PREDICTION INFORMATION TO IMPROVE NAVIGATIONAL PERFORMANCE

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Introduction

The human's task in ship control is changing rapidly. Until the late eighties, the ship navigator was primarily involved in manual control of single processes and to a certain extent in supervising automated stand-alone systems. Today, automated control systems are applied on a large scale, resulting in a considerable change in operator tasks. The role of the navigator as a direct controller has been transformed into that of a supervisor who is monitoring different processes controlled by semi-intelligent subsystems, and also into that of a manager who is performing additional planning and decision-making activities. In this *supervisory control* role the navigator specifies the goals, constraints and procedures in terms of setpoint changes (process tuning actions) for the automated systems rather than controlling the process directly. The computer system transforms information from the operator to the controlled process and from the controlled process back to the operator. At the same time, the computer system closes control loops with the process, making the computer a semi-autonomous controller. Situations exist where the operator directly observes the process state, such as a navigator who observes the movements of his automatically controlled vessel with respect to the environment. In other situations, displays are used to inform the operator about the current state of the process and about the future plans. Sheridan (1992) compares this computer-mediated control situation with the situation that an operator observes the controlled process through a keyhole.

Humans are limited in task performance, particularly when they monitor slowly responding systems, i.e., processes in which control actions given at one time will not effectively alter the process state until some time (often minutes) later. When operators are not able to immediately see the results of a control action, they have difficulties in understanding the functioning of the underlying process. They are not able to accurately generate future process state information based on their perception of changes in the process state (Wagenaar & Sagaria, 1975; Wickens, 1986). Moreover, mental predictions may impose considerable cognitive workload (Johannsen et al., 1979). For accurate control it is essential that operators be able to correctly anticipate process responses in order to prevent control errors due to time lags. Correct anticipation requires knowledge of the goals, the process characteristics, the disturbances that may act on the system, and consideration of the current control actions and observed changes in the process state. It is known that operators may learn rules to predict process changes However, these rules may not be valid in unexpected task conditions (Broadbent, Fitzgerald & Broadbent, 1986). Schuffel (1986) showed that knowledge of control-effect relationships in ship control is rather inaccurate.

Computer systems can to a large extent compensate for these human limitations. In particular, computers can help operators to better understand the process by displaying the appropriate information. Kelley (1968), McLane and Wolf (1965), Kraiss (1980), and Wickens (1992) indicated that control performance improves by having a computer perform calculations to predict the future state of the controlled process. Information that predicts the future state of a process has become particularly important as an aid to improve the controllability of slowly responding processes. An example in ship control is the use of path prediction for guiding a large vessel in a narrow fairway along a planned route. Path prediction information that shows the predicted track ahead of the controlled vessel on a navigation screen may be very helpful in *guidance tasks*, i.e., in routine task conditions where operator's activities are mainly controlled by a set of rules that have proven to be successful. Accurate control is then obtained as long as the navigator matches the predicted track ahead with the planned route by responding to the predicted error rather than to the current error. In particular in conditions where the planned route is known in advance this task is a well-defined tracking task (Schuffel, 1986). Note that this is only true when the path predictor is accurate and the future disturbances acting on the vessel are known. In *navigation tasks*, however, where non-routine task conditions occur, no match or only a partial match exists between the actual situation and the past experience. In that case, proven rules are not available, for instance, when there is a mismatch between the predicted track ahead and the planned route due to:

- Disturbances that vary in time and space, or due to inaccuracy of the prediction itself
- A sudden failure in one of the subsystems that may cause the controlled process to respond differently
- A sudden change in the immediate goal, for instance when the fairway is partly blocked so that an alternative route must be chosen.

Lee and Moray (1992) suggest that experienced operators, who have fixed control strategies that rely upon feed-forward manual control and fixed allocation of automated control, will switch back to exploratory behaviour (feedback control) as soon as a problem occurs, while they try different means of control to maintain system performance. Human behaviour may then be goal-controlled in a sense that different attempts are made to reach the goal, and that a sequence of actions thought to be successful is selected. In such a problem-solving exercise, an internal representation of the process properties and of the environment is used. Unfortunately, operators generally have a poor internal representation of higher-order non-linear dynamic systems (Schuffel, 1986; Schraagen, 1994; Diehl & Sterman, 1995; Endsley & Kiris, 1995), causing loss of controllability. Adequate operator support should therefore show the predicted process state relative to the goal as a consequence of multiple process tuning actions.

Path prediction

To obtain accurate control of a vessel, the navigator anticipates the estimated future deviation between the planned and expected route of the vessel. Exploratory studies revealed that human control of ships might be improved when path prediction information is available. Path prediction is computer-based calculation of the future track ahead of a vessel based on a single process tuning action, given the actual state, the control signals, the vessel dynamics, and the disturbances, while showing a representation of the calculated predicted track ahead on a situation display. In the calculation, certain assumptions are made concerning the navigator's future control activities, e.g., that the control signal is kept constant at its current value for a certain amount of time, and that the future disturbances remain the same. The accuracy of the prediction is a function of the accuracy of the predictive model that is used and the accuracy with which actual state information is obtained. Bernotat and Witlok (1965), and Berlekom (1977) investigated path predictors for ships based on extrapolation; Kelley (1968) and McLane and Wolf (1965) showed positive effects of path prediction on navigational accuracy, and on the learning of ship control tasks. Also, Pew (1966), Bertsche and Cooper (1979), and Hayes (1979) argued that path prediction based on speed vectors could enhance ship control accuracy. Although these studies pointed out in a quantitative way that path prediction improves control performance of ships, no application was identified until recently. Presumably, this was caused by difficulties in establishing the requirements for interfacing the path predictor with the navigation systems on board ships. Current computer systems seem to have solved this problem (Heikkilä, 1993). High-precision position and movement information, being a most essential element for path prediction, may be obtained by means of existing Differential Global Positioning Systems (DGPS). Nowadays, the long-term accuracy position information is better than 2 m (Heikkilä, 1996); the same accuracy was found by Offermans, Helwig and Van Willigen (1997), who combined Global Navigation Satellite System (GNSS) with the long-range radio navigation system Loran-C.

Van Breda, Passenier, and Schuffel (1990) investigated the use of an adaptive path predictor, i.e., a path predictor that continuously adapts its predictive model parameters to the changing navigational conditions (Passenier, 1989). It was found that the use of such a path predictor considerably improved ship control accuracy compared to situations with conventional navigation methods. Another study by Van Breda & Passenier (1998) demonstrated that highly accurate path prediction is not always needed for accurate control. The use of a simpler extrapolation-based prediction model may lead to comparable results, as long as the state variables speed and rate of turn are included in the prediction model. One of the conclusions of this study addressed a possible drawback of path predictors: Calculation of the predicted path is generally based on the current control settings. This means that no information is provided about what the ship's path would be in case the ship's state would significantly change (e.g., due to sudden changes of control settings). In such circumstances, the experimental results showed a considerable direction error of the ship's path with respect to the planned route. It was suggested that provisions for a trial manoeuvre would better support the navigator so that better insight is obtained in the ship's manoeuvring capabilities and limitations.

Capability prediction

Capability is a model-based concept that takes dependencies between control (rudder) and effectiveness (resulting thrust) parameters into account. This involves calculation and presentation on a navigation display of the total manoeuvring margins of the vessel, the so-called Predicted Capability Envelope (PCE). The PCE involves multiple process-tuning predictions. The predicted margins may include restrictions due to fairway boundaries and due to other traffic ships. The PCE represents the complete reach of the controlled vessel for a particular time horizon. By intersecting the PCE with a required minimum safety distance, an integral representation of (other traffic) threats and (controlled ship) capabilities is obtained. Provided course and speed of other ships remain the same, the presented threats will be geographically stable areas. Navigators may consider these threats as obstacles in the fairway. Thus, an integrated navigation display is obtained which provides an overview of the ship's manoeuvring and collision avoidance information for a particular navigation task.

Experiment

In the present study, the results of a human-in-the-loop simulator experiment are presented, investigating the use of the PCE concept. Participating subjects were requested to follow a predetermined route with a medium size vessel across a busy traffic separation scheme. They were told to keep other vessels at a minimum safety distance of 1 nautical mile (nm). This was considered a highly-demanding task, since high-density traffic situations may be expected. To maintain the voyage plan, it is essential that navigators keep a safe distance to other traffic ships while maintaining their initial course and speed as much as possible. Traffic ships approached from port and from starboard side. Vessel traffic initially was such that no course or speed alterations were required in order to follow the planned route. At a certain instant, an unexpected change in the traffic situation occurred, for instance, because one of the traffic ships changed its speed and caused collision risk. In these circumstances, navigators cannot just perform a passing manoeuvre to avoid the problem; course alterations could introduce collision risk with other traffic ships, or, could cause the ship to exceed the fairway boundaries. To solve the problem situation, alternative safe routes for navigation must be considered and possibly selected first. PCE information was expected to facilitate this process, where the voyage plan, the safety regulations, traffic rules, and fairway boundaries are considered.

Task performance was expected to be best in conditions where PCE was used. PCE information shows the total manoeuvring margins of the controlled vessel as well as the safe areas to proceed. Selecting the safest alternative route is then a matter of considering the presented safety margins. Once the alternative route is selected, task execution only concerns guidance of the vessel along this route. The use of a speed selection option was expected to give the best results.

Method

Participants

Twelve final-year maritime students participated voluntarily in the simulator experiment. All students had finished their year of practical training.

Task

Each participant was required to accurately navigate a 110,000 dwt tanker across a traffic separation scheme, in a perpendicular crossing lane. The lanes of the traffic scheme were 1.5 nm wide, with a 0.5 nm separation zone. The participant's vessel started 3 nm from the centre line of the separation zone, with a nominal speed of 15 knots. Traffic vessels were approaching from port side in the first lane to cross, and from starboard side in the second lane to cross. A night scene was created; navigation lights and traffic signals were visible in the external world scene of the simulator. Normal safety and navigation rules with respect to other vessels and traffic signals had to be followed. The participants were required to cross both lanes and to follow the planned route as much as possible, while looking outside and considering information presented on the navigation display. For safe navigation, it was of primary importance that a 1 nm minimum passing distance to other ships was maintained. Collision avoidance manoeuvres could be initiated by performing a course change or a speed adjustment. Each experimental trial ended after 20 minutes.

Trials were executed under normal and under high workload conditions. High-workload task conditions were created by an additional continuous memory task (CMT), which consisted of a letter-detection task. Every 1.5 s, a letter was presented by headphones. The participants had to press a button each time they recognised one out of four target letters. In addition, the number of target letters had to be counted in separate tallies. The button had to be pressed twice every time a target letter was repeated. The total duration of the CMT was 3 minutes. Trials were presented in three blocks of four, each block representing a display type. The normal and high-workload task conditions were presented in balanced order.

Apparatus

The experiment was carried out in the TNO-HFRI ship-manoeuvring simulator. A three-channel Evans and Sutherland ESIG2000 high-speed graphics processor was used to generate synthetic out-of-the-window scenes. This processor generated multiple-channel high-resolution video images (1500 - 2000 textured polygons and 800 x 600 pixel resolution per channel). The image update frequency was 30 Hz. For three channels, the total viewing angle was 156° horizontal and 42° vertical. The images were presented on a spherical dome. In the centre of the dome, a mock-up of the ship's bridge was installed. Observation distance was about 3 m.

The mock-up was a partially instrumented bridge of a modern tanker. For course control, an autopilot system was installed. The participants first had to select a new desired course, then start the execution of the course-changing manoeuvre by pushing an execute button. Maximum rudder deflection could be selected to limit the rate of turn. The minimum rudder limit was pre-set at 10°. A push button telegraph system was used to select the propulsion setting: 0 for stop, and 110 for full ahead. An intercom system was used for speech communication between experimenter and the participant on the bridge.

The hydrodynamic model of the vessel was based on an accurate manoeuvring model of a 110,000 dwt tanker. This model was simplified to a multi-variable model (De Keizer, 1977) with which relevant non-linear manoeuvring effects could be reproduced. The estimated time constant of the vessel's rate of turn at a cruising speed of 8 knots was 107 s. For calculation of the predictions, the same model was used.

Displays

Three navigation display types were investigated:

(a) ARPA display; baseline radar and collision avoidance information, in relative motion, north-up mode (Figure 1). The ship's fairway was visible as an electronic chart superimposed on the radar picture, with the planned route depicted as a solid line. Other vessels were shown as targets. Along the right-hand screen edge, a menu for display interaction was presented, showing 'soft' push buttons for the radar display setting, and windows for general collision avoidance information such as heading and speed of the vessel, radar range, range ring distance, and vector length. Variable range marker (VRM) and parallel-index (PI) lines could be selected and manipulated. A cursor was always present on the screen; range and bearing of its position were continuously presented in a separate window. This cursor could also be used to select targets for collision avoidance information. The selected target would start to blink amber while the target's range, bearing, speed, course, minimum passing distance (closest point of approach, CPA) and time to minimum passing distance (TCPA) were presented. Targets were always plotted in a selectable mode (i.e., true or relative vector mode). Along the screen edges, indicators for vessel's state variables were presented: actual heading, selected course, rate of turn, rudder deflection, log speed, revolutions of the propeller shaft, absolute wind and current data, and time of day. The participant interacts with the navigation display by using a separate mouse.

(b) ARPA/PCE/course display; baseline ARPA radar and collision avoidance information supplemented with PCE information (Figure 2). The display shows the vessel's actual heading; the predicted track ahead, given the selected radar range and heading set point of the autopilot (course controller); a trial value for a new heading setting, selectable by turning the selector of the autopilot; the vessel's inherent manoeuvring area (within maximum rudder deflection and within 110° course change); zones indicating areas with a passing distance to other traffic ships less than 1.0 nm. The maximum prediction time (time horizon) was 30 minutes.

(c) ARPA/PCE/course/speed display; display type (b) supplemented with a speed-trial facility. The speed-trial was activated by pressing a hardware '+' button (PCE on the basis of increasing revolutions of the propeller shaft) or a '—' button (decreased revolutions). The trial value of the propeller revolutions was presented in red on the RPM indicator. To avoid confusion with the actual RPM-values, a triangle would appear on the screen to warn the operator that the presented information did not correspond to the actual status. The speed-trial was ended by pressing the '+' and '—' buttons simultaneously.

Scenarios

The participant's vessel started 3 nm from the centre line of the separation zone, with a nominal speed of 15 knots. Vessels approaching from port side were scheduled such that an initially close approach existed. This forced the participants to maintain their initial speed during the first part of the trial, and prevented them to quietly determine their strategy. In the high-workload task conditions, an additional CMT task was started during this part of the scenarios. Vessels approaching from starboard side were scheduled in dynamic scenarios. During the experiment, the display types were presented to the participants in balanced order. The vessel traffic scenarios were randomised. All vessels followed the lanes and did not alter course. There was no wind and the current was 3 knots in the direction 90°.

Procedure

The participants contributed for half a day. In an introductory session, they were familiarised with the simulator. This was followed by a 30 minutes practice trial with each display type. On the basis of pilot studies, it was determined that this amount of trials would be sufficient to obtain a stable performance level. If this was not the case, additional practice trials were allowed for. The experimental trials consisted of 3 blocks of 6 trials. Each block represented a display type; each trial represented a different traffic scenario. To avoid order effects, display types and traffic scenarios were presented in balanced order.

Performance measurement

The state variables of position, heading, speed, rate of turn, rudder deflection, autopilot set-point, and propulsion set-point, were sampled and stored every 1 second. Performance was recorded in terms of navigation safety, operationalised as the violation of the minimum safety distance, the position error, and the average speed of the vessel. Only (priority) vessel traffic, approaching from starboard side, was considered in the data analysis. Violation of the safety distance was defined as the distance and time during which the participant's vessel had been within 1.0 nm from any of the traffic vessels. Distance was calculated as the Root-Mean-Square (RMS) distance error, expressed in nm. The position error was defined as the RMS deviation between the planned route and the actual sailed path, expressed in nm. Speed was defined as the average speed of the vessel, expressed in knots. Finally, the autopilot and propulsion setting frequency was determined as a measure of control effort.

Results

Violation of the minimum safety distance

All participants were able to perform the experimental trials. Two trials with the PCE/course/speed display type were aborted because one of the participants was confused about the way the speed trial facility was working.

A within-subject analysis of variance (ANOVA) on the violation distance, with display type (ARPA, ARPA/PCE/course, or ARPA/PCE/course/speed) and workload task condition (normal or high) as independent variables, showed a main effect of display type, $F(2,22)=3.77$; $p<.05$. This means that the distance violation differed for the three investigated display types. Distance violation was largest when the baseline ARPA display type was used. Note that this differed a factor of four with respect to conditions where PCE information was used (Figure 3). No difference was found between the two PCE display types. A post-hoc Tukey comparison test confirmed the finding that distance violation with the baseline ARPA display type differed significantly from that with both the PCE display types ($p<.05$). No interaction was found between display type and workload task condition.

Analysis of the violation time leads to the results shown in Figure 4. A histogram is presented, depicting the mean period of time that the minimum safety distance of 1.0 nm was violated, averaged across participants. The horizontal axis is divided into intervals of 0.1 nm, starting 0.5 nm from the threat vessel and ending up at the minimum safety distance of 1.0 nm. With the baseline ARPA display type, a considerable amount of time was spent within the minimum safety distance of 1.0 nm. With both ARPA/PCE display types this was not the case; safety distance violations occurred mainly in the interval 0.9 to 1.0 nm distance. A Pearson Chi-square test indicated that the results with the baseline ARPA display type differed significantly from both PCE display types, $\chi^2(5)= 30.4$; $p< .001$ and $\chi^2(5)= 35.6$; $p< .001$, respectively.

Position error

An ANOVA on the position error, with display type (ARPA, ARPA/PCE/course, or ARPA/PCE/course/speed) and workload task condition (normal or high) as independent variables, showed no significant effect of any of the independent variables. The mean position error with the standard ARPA display was 0.359 nm, with the ARPA/PCE/course display this was 0.362 nm, and with the ARPA/PCE/course/speed display this was 0.411 nm. No significant effect of workload task condition was found. No interaction was found.

Speed

An ANOVA on the average speed showed no significant effect of any of the independent variables. The average speed was about 7.3 knots with each of the display types. Largest standard deviations were found when the ARPA/PCE/course/speed display type was used. No interaction was found.

Control effort

An ANOVA on the propulsion and autopilot (heading) setting frequencies showed no significant effect of any of the independent variables. The mean propulsion setting frequency was about 1.7 per trial for all display types. The range of mean autopilot setting frequency differed was 7.1 with the ARPA display, 6.1 with the ARPA/PCE/course display, and 6.0 with the ARPA/PCE/course/speed display. Because of the large standard deviations, no significant effect of workload task condition was found. No interaction was found.

Discussion

The potential benefits of capability prediction for ship navigation support were investigated in a simulator study. The results of this study indicated that navigation performance was significantly improved when the participants used PCE information in addition to baseline ARPA navigation information. The minimum safety distance to other traffic ships was less frequently and less seriously violated, by a factor of four on average. PCE information enabled the participants to better anticipate and assess critical traffic situations. Some differences in task performance between the two PCE display types were found. The PCE/course display type produced the most accurate navigation and did not produce any difference in task performance due to workload task condition.

The availability of a speed-trial facility was found to confuse the participants. Observations by the experimenter and self-observations by the participants revealed that the participants were not interested in reducing the vessel's speed. Navigators prefer to plan their manoeuvres on the basis of a constant speed. Interestingly, it was found that fewer autopilot setpoint corrections were made in task conditions with PCE information. This is in contradiction with the findings of the earlier experiments (Van Breda, Passenier & Schuffel, 1990). With PCE, navigators have more overview. This enables navigators to better use safe areas of navigation. The PCE speed-trial facility, however, needs more investigation.

Conclusion

Literature indicates that path prediction may be used to effectively help navigators controlling their vessel along a predetermined route in routine task conditions (ship guidance). In non-routine task conditions (ship navigation), where no action rules are available from previous experiences, additional information is needed to support the navigator. In those circumstances limited control corrections no longer suffice, so an alternative route must be selected. The study presented here shows that information concerning the predicted manoeuvring margins (capability prediction, PCE) provides adequate support in the selection of such safe alternative routes: The route was properly re-planned, and the available path prediction information allowed safe guidance along that re-planned route.

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References

1. Berlekom, W.B. (1977). Simulator investigations of predictor steering systems for ships. *The Naval Architect*, 13-34.
2. Bernotat, R., & Widlok, H. (1965). Principles and application of prediction displays. *The Journal of Navigation*, 19, 361-370.
3. Bertsche, W.R., & Cooper, R. (1979). Simulator evaluation of advanced ship bridge displays. *Proceedings Third Annual CAORF Symposium* (pp. 21:1-21:13). New York: Merchant Marine Academy
4. Broadbent, D.E., Fitzgerald, P. & Broadbent, M.H.P. (1986). Implicit and explicit knowledge in the control of complex systems. *British Journal of Psychology, 77,* 33-50.
5. De Keizer, C. (1977). Een multi-variabel model van de 'Zeefakkel' [*A multi-variable model of the 'Zeefakkel'*]. Technical report. Delft: University of Technology.
6. Diehl, E. & Sterman, J.D. (1995). Effects of feedback complexity on dynamic decision making. *Organizational Behaviour and Human Decision Processes, 62,* 198-215.
7. Endsley, M.R. & Kiris, E.O. (1995). The out-of-the-loop performance problem and level of automation. *Human Factors, 37,* 381-394.
8. Hayes, J.N. (1979). Value of the anti-grounding and collision avoidance displays in restricted waters. *Proceedings Third Annual CAORF Symposium* (pp. 14:1-14:15). New York: Merchant Marine Academy.
9. Heikkilä, M. (1993). A simulation study on the format of ship motion display to improve steering accuracy in restricted fairways. *Joint International Conference on*

Marine Simulation and Ship Manoeuvrability MARSIM & ICSM 93 (pp. 179-188). St John's, Canada: International Maritime Simulator Forum.

10. Heikkilä, M. (1996). Ship-shore and ship-ship data transfer. *The Journal of Navigation,* 49, 309-316.
11. Johannsen, G., Moray, N., Pew, R.W., Rasmussen, J., Sanders, A.F. & Wickens, C.D. (1979). Final report on the experimental group. In N. Moray (Ed.), *Mental workload: Its theory and measurement.* New York: Plenum.
12. Kelley, C.R. (1968). *Manual and automatic control — A theory of manual control and its applications to manual and automatic control.* New York: Wiley.
13. Kraiss, K.F. (1980). Analytical evaluation of manual systems with task network models. In J. Moraal & K.F. Kraiss (Eds.), *Manual system design: New methods and equipment.* Freiburg, Germany: North Atlantic Treaty Defense Research.
14. Lee, J. & Moray, N. (1992). Trust, control strategies and allocation of functions in human-machine systems. *Ergonomics,* 35, 1243-1270.
15. McLane, R.C. & Wolf, J.P. (1965). A comparative evaluation of pictorial vs. symbolic displays for submarines. *Proceedings of the AIAA/USN Marine Systems and ASW Conference (AIAA Paper No. 65-246).* San Diego, CA.
16. Offermans, G.W.A., Helwig, A.W.S. & Van Willigen, D. (1997). Test results of a cost-effective DGNSS augmentation system. *The Journal of Navigation*, 50, 209-223.
17. Passenier, P.O. (1989). *An adaptive track predictor for ships.* Doctoral Dissertation. Delft: University of Technology.
18. Pew, R.W. (1966). Performance of human operators in a three state relay control system with velocity augmented displays. *IEEE Transactions for Human Factors in Electronics,* 7, 77-83.
19. Schraagen, J.M.C. (1994). *What information do river pilots use?* (Report TM-96-C064). Soesterberg, The Netherlands: TNO Human Factors Research Institute.
20. Schuffel, H. (1986). *Human control of ships in tracking tasks.* Doctoral thesis. Soesterberg, The Netherlands: TNO Institute for Perception.
21. Sheridan, T.B. (1992). *Telerobotics, automation and human supervisory control.* Cambridge, MA: Massachusetts Institute of Technology.
22. Van Breda, L., Passenier, P.O., & Schuffel, H. (1990). Ship control with electronic chart and path prediction. *Joint International Conference on Marine Simulation and Ship Manoeuvrability MARSIM & ICSM 90* (pp. 203-208). Tokyo.
23. Van Breda, L. & Passenier, P.O. (1998). The effect of path prediction on navigational performance. *The Journal of Navigation,* 2, 216-228.
24. Wagenaar, W.A. & Sagaria, D. (1975). The perception of exponential growth. *Perception and Psychophysics, 18,* 416-422.
25. Wickens, C.D. (1986). The effect of control dynamics on performance. In K. Boff, L. Kaufman & J.P. Thomas (Eds.), *Handbook of perception and human performance* (pp. 39.1-39.60). New York: Wiley.
26. Wickens, C.D. (1992). *Engineering psychology and human performance.* New York: HarperCollins.

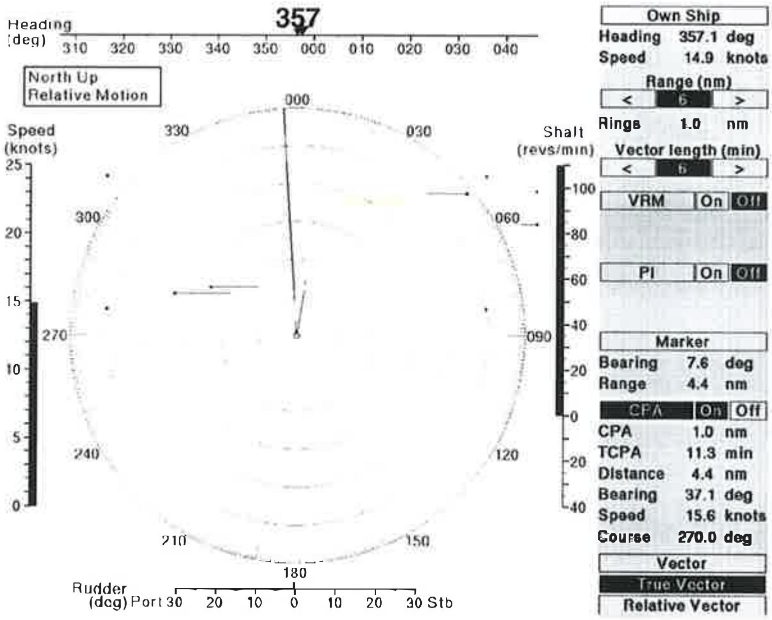


Figure 1. The ARPA navigation display. Collision avoidance information is presented on the right hand edge. Radar information is surrounded by vessel status information presented in scales. The position of the controlled vessel is the screen centre.

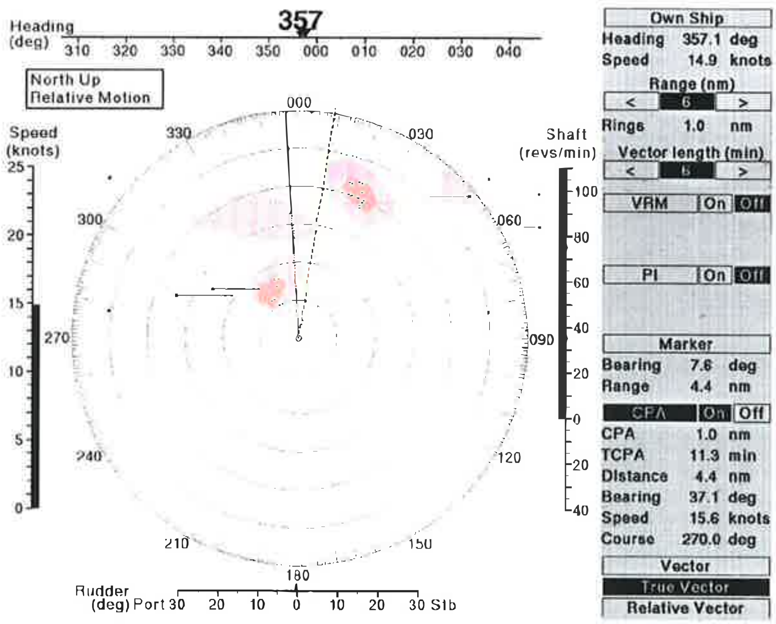


Figure 2. The ARPA/PCE/course navigation display. Baseline ARPA information is supplemented with PCE information: the vessel's heading line, the vessel's predicted track ahead (30 minutes prediction), the vessel's inherent manoeuvring area, and zones indicating areas with a passing distance to other traffic ships less than 1 nm. The dark zones represent areas with a passing distance less than 0.5 nm.

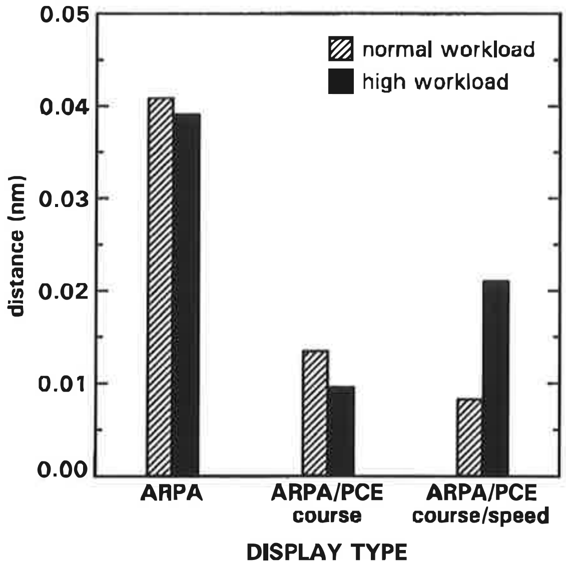


Figure 3. Violation of the minimum safety distance (calculated as RMS distance error) as a function of display type and workload task condition, averaged across participants.

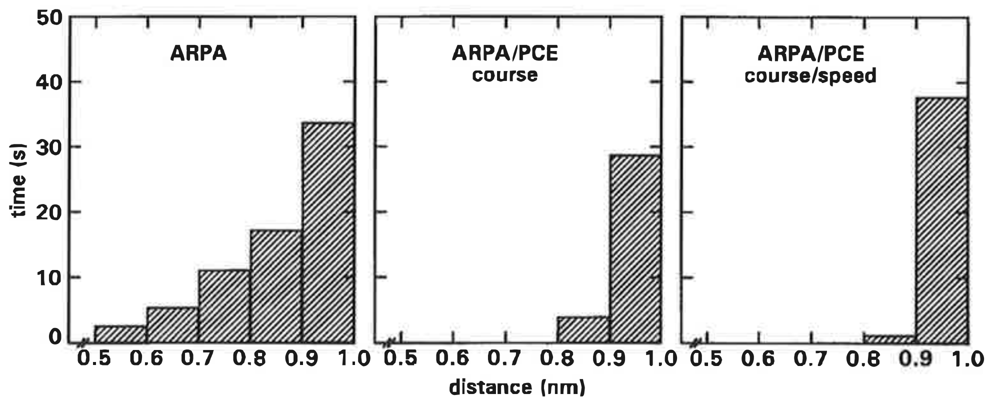
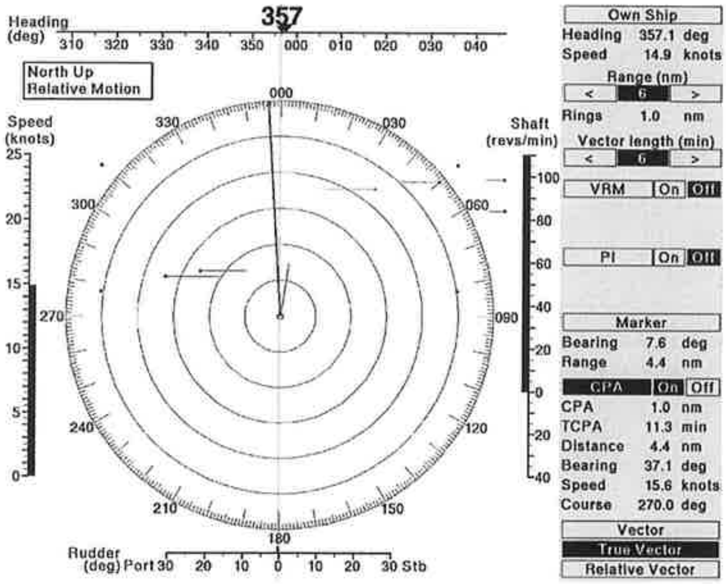
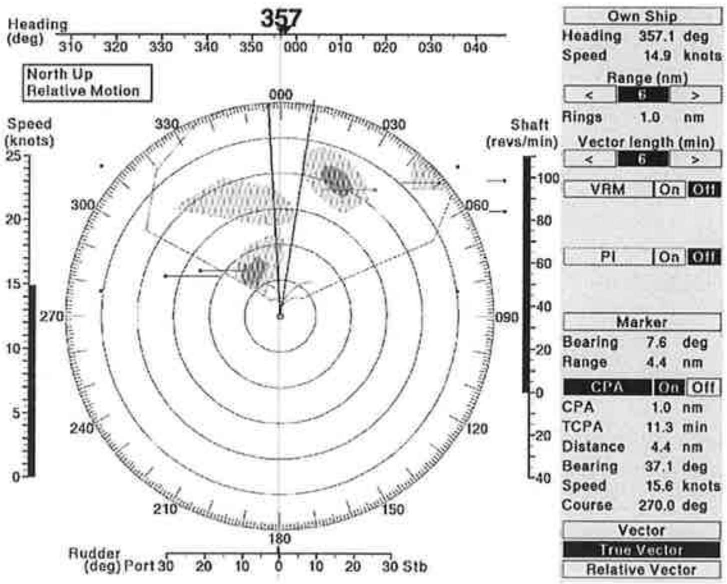


Figure 4. Period of time that the minimum safety distance of 1 nm was violated as a function of display type, averaged across participants.


Heading (deg)
357
310 320 330 340 350 000 010 020 030 040
North Up
Relative Motion
Speed (knots)
Shaft (revs/min)
Rudder (deg) Port 30 20 10 0 10 20 30 Stb
Own Ship
Heading 357.1 deg
Speed 14.9 knots
Range (nm)
6
Rings 1.0 nm
Vector length (min)
6
VRM On Off
PI On Off
Marker
Bearing 7.6 deg
Range 4.4 nm
CPA On Off
CPA 1.0 nm
TCPA 11.3 min
Distance 4.4 nm
Bearing 37.1 deg
Speed 15.6 knots
Course 270.0 deg
Vector
True Vector
Relative Vector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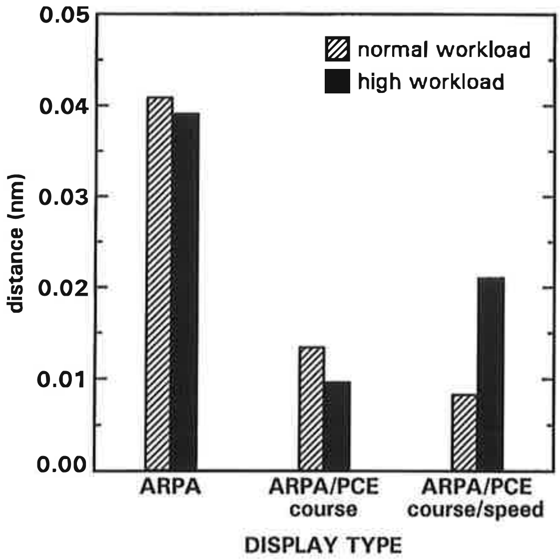
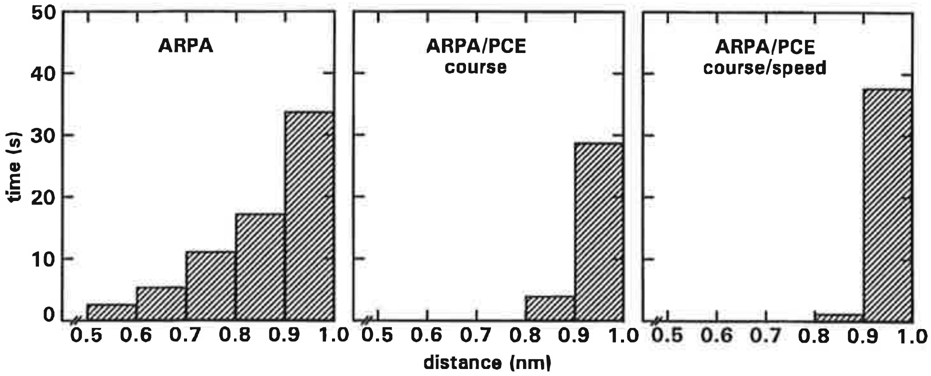
North Up
Relative Motion
Speed (knots)
Shaft (revs/min)
Rudder (deg) Port 30 20 10 0 10 20 30 Stb
Own Ship
Heading 357.1 deg
Speed 14.9 knots
Range (nm)
6
Rings 1.0 nm
Vector length (min)
6
VRM On Off
PI On Off
Marker
Bearing 7.6 deg
Range 4.4 nm
CPA On Off
CPA 1.0 nm
TCPA 11.3 min
Distance 4.4 nm
Bearing 37.1 deg
Speed 15.6 knots
Course 270.0 deg
Vector
True Vector
Relative Vector


0.05
0.04
0.03
0.02
0.01
0.00
distance (nm)
normal workload
high workload
ARPA
ARPA/PCE course
ARPA/PCE course/speed
DISPLAY TYPE


50
40
30
20
10
0
time (s)
ARPA
ARPA/PCE course
ARPA/PCE course/speed
0.5 0.6 0.7 0.8 0.9 1.0
distance (nm)

INTERNATIONAL CONFERENCE ON MARINE SIMULATION AND SHIP MANEUVERING

MARSIM 2000

CONFERENCE PROCEEDINGS

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Simulation, Training, Assessment & Research

Orlando, Florida, USA
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