Mariner's Use of Automated Navigation Systems

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As part of a recent United States Coast Guard evaluation of Electronic Chart Display and Information Systems (ECDIS), an experiment was conducted to examine the mariner's use of such systems in the controlled setting of a shiphandling simulator. Two ECDIS systems were interfaced with the simulator at MarineSafety International/Computer Aided Operations Research Facility in Kings Point, New York. On the simulator, experienced mariners each made multiple port arrivals and departures as a lone watchstander on the bridge: navigating a planned route, responding to the traffic of a busy harbor, and managing the preparations for the arrival or departure. During transits under baseline conditions, the conventional methods of navigation were available: plotting on the paper chart, radar/automated radar plotting aid (ARPA), and visual piloting. During the test conditions, one of the ECDIS systems was added to the bridge, with or without automatic updating of own ship's position, and with or without the integration of radar features. ECDIS increased safety, both by decreasing the cross-track distance of own ship from the planned route and by increasing the proportion of time that the mariner spent on look out and collision avoidance. ECDIS significantly decreased the mariner workload for navigation when automatic updating of position was available. The mariners expressed a preference for a relatively simple chart display for route monitoring, with the immediate availability of a larger set of chart information. No measurable effects of radar features on ECDIS were found, although the mariners believed that this would be a valuable addition.

In the past few years, the Electronic Chart Display and Information System (ECDIS) has emerged as a powerful addition to the modern bridge, offering the possibility of effecting major changes in the navigation process and improving the safety and efficiency of maritime operations. By superimposing an electronic chart, ship's position, and radar video on one display, ECDIS has the potential to improve the accuracy of navigation, increase awareness of dangerous conditions, and reduce the mariner's workload. This report describes an examination of these potential effects using the special capabilities of a full-mission ship's bridge simulator. As of this writing, a larger report is being revised (*1*).

The International Maritime Organization (IMO) is in the process of establishing a Performance Standard (PS) for ECDIS (*2,3*). The United States Coast Guard's primary purpose in sponsoring this simulator evaluation was to contribute to a 1993 report to IMO and to the U.S. position on PSs.

The objectives of the experiment were to examine several broad issues underlying the IMO PS, those for which the simulator was especially appropriate as a tool. The simulator makes it possible to examine the dynamic situation of route monitoring with a control that would be difficult or impossible at sea. Four issues, used as organizing concepts to plan the evaluation and to select the performance measures, follow.

- *Contribution of ECDIS to the Safety of Navigation.* ECDIS should enhance safety by affording the mariner a more timely and accurate knowledge of the ship's position and its relation to a planned route and to potential hazards than is possible with conventional bridge procedures and a paper chart.
- *Reduction of Navigational Workload by ECDIS.* ECDIS can integrate information from a number of sensors and can automate the primary, and generally time-consuming, navigation function of position fixing. This automation should reduce the mariner's workload. The experiment was designed to examine ECDIS's potential to reduce workload during relatively demanding transit conditions, assuming that a reduction would mean an increase in the mariner's ability to control the ship and, therefore, greater safety (*4,5*). This experiment did not consider low workload conditions and the possibility that ECDIS might reduce workload to the point of boredom and inattention.
- *Chart Features and Navigational Functions on ECDIS.* At this early point in the development of ECDIS technology, there is no industry consensus about which electronic chart features and which computer-based navigation functions will be needed by mariners. The simulator experiment allows observation of the mariners' actual selections of features and functions from the two sample systems under a variety of conditions.
- *Integration of Radar Features on ECDIS.* A highly integrated navigational system would combine two plan-view displays—the electronic navigation chart and radar/automated radar plotting aid (ARPA)—on one system. This integration would have positive effects on safety and workload.

METHODOLOGY

Shiphandling Simulator

The experiment was run at MarineSafety International/Computer Aided Operations Research Facility (MSI/CAORF) in Kings Point, New York. The simulator has a realistically equipped full-mission bridge and a considerable history of human factors and ship control research. MSI/CAORF's capabilities include sophisticated ship models, harbor data bases, observational and data collection methods, and an engineering and research staff able to adapt these capabilities to new operational problems. For this study, two commercial ECDIS systems were integrated with the simulator and were available to the watchstander as required by the experimental plan.

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Commercial ECDIS Systems

The two systems selected were Offshore Systems Limited's (OSL) Precision Integrated Navigation System and Robertson Marine Systems Incorporated's Disc Navigation System.

The two systems used for this study differed from each other in a number of ways, most of which are summarized in Table 1. The differences most prominent in the experiment were display configurations, chart presentations, and radar integration. The OSL system had a single display screen that could be configured by the user to present several graphic and alphanumeric windows; the Robertson system had a display screen dedicated to the chart presentation and a separate liquid crystal display (LCD) to present alphanumeric information. The OSL had relatively simple stylized charts that could be viewed in separate windows at different scales; the Robertson had a more complex paper chart–like presentation on the single dedicated screen. The OSL presented complete radar video as an overlay to the chart and presented target range and bearing information in an alphanumeric window; the Robertson system presented only the targets acquired by the separate ARPA on the bridge and their vectors on the chart display and presented range, bearing, closest point of approach (CPA), and time to CPA on the separate alphanumeric LCD. The single screen, stylized chart, and radar video of the OSL system are illustrated in Figure 1. This figure is adapted from an OSL photo. The actual view shown did not appear in the experiment. Note that both systems are prototypes and not representative of the systems now available from the manufacturers.

Primary Experimental Manipulation

The primary experimental manipulation was in the methods of navigation available to the watchstander in a given scenario. In all scenarios the conventional choices for navigation were available: position fixing on the paper chart, radar/ARPA, and visual piloting. In two baseline scenarios, only these conventional methods were available. In the remaining scenarios, one of the commercial systems was added to the bridge in one of three modes:

- ECDIS with automatic position updating and radar features (positioning was to an accuracy of 5 m or better. Mariners were told that differential Global Positioning System was in use.),
- ECDIS with automatic position updating and no radar features, and
- ECDIS without automatic position updating (and with instructions to update manually).

Content of Experimental Scenarios

All the scenarios were transits through the Coastal and Harbor/Harbor Approach phases of navigation (*6*) in New York or San Francisco. As is frequently done in simulator research, the workload was increased beyond realistic levels on the assumption that a high but sustainable workload increases the sensitivity of the mariner to the experimental manipulations and, therefore, increases the sensitivity of the performance measures. To ensure a high workload, each participating mariner made port arrivals and departures as the one officer alone on the bridge. In addition, no pilot came on board when the ship passed the pilot station. To keep the workload sustainable, the equipment consoles were arranged for "centralized control" to minimize movement around the bridge. This arrangement is illustrated in Figure 2. Also indicated in the figure are video cameras (numbered as 1, etc.) and microphones (labeled as M1, etc.). A qualified helmsman was present in all scenarios.

As the single officer on the bridge, the subject mariner was responsible for navigation, collision avoidance, and bridge management activities. The scenarios were designed by MSI/CAORF mariners to be approximately equal to each other in their density of events representing each of these three categories of activities. The experimental approach requires any differences in observed performance among scenarios to be attributable to the primary experimental manipulation and not to differences in scenario background content. This scenario design is an example of the type of control that is possible on the simulator but not at sea.

Participating Mariners

Four masters and two mates each spent a week at MSI/CAORF. They all had extensive resumes, and simulator or computer experience, or both. The intention was to select mariners who could be expected to adapt to the new technology and provide good performance and meaningful reactions in a relatively short time. During

TABLE 1 Major Differences between Two Commercial Systems

	Offshore Systems Limited PINS -VME	Robertson Marine Disc Navigation
Computer	68030 @ 25 MHz	80386 @ 33 MHz
Screen	19 inch, 1024 x 788 pixels	25 inch, 1080 x 1040 pixels
Displays	configurable into windows, chart or text	chart on screen, text on LCD
Electronic chart	landmass, contours, channels, aids	complex, "chart-like"
Interface	touch screen and trackball	keyboard and trackball
Radar features	video overlay, some ARPA info	ARPA targets, some ARPA info
Own ship symbol	scaled outline	outline not to scale

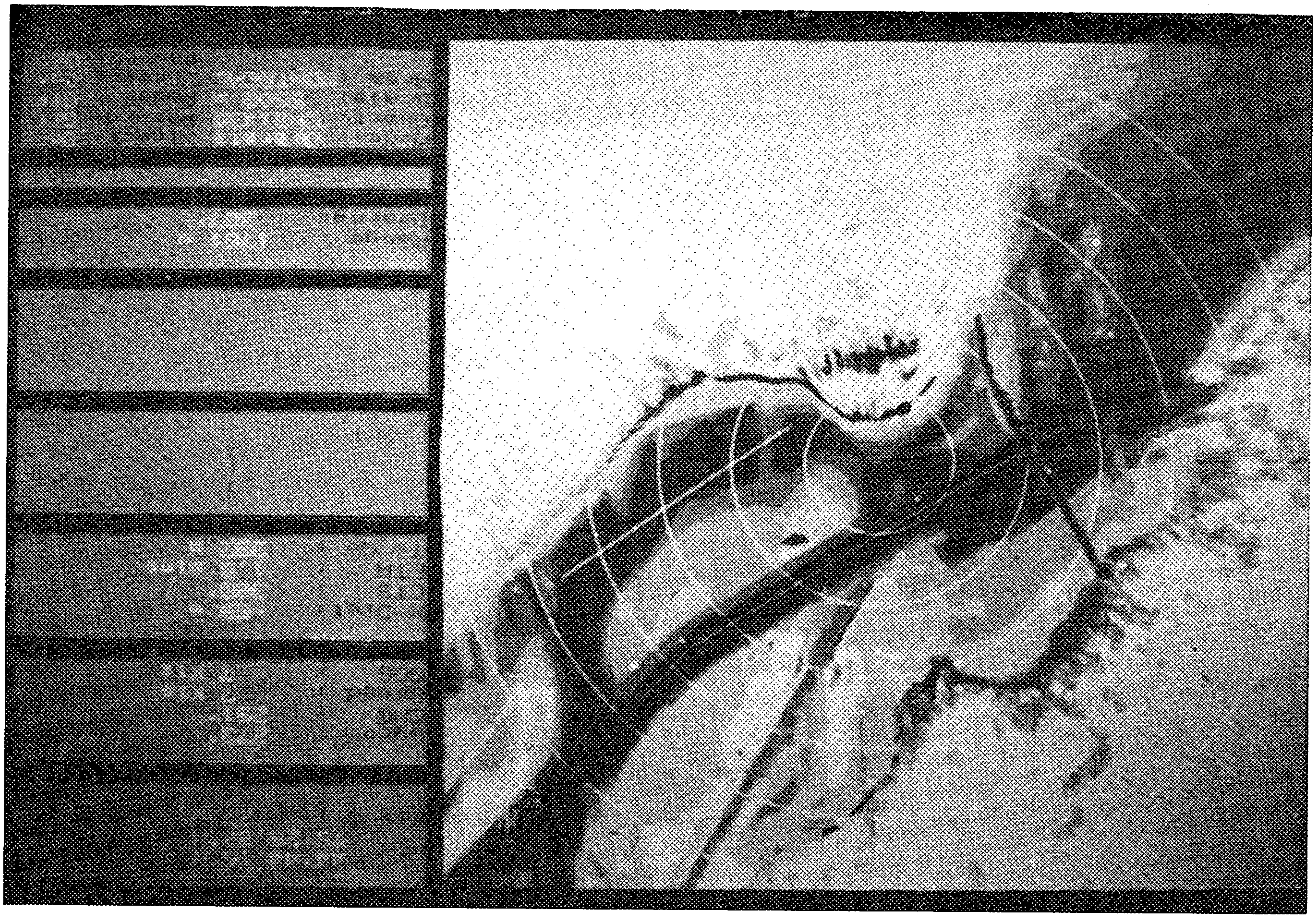

FIGURE 1 Offshore Systems Limited's PINS VME display screen.

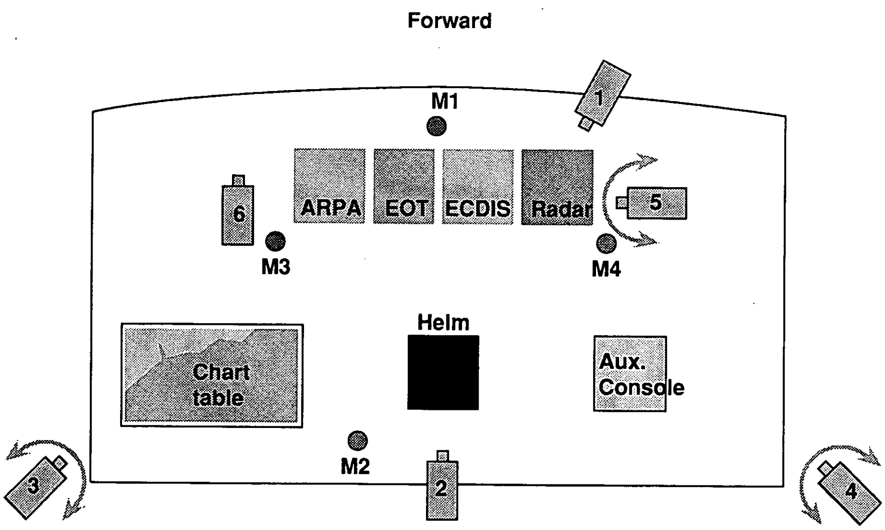

FIGURE 2 Shiphandling simulator's bridge arranged for centralized control.

each week, the mariner received brief formal training on each of the two ECDIS systems and ran through all the experimental scenarios in a different counter-balanced order.

Performance Measures and Data Analysis

A variety of ship control and human factors data was collected and analyzed. Those that proved the most productive in investigating each experimental objective are discussed in the section that follows. All measures based on mariners' reports were subjected to analyses of variance. Specific hypotheses were tested using single degree of freedom contrasts. Cross-track distance data were compared between scenarios by using t-tests. All effects discussed here were statistically significant ($p < 0.05$).

RESULTS

Primary Method of Navigation

Each mariner reported the primary method of navigation used for each identifiable segment of the transit after each scenario. The assumption was that the selection of method would reflect the mariner's view of the best combination of safety and workload for the conditions. The results are summarized in Table 2 for the Harbor/Harbor Approach phase of navigation, with its relatively high risk and high workload. With this high workload, plotting on the paper chart for position fixing was rarely used. Instead, in conventional bridge conditions, without ECDIS available, visual piloting and radar/ARPA were the methods reported. When ECDIS with automatic updating of position was available, it was reported to be the predominant method of navigation; however, without automatic updating of position and with the requirement for manual updates, ECDIS lost its preferred status.

Safety Measured by Accuracy of Trackkeeping

Safety of navigation has been measured in simulator research (*7,8*) and in sea trials (*9*) by cross-track distance from a planned trackline. Although no special instructions to keep the ship close to the line were given in this experiment, it was hypothesized that ECDIS would increase safety by reducing cross-track distance. At some critical points, such as approaches to bridges or to major turns, the availability of ECDIS with automatic positioning resulted in substantial reductions in mean cross-track distances. A notable example is illustrated in Figure 3. These figures are plots of the simulator's harbor data base with the actual tracks traced by own ship's center of gravity for each of the mariners superimposed on them. This treatment provides a composite track plot. The upper half of Figure 3 represents performance using ECDIS with automatic updating of position (Scenario 5); the lower half represents performance with the baseline conventional bridge (Scenario 9). Note that the tracks in the upper half, using ECDIS, are more tightly clustered than are the tracks in the lower half of the figure, using conventional methods. This difference is particularly obvious as the tracks pass under the Golden Gate Bridge and as they round the turns to the southeast of Alcatraz Island.

Summary data from the track plots in Figure 3 are presented in the top half of Table 3. The use of ECDIS decreased the mean cross-track distance to approximately one-third of what it was with conventional methods. The bottom half of the table shows the effect of the failure of automatic updating of position and the necessity of manually updating position: cross-track distance is increased and ECDIS loses its advantage in track-keeping accuracy.

Workload Measured by Time Spent and by Mariner's Ratings

Workload was measured by asking the mariner after each scenario what proportion of the time was spent on navigation, collision avoidance, and bridge management. The mariner was also asked to rate workload on each of these three categories of tasks separately, using the National Aeronautics and Space Administration's Task Load Index (*10,11*). This is a frequently used rating scale that yields a score from zero to 100 representing the perceived demand of a task. The hypothesis was that ECDIS would reduce the workload of navigation.

A summary of the findings are presented in Table 4. The availability of ECDIS with auto positioning decreased the mean workload for navigation and the mean reported proportion of time spent on navigation below that measured for conventional bridge procedures. The necessity of manually updating position increased the navigation workload and the proportion of time spent in navigation. Workload was increased over that for the conventional bridge and ECDIS with automatic positioning.

TABLE 2 Reported Primary Method of Navigation for Bridge Conditions (in Harbor/Harbor Approach)

	Proportion of Total Transit Segments for Which Method was Reported as Primary for Each Bridge Condition*				
Bridge Conditions	Plotting/ Paper Chart	Radar/ ARPA	Visual Piloting	ECDIS	Total Transit Segments
Conventional bridge	0.03	0.25	0.73	NA	40
ECDIS auto positioning	**0.00**	**0.15**	**0.18**	**0.67**	**79**
ECDIS no auto positioning	0.05	0.61	0.28	0.05	18

* Proportions do not sum to one due to rounding error.

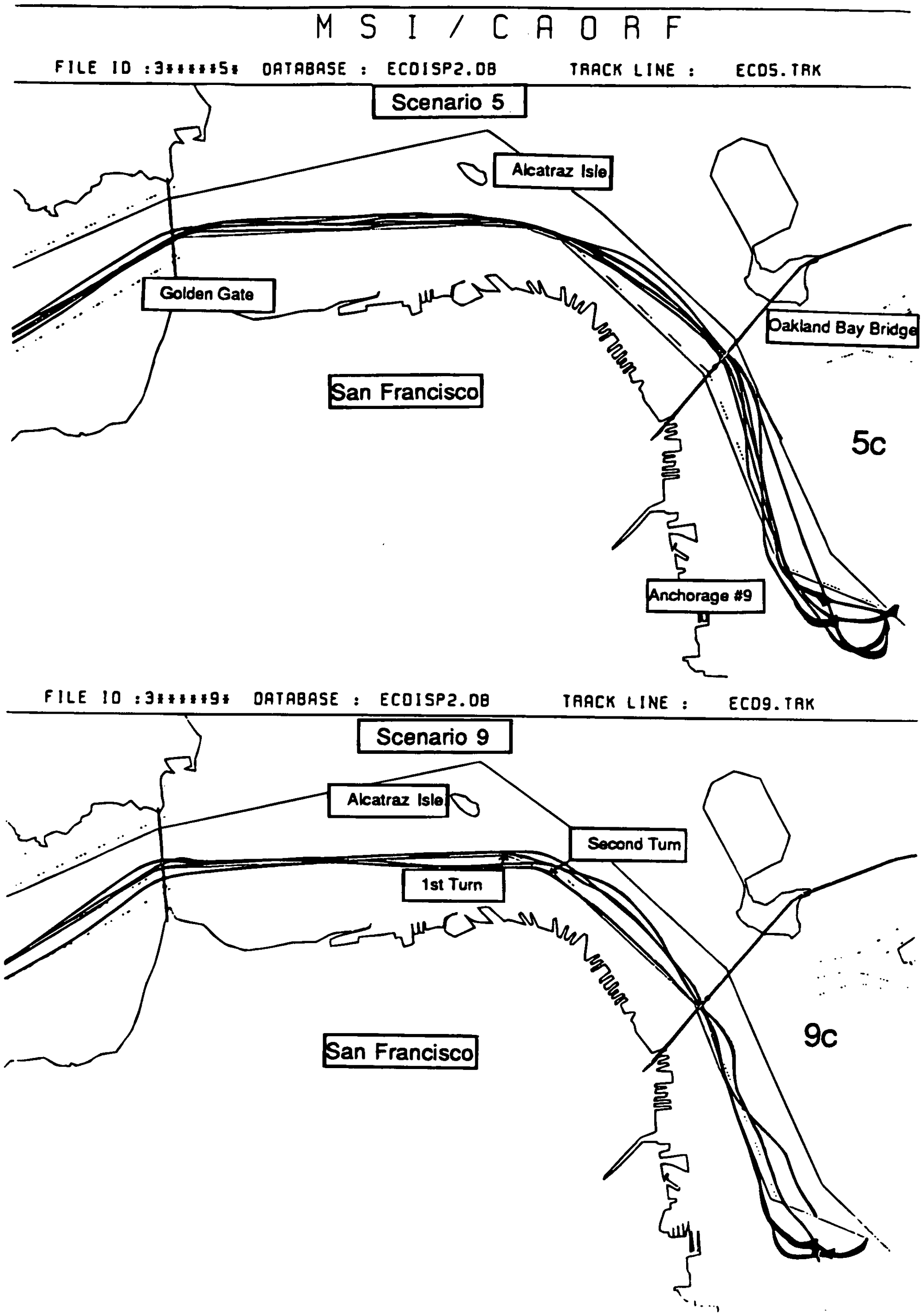

FIGURE 3 Track plots illustrating effect of ECDIS on track-keeping accuracy.

Time Spent on Navigation Versus Time Spent on Collision Avoidance

Table 4 also shows a reciprocity between navigation and collision avoidance. With the decrease in proportion of time spent on navigation using ECDIS with automatic positioning, there was a corresponding increase in the proportion of time spent on look out and on collision avoidance. The mariners indicated, both in spontaneous comments and in formal questioning, that in their view this shift represented an increase in safety. Navigation workload and the proportion of time spent on navigation were positively and significantly correlated with each other. Navigation workload and the proportion of time spent on collision avoidance were negatively and significantly correlated. ECDIS with no automatic

TABLE 3 Mean Cross-Track Distance at Selected Points in Transit for Bridge Conditions

Location	Mean Cross-track Distance (Meters*)		Probability
San Francisco	**ECDIS auto positn (Scenario 5)**	Convention bridge (Scenario 9)	
Golden Gate Bridg	**32**	117	0.05
Alcatraz 1st turn	**18**	100	0.09
Alcatraz 2nd turn	**29**	98	0.06
New York	**ECDIS auto positn (Scenario 1)**	ECDIS no auto (Scenario 3)	
Ambrose 1st turn	**41**	128	0.09
Ambrose 2nd turn	**59**	219	0.006
Verrazano Bridge	**18**	148	0.18

* 1 meter = 3.3 feet.

TABLE 4 Mean Navigation Workload and Reported Distribution of Mariner's Time for Bridge Conditions

		Proportion of Time on Task*		
Bridge Conditions	Navigation Workload	**Navigation**	Collision Avoidance	Bridge Management
Conventional bridge	52	0.46	0.33	0.21
ECDIS auto positioning	**36**	**0.37**	**0.41**	**0.21**
ECDIS no auto positioning	63	0.49	0.34	0.17

* Proportions do not sum to one due to rounding error.

updating of position again showed the most unfavorable results on all measures.

Feature and Function Use

The use of chart features and navigation functions on ECDIS was examined in a number of ways. Experimental observers watched on video monitors and tallied features and functions enabled on the ECDIS systems by the mariner, questionnaires after each scenario contained checklists for reports of what had been used and what was wanted, and a final questionnaire contained a checklist asking the mariner to recommend what should be available.

The results obtained with this final measure are summarized in Table 5. Only a few features were recommended by most mariners as "display always." The asterisks mark items selected as one of the three most important by most mariners. A much larger set was recommended by most to be available "at user's option."

Corresponding recommendations on the ECDIS-based navigation functions are summarized in Table 6. The mariners' use of such functions and their comments are further discussed in the larger report on this study (*1*).

Results on Use of Radar Overlay

No significant differences were found, either between ECDIS with and without radar features or between ECDIS with the complete radar video and ECDIS with targets only. Mariners believed that radar integration should be a valuable addition to ECDIS but that the examples that they saw were not satisfactory. The principal drawbacks mentioned were an overly cluttered screen and incomplete ARPA information that did not allow them to depend on that single system for both navigation and collision avoidance.

DISCUSSION AND CONCLUSIONS

Contribution to Safety of Navigation

The use of ECDIS during route monitoring has the potential to provide equivalent or greater safety than that provided by the paper chart and conventional procedures. Two mechanisms to provide this increased safety were identified: (a) decreased cross-track distance from the planned route and (b) an increased proportion of time spent

TABLE 5 Mariners' Recommendations of Charted Features

Charted Features	Display Always	At Users Option	Display Never
	(number of mariners of six)		
coastline/landmass	**6**	0	0
indication fixed aids to navigation	**6***	0	0
indication floating aids to navigation	**6***	0	0
federal channel lines	**4**	2	0
navigation lanes/fairways	**4***	2	0
pilot areas	**4**	2	0
indication of isolated dangers	**4**	2	0
spot soundings	0	**6**	0
names-landmasses, islands, etc.	1	**5**	0
light / sound characteristics	1	**5**	0
cable/pipeline areas	1	**5**	0
details of isolated dangers	1	**5**	0
lat/long grid lines	1	**5**	0
bottom characteristics	0	**5**	1
details of cautionary notes	0	**5**	1
ENC edition date	0	**5**	0
anchorages	2	**4**	0
bottom contours	2	**4**	0
compass rose	2	**4**	0
physical classification (can/nun)	1	**4**	1
physical description (e.g. white tower)	1	**4**	1
magnetic variation	0	**4**	2
geodetic datum	0	**4**	2
prohibited and restricted areas	3	3	0
indication of cautionary notes	3	3	0
indication of units of depths/ heights	3	3	0
radio characteristics (RACON)	2	3	1
coastal topography	1	3	2
land feature/characteristics	1	3	2
visual and radar conspicuous features	2	2	2

* also rated as one of three most important features by majority of mariners

on look out and collision avoidance. These findings, that ECDIS supports more accurate ship control and allows more time to be spent on non-navigation tasks, support simulator evaluations of the use of automation for one-man bridge operations (*12*).

Effect on Workload

The use of ECDIS during route monitoring has the potential to reduce the navigation workload compared with using the paper chart and radar and visual piloting techniques. The major factor in the reduction in workload is the automation of position fixing that allows navigation at a glance. Automatic updating of position and a generally high level of display accuracy are critical to the effectiveness of ECDIS in the Harbor/Harbor Approach region. Refinements in the design of the system may also contribute to the reduction of workload.

Chart Features During Route Monitoring

A relatively simple display was recommended by the participating mariners during the dynamic situation of route monitoring to avoid a cluttered display. The consensus of features to display always corresponds approximately to the standard display of the IMO PS (*2,3*). The preference for a simple display for route monitoring is consistent with conclusions in other reports (*13–16*). At the same time, the participating mariners recommended immediate and easy reference to a much larger set of features.

It appears worthwhile to make a distinction between two functions of a navigational chart: a dynamic function for the route monitoring, which needs only the information used in ship control, and a static function as a geographic information system (GIS), which provides much more extensive information for reference. The mariners' preferences for features and functions were based on the route monitoring task they experienced. The use of ECDIS for the navigation task of passage planning was not addressed in this experiment.

ECDIS-Based Navigation Functions

Given the capability of a microprocessor, the functions that might be added to an ECDIS are limited only by the ingenuity of the manufacturers. The valid needs of the user should be met, but, at the same time, a system should not be overly complicated, cluttered, and confusing. A similar approach could be taken for navigation functions as has been taken for chart features (*2,3*). That is, there could be a base set provided in every mode on every model by every manufacturer. In addition, there could be additional functions to be

TABLE 6 Mariners' Recommendations of ECDIS Based Navigation Functions

ECDIS-Generated Information	Display Always	At Users Option	Display Never
	(number of mariners of six)		
navigation fault alarm (eg. GPS down)	6*	0	0
own ship outline	5	1	0
display planned trackline	5*	1	0
display waypoint /waypoint number	4	2	0
past track	1	5	0
vector of course /speed made good	1	5	0
display overlay of actual radar	1	5	0
set and drift	1	5	0
display range rings	0	5	1
vector of own ship heading and speed	2	4	0
display selected ARPA targets	2	4	0
display current vectors	1	4	1
ETA to waypoint	1	4	1
display dead reckoned position / time	1	4	0
scale bar	1	4	0
chart scale boundaries	1	4	0
display wheel over points/turn radius	3	3	0
grounding alarm	3	2	1
own ship's safety depth contour	3	1	1
zoom in/ out function	3	1	1
display chart north up and course up	2	3	0
off track alarm	2	3	1
display fix marker and time	1	3	0
course to steer (trackline)	1	3	2
provide method for manual fix taking	1	3	2
display visual limits of lights	1	2	3

* also rated as one of three most important features by majority of mariners

selected by the user. Finally, manufacturers could have the opportunity for product differentiation and innovations that do not interfere with the base set. According to the expressed needs of the mariners participating in this study, there should be sufficient standardization across systems that an experienced individual can make safe use of a different system. The marine pilot, who must board a strange ship and make immediate use of available equipment, would have even greater needs for standardization.

Radar Features During Route Monitoring

No definite conclusions are possible from this experiment on the issue of whether, or how, radar should be integrated with ECDIS. The mariners' understandable concerns with the use of ARPA for collision avoidance in harbor entrances and departures suggest a need for further studies on the use of integrated systems.

Integrated Navigation Systems

The U.S. Coast Guard is involved in several studies of integrated systems. In cooperation with the Canadian Hydrographic Service, a further study is in preparation at the Centre for Marine Simulation at the Marine Institute in St. John's, Newfoundland. This study will examine the contributions of an integration of ECDIS and radar to navigation and collision avoidance. No published report is available. The U.S. Coast Guard is also a co-sponsor, along with the Maritime Administration, of the Shipboard Piloting Expert System. This ambitious project is a real-time expert system that reasons about the available data and formulates recommendations to the mariner (*17*). Sea trials are planned.

ECDIS as Automation

Many of the ECDIS issues considered during this study—effects on workload, situational awareness, safety, need for special training, and so forth—are general to the use of automated systems. The consequences of the increased use of technology on ships and related changes in the mariner's role are of great interest in the marine industry at the present time. Many comments from the mariners who participated in this study suggest concern that the consequences might be negative as well as positive: junior officers might become over-confident or overly complacent, they might fail to keep proper look out or notice targets not acquired by ARPA, they might not learn or maintain the necessary skills to function in case of system failure, or they might not be aware of system inaccuracies or malfunction. Owners might take a person off the bridge for every ECDIS they put on it. Because of the broad implications of these types of issues for maritime safety, the U.S. Coast Guard has begun a major study of the effects of automation. As of this writing, a task to define the study methods is nearing completion (*18,19*).

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