and radar displays were located forward on the right side of the wheelhouse (Figure 1). The electronic chart display is shown in Figure 2. During the exercises, the navigating officer issued engine and rudder commands to a helmsman (a student) who carried them out on the steering stand (Figure 1) which for the duration of this study also contained the engine controls.

2.2. *Method.*

2.2.1. *Simulated ship.* The simulated ship was a ferry with good manoeuvring characteristics and a high freeboard that made it wind-sensitive. The additional control difficulty presented by wind sensitivity was expected to amplify differences among the experimental conditions.

2.2.2. *Geographical area and route.* The area was Halifax, Nova Scotia, within the limits of Canadian Hydrographic Service (CHS) chart X4023 (Black Point to Point Pleasant), available in both paper and electronic versions. The course was laid off as leading lines on the paper and electronic charts and was designed to keep the ship out of danger. The route was reviewed with each mariner prior to the start of each run, and mariners were asked to keep the ship as close to the planned route as possible.

2.2.3. *Experimental design.* The navigation methods tested were the traditional paper chart with radar, ECDIS with separate radar and ECDIS with radar overlay. The goal was to determine which method was best for safety and collision avoidance. Safety was defined as the ability to keep the ship on the previously planned track. Collision avoidance was defined as the ability to maintain safe passing distances from other ships. It was assumed that each mariner would change the passing distance

Brg: N/A
Rng: N/A
Route: Dang
wp 16 to wp 15
XTD: P4150.2 nm
WP Brg: 323.8 deg
DST: 3945.15 nm
TTG: 369:00:39
Reference: VESSEL-R
Cursor: Wreck
Bearing: 317.7°
Range: 4292.49 nm
Lat: 044° 38.422' N
Lon: 063° 33.323' W
Sensor: NO FIX
HDOP: 0.00
Sats: 0
Beac Freq: 0.0
Beac SNR (dB): 0.0

Figure 2. Photograph of an OSL ECPINS display.

from other ships if they were uncomfortable with the situation as it developed. Each navigation method was tested under good (10·0 nm) and bad (0·6 nm) daytime visibility conditions, both of which are regularly encountered in the Halifax harbour approaches. The study mariner was the only navigating officer on the bridge during the simulator runs. In order to maintain consistency in responding to helm orders, the same helmsman answered rudder commands on all runs for all mariners.

Cross-track distance data in the form of signed deviations from the planned track in units of 0·1 nm was recorded at 5-second intervals. The number of helm orders issued per run was also recorded. The NASA Task Load Index (TLX), a standardized questionnaire that is widely used to evaluate the workload imposed by complex cognitive and motor tasks, was administered to mariners after each run to assess both navigation and collision avoidance workload. Mariners' activities during each run were video recorded.

2.2.4. *Scenarios*. Each of six scenarios was presented once to each mariner. Each scenario followed the same planned route but with different traffic. Wind and currents generated by the simulator were varied across scenarios in order to prevent the mariners from learning the overall task by rote. The simulated tasks were thus similar to real tasks experienced by a mariner entering the same harbour many times under different weather conditions. The scenario order of presentation was randomized for each mariner except that the first scenario always included ECDIS in order to reinforce the ECDIS training each mariner had already received. For each mariner a minimum of 24 hours elapsed between consecutive scenarios, except for a few cases when scheduling changes reduced the elapsed time to 16 hours.

Before the experiment began, a licensed Port of Halifax pilot assisted by a watch officer and a helmsman ran each scenario under good visibility conditions in order to evaluate its realism and difficulty level. Based on his advice, minor changes were made to the ship traffic in some of the scenarios in order to maintain a similar level of difficulty across all scenarios. Each scenario was also pre-tested by a mariner whose background and experience was similar to that of the study mariners. These tests allowed us to refine each scenario under actual data collection conditions.

2.2.5. *Mariners.* The six mariners all held Canadian Certificates of Competency at the command level and all had sailed as Masters. Five had at least 15 years' experience while one had 10 years. They had sailed on average 6.5 months during the preceding 12 months: three as master, two as chief officer and one as both master and chief officer. Vessels included chemical tankers, cable repair ship, product tanker, fishing vessel, passenger ship, roll on/off, and an offshore supply vessel. The routes were concentrated in the North American coastal trade and North Sea offshore. One mariner reported 12 transits of Halifax harbour in the previous 12 months while all others reported no transits. None had previous ECDIS experience. One reported previous familiarity with the DB2000 Radar. All reported previous familiarity with GPS but two said that they were unfamiliar with differential GPS. Four reported some previous experience involving ship simulators ranging from tours of several facilities to a one – week course. All reported that they were familiar with personal computers and used them almost every day.

2.2.6. *Training.* Two training sessions were organized to make sure that mariners were familiar with the simulator and could operate the ECDIS equipment at the level required for the study. Session 1 took three hours with all mariners present. The researchers discussed the nature of the research and introduced and explained the NASA Task Load Index and its rating scales. Approximately 1 hour of instruction was provided on the ECDIS display. This instruction focused on the features which would be used during the study. The rest of the session was used to allow all mariners to operate the ECDIS equipment and the simulator. Training was carried out in a different geographical area than that used in the actual study. Session 2 was scheduled for the day immediately prior to the start of data collection. The mariners were given the same instruction as in the previous session and were again given the chance to use both the ECDIS and the simulator. This was the last training session before the actual data collection runs began.

Just before each run, the OSL ECPINS system was reviewed with each mariner. Their questions were answered by the researchers as required. In the post-experiment debriefing, all mariners said that the training they received was adequate. Four mariners reported that they felt comfortable using the ECDIS for navigation after one run while one reported that it took more than two runs before he felt comfortable using ECDIS for navigation.

Before each run, mariners were given the weather conditions and the traffic situation in hard copy and the information was reviewed orally in detail. In order to ensure that all mariners executed each run the same way, the "rules of the run" were reviewed before each run. They included the maximum allowable ship speed, the route to be followed, what conversation was allowed between the helmsman and mariner, and the VHF communication protocol. Mariners were told that traffic ships would report at the appropriate calling-in points in order to provide them with updated traffic movement information. Then the proposed route was reviewed and questions were answered. The researchers accompanied the mariner to the bridge and reviewed the radar operation and the operation of other equipment required. Where appropriate, the operation and layout of the ECDIS was also reviewed, and other questions were answered if necessary.

2.2.7. *Data collection.* During each run, the simulator time, ship heading, rudder order, course through water and distance along the track was recorded to a data file at five-second intervals. The cross-track error distance was calculated from a

Table 1. Study 1: Navigation performance comparison between paper chart and ECDIS.

Measure	Exercise type Paper chart	 ECDIS no overlay	 ECDIS with overlay
Cross-track error (0·01 nm)	2·2096	−0·3382	0·0995
Closest pt. of approach (0·01 nm)	0·0285	−0·0059	−0·0007
No. of helm orders	8·0833	13·0833	10·0833
Pct. radar monitor use	35·89	15·90	15·30
Navigation workload rating	63·50	51·33	43·16

Loran C receiver that was pre-programmed with the same waypoints as the simulator, and the receiver was interfaced to a computer which recorded the data to a file. An observer in the control room monitored the remote audio and video monitors and the remote ECPINS and radar displays. He produced a time-based task record for these activities: looking out the window, looking at the radar display, looking at the ECDIS (or paper chart), helm orders and course changes. Additional time-based records were obtained for range changes and range and bearing measurement using the radar, and for obtaining range and bearing information from the ECDIS display.

The actual closest point of approach (CPA) of all target ships which passed the ownship position was measured using the instructor's situation display in the simulator control room. The actual CPA was then compared to the optimum CPA. Since the preplanned ownship course was parallel to the courses of all of the other ship traffic, the optimum was defined by measuring the distance between the preplanned ownship and passing ship track at their closest points.

After each run, mariners completed the NASA task load indices (TLX) for navigation and collision avoidance. The TLX measures workload defined by six categories of operator experience: mental demand, physical demand, time demand, subjective performance, overall effort and level of frustration. These indices were completed for three classes of activity during each run: 1) the single most difficult event, 2) navigation, and 3) collision avoidance. After all six runs were completed, each mariner made a forced-choice decision about which one of the six TLX categories was most directly relevant to the workload experience for each of the six scenarios. From this data plus the recorded TLX scale values, an overall rating was obtained for each TLX category on each scenario. Each mariner was also asked to provide a description of "safe navigation." The six responses were synthesized into a consensus description which we related to aspects of the ECDIS display. Finally, we recorded which ECDIS features mariners said should be always displayed and which could be user-selected, considering the requirements of safe navigation.

2.3. *Results.*

2.3.1. *Objective measures.* Table 1 presents the average values of the performance variables recorded for all three conditions. Mean cross-track error was smallest when ECDIS was used with the radar overlay, followed by ECDIS with no overlay and then by paper chart. The three conditions were significantly different from each other when evaluated by the Scheffé multiple range test, which is a very conservative test of the differences among individual scores when an analysis of variance shows that the overall differences among conditions is greater than could have occurred by chance. Cross-track error was significantly smaller under high visibility (M = 0·3478)

Table 2. TLX workload ratings for each exercise type and each visibility level.

TLX rating scale	Paper chart	ECDIS no overlay	ECDIS with overlay
Good visibility			
Mental Demand	2·66	0·50	0·83
Physical Demand	3·16	0·50	1·00
Time Demand	3·33	0·50	0·66
Overall Effort	3·16	0·83	0·50
Frustration	2·66	0·33	1·50
Own Performance	1·00	4·00	4·00
Poor visibility			
Mental Demand	4·66	2·83	3·50
Physical Demand	4·83	2·66	2·82
Time Demand	4·83	2·83	2·83
Overall Effort	4·83	3·00	2·86
Frustration	4·33	2·66	3·50
Own Performance	0·16	3·00	2·83

than low visibility (M = 0·8793). The number of helm orders was greatest for the ECDIS no overlay condition, followed by the ECDIS with overlay and then the paper chart condition: the significant difference was between the paper chart and the ECDIS condition (Table 1). Visibility level had no significant effect. The differences in closest point of approach between the paper chart group and the two ECDIS groups were significant (Scheffé test). The large and significant difference between percentages of radar monitor use was due entirely to the difference between the paper chart condition and the two ECDIS conditions (Scheffé test). Self-reported navigation workload was significantly different between the paper chart condition and the two ECDIS conditions (Scheffé test). All of the self-rating variables except collision avoidance workload (not shown in Table 1) showed significant differences among all conditions.

Table 2 shows the average TLX ratings given for each type of effort and for self-rated overall performance, for the three exercise types under good and poor visibility. The highest overall demand occurred in the paper chart condition under poor visibility. Both ECDIS conditions produced lower workload demand averages, and better self-rated performance, under good and poor visibility. The lowest overall demand occurred in the ECDIS condition without overlay under good visibility, and self-rated performance was highest under the two ECDIS conditions under good visibility.

2.4. *Discussion.* This experiment tested the effectiveness of an ECDIS system by comparison to conventional paper chart and radar during high traffic, harbour entrance navigation. The ECDIS system with or without the radar overlay was better than paper chart navigation on both objective and subjective performance measures. ECDIS with radar overlay was better than ECDIS with a separate radar display in reducing cross-track errors, optimizing closest point of approach and reducing workload. This experiment, taken together with the results of the Smith *et al.* (1994), supports the conclusion that ECDIS is better than paper chart navigation in piloting situations. The improvement in cross-track distance error and closest point of approach should decrease the chances of collision in areas where traffic routes are well defined.

The study mariners stayed very close to the optimum CPA while using ECDIS as a navigation device. Using ECDIS they may have been better aware of their own vessel in relation to specific targets. The fact that the number of helm orders increased with ECDIS use strengthens the idea that mariners are more aware of their position relative to the planned route, and so make more helm corrections to regain the planned route.

ECDIS decreased self-rated mariner workload. It gives a real-time display of chart position, eliminating the time-consuming tasks of taking bearings and plotting position. Mariners spent considerably more time monitoring the radar during the paper chart condition than during either ECDIS condition. But it was interesting that there were no significant differences in frequency of radar use between ECDIS with separate radar and ECDIS with a radar overlay. We have no explanation for this.

3. EXPERIMENT 2: ECDIS WITH SEPARATE, OVERLAY AND CHOICE RADAR DISPLAYS AT THREE LEVELS OF NAVIGATION DIFFICULTY.

3.1. *Introduction.* Smith's (1994) data and Experiment 1 show that ECDIS improves simulated navigation efficiency by comparison with paper chart navigation. Experiment 2 tested the efficiency of three ECDIS – radar combinations: ECDIS with radar always overlaid, ECDIS with radar always separate, and ECDIS with radar overlay optional. Nine exercises included simple and complex charts and high and low traffic. We set visibility to daylight fog (0·4 nm) and eliminated radio traffic in order to force the mariners to depend on the electronic navigation information.

3.2. *Method.*

3.2.1. *Simulated ship.* The ship model was the tanker "Nordtramp," a ProdC ship, in ballast, with a draft of 8·3 metres and a displacement of 40 000 tons.

3.2.2. *Exercises.* Six of the nine exercises were in confined water with complex charts (high chart complexity, CH) and three exercises were in open water with simple charts (low chart complexity, ch). Six exercises had between five and nine ships tracked on radar (high traffic density, T) and three exercises had two or three traffic ships (low traffic density, t). The exercises were divided into three groups of three each as shown in Table 3. Group T/CH had high traffic density (T) and high chart complexity (CH), group T/ch had high traffic density (T) and low chart complexity (ch), and group t/CH had low traffic density (f) and high chart complexity (CH).

The pre-plotted course for each exercise was projected on the ECPINS display. The instruction was to follow the course as closely as possible with due regard to navigation hazards including approaching, crossing and passing traffic. The mariner could vary the course and speed of the vessel at any time.

3.2.3. *ECDIS display conditions.* The three display conditions were separate (S), overlay (O) and choice (X), referring to how the radar display was used. In the separate condition, the radar and the electronic chart display were on separate but adjacent screens as shown in Figure 1 and the radar could not be superimposed on the ECDIS. In the overlay condition, the radar information was displayed as a transparent overlay on the electronic chart but was not available on a separate display. In the choice condition, the mariner could turn the radar overlay off or on at will, and could use either the electronic chart display or the radar display at any time.

Table 3. Description of the nine exercises in study 2.

Exercise	Traffic targets	Location and direction of movement
Heavy traffic density, high chart complexity (T/CH)		
1	9	Halifax approaches inbound
4	4	Halifax harbor outbound from Bedford Basin
7	5	St. Lawrence up bound from Toussaint Il.
Heavy traffic density, low chart complexity (T/ch)		
3	6	Come-by-chance outbound
6	5	Come-by-chance inbound
9	7	Halifax outbound from south of Mars Rock buoy
Low traffic density, high chart complexity (t/CH)		
2	3	Halifax inbound to Bedford Basin
5	2	St. Lawrence above Brockville Narrows, down bound
8	2	St. Lawrence below Brockville Narrows, up bound

3.2.4. *Mariners.* Six licensed mariners, all men with from eleven to 40 years of experience, participated in Experiment 2. Four had been seagoing during the year preceding the study: one in the Arctic trade, one in coastal trade, one on offshore supply, and one on a foreign-going research vessel. All were instructors at the Centre for Marine Simulation. Only one had previous practical experience with electronic chart systems, and he had not used a radar overlay. None participated in Experiment 1.

Each mariner was given a preliminary session consisting of a tour of the wheelhouse and its facilities as arranged for this experiment plus a 45-minute training exercise (entrance to St. John's Harbour) that was not used during the experiment. Mariners were briefed in advance about the purpose of the study and were encouraged to contribute written comments following each run.

3.2.5. *Experimental design.* Following the training session, each mariner was tested on the nine exercises. One exercise of each of the three types (T/CH, t/CH, T/ch) was randomly assigned to the choice condition (X), one to the separate condition (S), and one to the overlay condition (O) for each mariner. Each mariner completed the exercises in an independently randomized order. Each exercise was completed within a two-hour time period which included a briefing on the exercise condition to be run (choice, overlay or separate), the exercise itself, and the post-exercise debriefing and self-rating. Mariners were scheduled for at most two sessions per day; one in the morning and one in the afternoon.

Four exercises out of the total of 54 (six exercises times nine mariners) had to be repeated (exercises 3 and 2 for mariner 2, and exercises 6 and 2 for mariner 3) because technical problems with the ECPINS system invalidated the data collected during the test run. The exercises were repeated after all of the other scheduled exercises for that mariner had been completed. The completed exercises lasted an average of 42 minutes (range 36 to 52 minutes).

3.2.6. *Data collection.* The simulation computer produced a control chart with course lines for all of the ships in the exercise. It printed out the latitude, longitude, heading, course made good and speed of the exercise ship (ownship) at ten-second intervals. The numerical data were scanned into computer files together with the waypoints for the start, course changes and finish of each exercise to provide the geographical and movement database for each exercise. Latitude distances are constant (1 nm per minute of latitude), but longitude distances varied from 0·67 nm per minute to 0·71 nm per minute over the latitude range of the exercises (44 to 47 deg N). We used an average longitude value of 0·7 nm per minute in distance calculations.

The cross-track deviation was found by calculating the distance between the ships' track and the nearest point on the planned track at each ten-second interval. A computer program calculated the average value and the rms value over the entire exercise. One data point was generated for each measure for each exercise and each mariner.

The average and rms values of the closest point of approach (CPA) of the ownship to the channel buoys and other hazards to navigation were calculated for each exercise and each mariner. One data point was generated for each measure for each exercise and each mariner. The CPA and rms CPA measures depend on the location of the particular buoys and hazards in each exercise. This dependence was eliminated by normalizing these values within exercises and across conditions in subsequent analyses.

Speed over ground was recorded at ten-second intervals. One value for average speed and one for rms speed was calculated for each exercise and each mariner.

An assistant in the simulator control room watched consoles that repeated the radar and ECPINS displays and listened to an intercom channel that broadcast the helm and engine orders. He recorded the time and type of each range change in either the radar or the ECPINS display and all changes from superimposed to separate radar displays in the choice (X) display condition. He also recorded all the helm and engine orders. The total of all of the display console changes and all of the engine and rudder orders was recorded for each exercise and each mariner.

After each exercise each mariner completed a self-rating form based on the NASA TLX workload scale (Hart & Staveland, 1988). They rated each exercise for mental demand, physical demand and time pressure. Then they evaluated their own performance, their overall level of effort, and their experienced frustration by checking off positions on a ten-position scale anchored at Low and High, which were converted into numbers from one to ten. A single scale measuring demand was created by averaging the ratings from mental demand, physical demand, time pressure and overall effort. Performance and frustration ratings were recorded separately. Mariners were also asked to write comments on their self-rating forms.

3.3. *Results.*

3.3.1. *Performance measures.* Comparisons across each exercise for each mariner (54 data points) showed that average and rms cross-track error were highly correlated ($r^2 = 0{\cdot}999$) as were average and rms closest point of approach ($r^2 = 0{\cdot}947$). However average speed and rms speed were uncorrelated ($r^2 = 0{\cdot}032$). The average cross-track error, average CPA, average speed and rms speed for the three display conditions and the three exercise types are presented in Table 4.

Analysis of variance showed that average cross-track error did not differ significantly across display conditions (Separate, Overlay or Choice), but did vary significantly across exercise types, and the interaction between display condition and exercise type was significant. This means that while the cross-track error was larger in the T/ch exercise type than in the other types, the difference among exercise types was even greater under the choice display condition (X). The interaction is illustrated in Figure 3.

Table 4. Average performance measures for display conditions and exercise type.

	Display conditions			Exercise type		
Measure	Choice	Overlay	Separate	T/CH	T/ch	t/CH
CTX (0·01 nm)	4·12	2·49	2·58	1·95	5·65	1·59
CPA (nm)	2·76	1·19	1·81	0·11	5·57	0·08
Speed (kts)	9·35	9·03	9·07	7·75	10·69	9·01
rms speed (kts)	0·88	1·04	1·37	0·85	1·36	1·08

Note: CTX = cross-track error, CPA = closest point of approach.

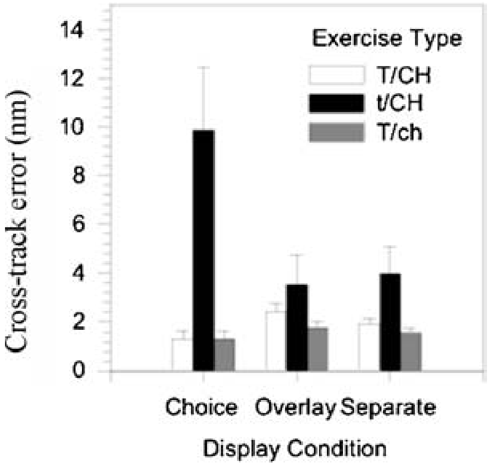

Figure 3. Average cross-track error for each display condition and each exercise type.

Average speed differed significantly across exercise types, with T/ch being significantly faster than the other two types. The rms speed also differed significantly across exercise types, and although average and rms speed were uncorrelated across mariners and exercises, T/ch also produced the largest rms speed.

Average CPA was significantly larger in the T/ch exercise condition. But CPA values are not comparable across exercises until they are normalized: an analysis we describe below.

The general linear analysis of variance model used (Littell, Freund & Spector, 1991) is influenced by the differences in the number of times each exercise was assigned to each display condition. The effect of these differences is corrected by the least-squares averages presented in Tables 4 and 5. In order to improve the sensitivity of our analysis of display condition differences, we also normalized all of the performance scores within each exercise across display conditions, thus eliminating any differences that depended on the exercise itself in favour of differences that depended only on the display condition under which the exercise was completed and the mariner who completed the exercise in that condition. We compared these normalized performance scores across display conditions with mariners as a random effect and order of presentation as a covariate. The only difference between our results using the normalized analysis and the results of the un-normalized, two-factor analysis of

Table 5. Self-rating and activity measures for display and exercise conditions.

	Display conditions			Exercise type		
Measure	Choice	Overlay	Separate	T/CH	T/ch	t/CH
Self-rating						
Demand	4·45	4·58	4·68	4·25	3·67	5·80
Frustration	3·68	4·65	3·87	3·52	3·44	5·25
Performance	7·89	6·43	6·58	7·39	7·30	6·16
Activity						
ECDIS changes	10·7	23·0	10·1	12·9	16·4	14·6
Helm/engine orders	25·2	21·8	24·8	25·3	20·2	26·3

variance reported above was that the normalized rms speed was significantly higher in the separate (S) than in the choice (X) condition.

3.3.2. *Activity*. The average number of ECDIS system changes was significantly greater in the overlay condition than in the other two other conditions (Table 5). The number of helm and engine orders did not differ significantly across display conditions or exercise types.

3.3.3. *Self-ratings*. Averages of three self-rating measures: demand, performance and frustration, across display conditions and exercise types are presented in Table 5. The three measures were analyzed together using a multivariate analysis of variance design, which demonstrated significant differences across exercise type, marginally significant differences across display conditions and no significant interaction. Performance under the choice display condition was self-rated as significantly better than under the separate or overlay conditions. For the t/CH exercise type, demand and frustration were rated significantly higher and performance was rated significantly lower than the other two types. Correlated across the 54 data points, performance was negatively correlated with demand ($r=-40$) and frustration ($r=-0{\cdot}24$), and frustration was positively correlated with demand ($r=0{\cdot}52$).

3.3.4. *Written comments*. Several mariners wrote that they preferred the separate radar and electronic charts, because, for example, "sailing with radar overlay through remarks and warnings printed on the chart was annoying and made it more frustrating." Another mariner said "using e-chart without radar overlaid gives a better display, closer to using paper charts." But a mariner commenting on a separate display said that "radar overlay would have reduced workload in this case as much attention had to be given to vessel being set down to port by winds." These comments show the importance of finding the right level of display complexity. Too much clutter can make a display unusable, but increasing complexity by adding radar information to a chart display was thought to be useful if it allowed the mariner to deal with all the relevant navigation information on the same spatial layout.

Written comments and the activity records confirm that three mariners left the radar overlay on all the time during the choice display condition. These same mariners could and did also use the adjacent radar display. Two mariners kept the overlay off during all of the choice display exercises, and one used the overlay on some choice exercises but not on others.

4. DISCUSSION.

Study 1 confirms the results of Smith *et al.* (1994) that simulated ECDIS navigation is better than navigation with paper charts and radar.

Experiment 1 also found better ECDIS performance with a radar overlay. Experiment 2 found no significant or important difference between ECDIS performance with a radar overlay and performance with adjacent separate displays, but experiment 2 was less sensitive to the separate – overlay difference because instead of comparing the ECDIS conditions on a single exercise, it used nine different exercises, and random differences among exercises may have obscured the relatively small differences between separate and overlay conditions found in Study 1.

In the t/CH exercise type of Study 2 (light traffic on complex charts), there was greater cross-track error under the choice display condition. This exercise type was self-rated as the most demanding, most frustrating, and worst performing. It could be that the choice option increased the decision workload for this exercise type so much that it produced both a greater required effort and less attention to the pre-plotted course than was enforced by the fixed conditions of either the separate radar or radar overlay display.

Experiment 1 mariners self-rated the navigation workload as slightly but not significantly lower in the overlay than in the separate condition and both electronic chart condition workload ratings were significantly lower than the paper chart workload rating. Experiment 2 mariners reported no difference in self-rated task demand among the three display conditions. However, except for the t/CH condition, these mariners rated their own performance as significantly better under the choice condition even though their objective performance was not significantly better under this condition. They also made significantly more display changes in the overlay condition.

The objective performance measures and the self-ratings show that the T/ch exercises (heavy traffic on simple charts) were the least demanding. They had significantly larger cross-track errors, smaller closest points of approach, and higher speeds than the other two exercise types, and they were also rated lowest (but not significantly so) on demand and frustration. T/ch exercises were high on self-rated performance (7·30 versus 7·39 for T/CH). The higher speed and larger cross-track error under T/ch showed that mariners tended to "cut corners" and go faster when the situation was objectively simpler, the perceived workload was lower, and self-rated performance was higher.

The significant performance and self-rating differences found as a function of exercise type point up the increase in attention and vigilance required when manoeuvring in narrow channels with fixed and transient hazards that generate complex charts (e.g. the St. Lawrence Seaway and Halifax Harbour exercises in T/CH and t/CH) as opposed to making a harbour approach or departure in more open waters with simpler charts (e.g. the Come-by-Chance and Halifax approaches exercises in T/ch). Open approaches are faster, require less attention to distance from navigation hazards, and do not demand as diligent a maintenance of the planned course.

The t/CH condition (light radar traffic in a complex chart environment) was self-rated as the most demanding and frustrating condition with the lowest performance. A possible explanation for this is that mariners feel anxious when extreme restricted visibility (the operating condition for all of these exercises) is combined with few radar targets in a complicated navigation environment. The continued presence of radar targets in the T/CH and T/ch conditions may act as a reassurance that another sensor is substituting for missing vision, and the fewer radar targets of t/CH probably left the mariners uncertain, frustrated and anxious about whether there were targets that were not identified by the radar.

Experiment 2 showed that across a wide range of piloting situations the ECDIS overlay display did not offer significant advantages over separate ECDIS and radar displays. Since the mariners preferred the choice condition, since Experiment 1 showed measurable advantages of the overlay display, and since mariners described both advantages and disadvantages of the overlay display, our studies suggest that both options should be available in ECDIS systems. It is also clear from mariners' comments that the design and the resolution of the electronic chart component of ECDIS displays are influential in determining the relative advantage of overlay versus separate radar displays.

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