The effect of radar and ECDIS display mode on navigational accuracy and situational awareness: A bridge simulation experiment

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Abstract In March 2010, a study was conducted in the full mission bridge simulator at the California Maritime Academy, examining the effect of the radar display mode on navigational accuracy and situational awareness. The purpose of the study is to inform bridge watchstanding practices and instruction of Bridge Resource Management courses. The participants in this study were 22 maritime cadets. The participants, in six teams of three or four students, attempted to follow three predetermined navigation routes. For each route, two teams used both radar and ECDIS in North-Up, two teams used both radar and ECDIS in Head-Up and the remaining two teams used radar in Head-Up and ECDIS in North-Up. Numerical data were collected on navigational accuracy as measured by cross-track error and perceived situational awareness was self-assessed by post-scenario survey. Statistical Package for the Social Sciences (SPSS) 18.0 was used for the statistical analysis of the quantitative and qualitative data and this paper reports the results.

Keyword: ECDIS, Bridge Resource Management, Situational Awareness, Maritime Education, Bridge Simulation, Marine Navigation, Radar Display Mode

1. Introduction

Modern radar and automatic radar plotting aid (ARPA) units may be used in either North-Up or Head-Up (and the similar, Course-Up) mode. In the Head-Up display mode, radar information from targets ahead of the vessel is displayed at the top ('y' axis) of the radar display screen. In the North-Up mode, radar information from north of the vessel is displayed at the top. Most professional mariners currently use the North-Up mode because paper charts, and the electronic equivalent raster charts, are constrained to that orientation. North-Up attempts to "maximize situational awareness by ensuring that the radar scene is matched to the paper or raster chart" [1]. As a consequence, however, the mariner must mentally reorient to correlate the radar and chart displays with the view seen through the bridge windows. This mental rotation has been shown to be "difficult and time consuming" [2]. Alternately, while the use of Head-Up on the radar might increase situational awareness by easing correlation between the visual scene and the radar display, it makes the correlation between radar and chart more difficult. The past decade has seen the advent of the Electronic Chart Display and Information System (ECDIS) and Electronic Chart Systems (ECS). When using these technological advances, the watch officer may choose between Head-Up mode and North-Up mode to display the navigational chart information. As a result, Norris states "on the fully electronic bridge there is no longer a need to be bound by this practice [using North-Up mode] and using Head-Up on both ECDIS and radar seems a very sensible choice, giving immediate tie-up with the view from the bridge windows" [3]. Although several studies have investigated the effects of map orientation, particularly in the field of air transportation, little, if any, empirical research has been conducted in the maritime industry.

In the maritime industry and related fields such as air and rail transportation, situational awareness is generally accepted as being a good thing to have [4]. One commonly cited definition of situational awareness is "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [5]. Or, to put it more simply, situational awareness (SA) is knowing what is going on around you [6]. Situational awareness can be measured in numerous ways, including questionnaires [7] & [8] and direct performance measures. Cross-track error (XTE), the lateral distance of the vessel from its intended track, is a commonly used performance measure used to determine navigational accuracy and situational awareness [9] & [10].

The research in map orientation has provided mixed results. Several aviation studies have shown that using charts and maps in the Head-Up mode increased navigational accuracy and efficiency [11], [12] and [13]. This is attributed to the increased effort required to mentally rotate a North-Up display so that it can be correlated to the visual [14]. Other studies, however, found no significant differences, neither positive nor negative, in situational awareness between the Head-Up display mode and North-Up [14] & [15]. In a study conducted by Porathe [2], participants navigated along a route marked through a 6 meter by 6 meter square room using a North-Up electronic map, a Head-Up electronic map, a 3-D map or a paper map. Participants using the 3-D map completed the route the quickest (111 seconds) and with the fewest errors (1.7), followed by Head-Up (142 seconds, 3.6 errors) and North-Up (142 seconds, 4.2 errors). Those participants that used the traditional paper map finished the route the slowest (167 seconds) and with the most errors (8.2). Porathe concluded that egocentric map orientations are more user friendly because they eliminated the need for mental rotation of a North-Up chart, improve the ease of understanding of other electronic navigational equipment, and increase situational awareness of the individual.

During navigation, radar and Bridge Resource Management (BRM) courses at the California Maritime Academy, most faculty regularly instruct cadets that North-Up is the proper display setting for radar, because, when used in conjunction with paper charts, radar/ARPA in the North-Up mode increases navigational situational awareness and reduces the chance of confusion. It is routine practice among instructors to correct cadets that attempt to navigate with radar set to the Head-Up mode. But, as Norris [3] has pointed out, ECDIS enables the mariner to orient both the chart and the radar in Head-Up, thereby eliminating the need for mental reorientation. The purpose of this study is to investigate the effect of radar and chart display mode on navigational accuracy and situational awareness. The results will inform the teaching of BRM, navigation and radar courses at maritime academies and bridge watchkeeping practices.

2. Methodology

This study was conducted in March 2010 during California Maritime Academy's elective *e*-Navigation course. The participants were 22 maritime cadets. Students registered for this course as they would for any other course at the Academy. The course met one hour per week in a classroom setting where students learned about topics related to *e*-Navigation and research methodology. During the first class meeting the participants completed an initial questionnaire that looked at background data and read and signed an Informed Consent form. Participants also met for four hours each week in a Lab section where they had an opportunity to participate in bridge simulation exercises that focused on different aspects of *e*-Navigation and to participate in the research that was being done.

During the semester, a total of 10 lab scenarios were conducted utilizing the Academy's 3 full mission bridge simulators. This paper reports the findings of Lab #7. In the first meeting of the course, the instructor grouped the students into 6 bridge teams; 2 teams consisted of 3 students and 4 teams consisted of 4 students. In each group a 4th year cadet (a Senior cadet) was selected to act as the watch officer, a 3rd year cadet (a Junior cadet) acted as the navigator/radar operator and a 2nd year cadet (a Sophomore cadet) served as the helmsman. The 4th member of each team, if any, acted as observer. In general, the participants maintained the same watch teams throughout the course, though there was some variance week to week due to absences. Prior to this study, the teams had worked together for 6 previous simulation labs during a period of 6 weeks.

In this study, the teams of participants stood watch on the navigation bridge of a simulated containership. The same ship model had been used in previous exercises, so the participants were familiar with the navigational equipment and handling characteristics of the vessel. The navigation equipment on the vessel consisted of an ECDIS and a radar/ARPA unit. Each team participated in a series of three scenarios with short breaks in between scenarios. Prior to the start of each scenario, the teams were given a navigation route which they were instructed to input into the ECDIS unit. Each route consisted of 7 waypoints and 6 legs, requiring 5 turns. The 3 routes were each approximately 6 nautical miles long and took approximately 30 minutes to complete. Route #1 was generally towards the north, Route #2 was generally towards the south and Route #3 was generally towards the west. Because only 3 full mission bridge simulators were available for use, an easterly route was not utilized in this study. None of the participants had previously navigated in the simulated geographic area. In each scenario, a one knot current was applied in a direction perpendicular to the intended track. The participants were not informed of the current prior to the commencement of each exercise.

In each scenario, two of the teams used both radar and ECDIS in the North-Up display mode, two teams used both devices in the Head-Up mode, while the remaining teams used ECDIS in the North-Up mode and radar in the Head-Up mode. (See Table 1). The researcher instructed each team to follow the route as closely as possible with the goal of minimizing cross-track error (XTE).

	ECDIS North-Up Radar North-Up	ECDIS North-Up Radar Head-Up	ECDIS Head-Up Radar Head-Up
Route #1 (Northerly)	Teams 1 & 4	Teams 2 & 5	Teams 3 & 6
Route #2 (Southerly)	Teams 3 & 6	Teams 1 & 4	Teams 2 & 5
Route #3 (Westerly)	Teams 2 & 5	Teams 3 & 6	Teams 1 & 4

Table 1. Team rotation and display modes

Data were collected on cross-track error at each waypoint and at the midpoint of each leg of the route to be used as a measure of navigational accuracy. The cross-track error was measured to the nearest 0.01 nm using measuring tools inherent in the Transas bridge simulator software.

Prior to commencing the exercise, each participant completed a 4-question survey on their preference of display mode when using radar and ECDIS. After completing the exercises, each participant completed a 10-question questionnaire on perceived situational awareness.

3. Results

3.1 Pre-exercise Questionnaire

The pre-exercise questionnaire consisted of 4 questions utilizing a Likert-type scale (5 = strongly agree, 4 = agree, 3 = neutral, 2 = disagree and 1 = strongly disagree). The mean for question #1, “I feel most comfortable using radar in Head-Up display”, was 2.36 (SD = 1.255), with 59% of participants disagreeing or strongly disagreeing. The mean for question #2, “I feel most comfortable using ECDIS in Head-Up display”, was 2.41 (SD = 1.221), with 59% of participants disagreeing or strongly disagreeing. The mean for question #3, “I feel I can identify points of land more easily when the radar is in North-Up display”, was 4.09 (SD = 0.811), with 82% agreeing or strongly agreeing. The mean for question #4, “I feel I can identify points of land more easily when the ECDIS is in North-Up display”, was 4.14 (SD = 0.774), with 77% of participants agreeing or strongly agreeing and 23% neutral.

3.2 Cross-track Error by Team

The mean cross-track error was calculated for each team. (See Table 2.) Team 2 achieved the smallest cross-track error, indicating a high level of navigational accuracy. The difference in the means between Team 2 and each of the other teams was statistically significant at the 95% confidence level. The differences in the means of the other teams were not statistically significant. Because of the small sample size (n=6), the researcher deemed it appropriate to exclude the data from Team 2 from the data analysis.

Team Number	Mean Cross-track Error	Standard Deviation
1	0.0585 nm	0.05599
2	0.0323 nm	0.02411
3	0.0567 nm	0.05007
4	0.0479 nm	0.04467
5	0.0518 nm	0.04279
6	0.0605 nm	0.05934

Table 2. Cross-track error by team

3.3 Cross-track Error vs. Display Mode

The mean cross-track error for the teams that had both the radar and ECDIS displays set to North-Up (n = 5) was 0.0534 nm (SD = 0.0408). The teams with radar and ECDIS both set to Head-Up (n = 5) achieved a mean cross-track error of 0.0514 nm (SD = 0.0495) while those teams with the radar set to Head-Up display and the ECDIS set to North-Up (n = 5) had a mean cross-track error of 0.0605 nm (SD = 0.0601). (See Fig. 1.) The differences in the means were not statistically significant at the 95% confidence level.

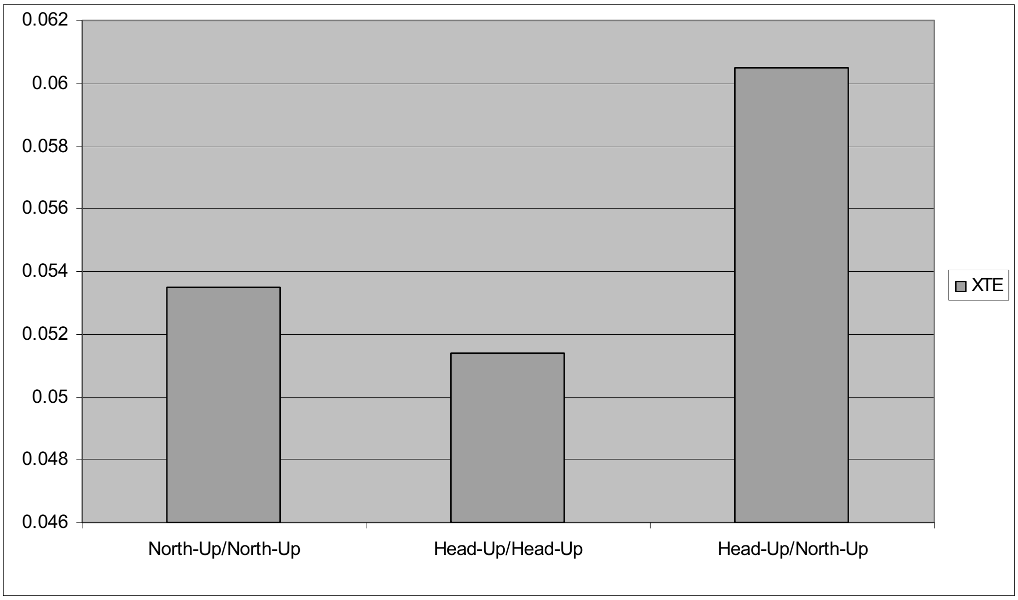

Fig. 1 Cross-track error (XTE) and display mode

3.4 Cross-track Error vs. Direction of Travel

Mean cross-track error was also calculated based on direction of travel. On Route #1, which required the vessels to proceed in a northerly direction, the teams (n = 5) achieved a mean cross-track error of 0.0545 nm with a standard deviation of 0.0460. For the 5 teams on Route #2 (southerly), the mean cross-track error was 0.0528 nm (SD = 0.0549) and for Route #3 the mean cross-track error was 0.0580 nm (SD = 0.0513). (See Fig. 2.) The differences in the means were not statistically significant.

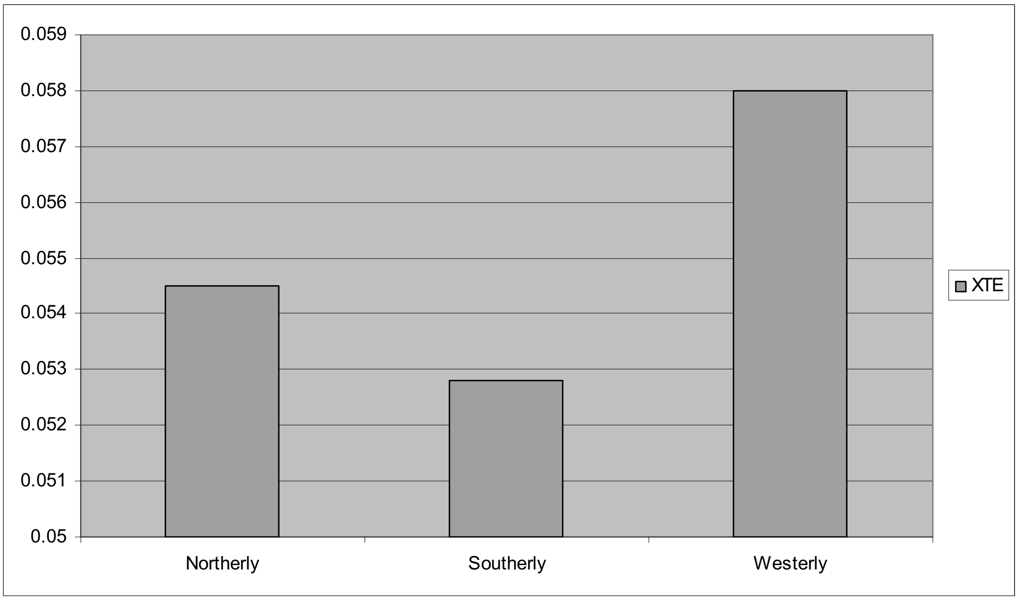

Fig. 2 Cross-track error (XTE) and direction of travel

3.5 Cross-track Error vs. Direction of Travel and Display Mode

The data were further analyzed to determine if there were any differences in cross-track error based on both direction of travel and display mode. Those teams (n = 2) on Route #1 with both radar and ECDIS displays set to North-Up achieved a mean cross-track error of 0.0542 nm (SD = 0.03951). The team (n = 1) on Route #1 with the radar on Head-Up display and the ECDIS on North-Up had an XTE of 0.0469 nm (SD = 0.03568), while those teams with both radar and ECDIS in the Head-Up mode (n = 2) had a mean cross-track error of 0.0585 nm (SD = 0.05655). The differences in the means were not statistically significant.

For the southerly route (Route #2), the two teams with both radar and ECDIS displays in the North-Up mode achieved an XTE of 0.0488 nm (SD = 0.04274). The teams (n = 2) on Route #2 with the radar on Head-Up display and the ECDIS on North-Up had an XTE of 0.0592 nm (SD = 0.06729), while those team with both radar and ECDIS in the Head-Up mode (n = 1) had a mean cross-track error of 0.0477 nm (SD = 0.05183). The differences in the means were not statistically significant.

For the westerly route (Route #3), the team with both radar and ECDIS displays in the North-Up mode achieved an XTE of 0.0608 nm (SD = 0.04132). The teams (n = 2) on Route #3 with the radar on Head-Up display and the ECDIS on North-Up had an XTE of 0.0685 nm (SD = 0.06729), while those teams with both radar and ECDIS in the Head-Up mode (n = 2) had a mean cross-track error of 0.0462 nm (SD = 0.04129). There was a statistically significant difference in the mean cross-track error of those teams using both ECDIS and radar in the Head-Up mode and those using ECDIS North-Up and radar Head-Up on Route #3. (See Fig. 3).

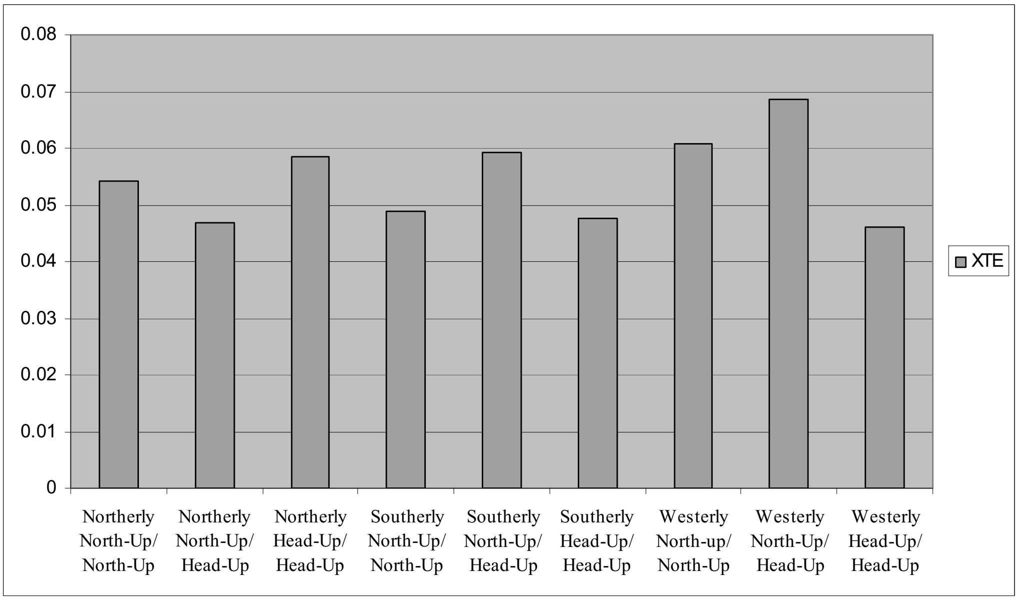

Fig. 3 Cross-track error (XTE) vs. direction of travel and display mode

3.6 Post-exercise questionnaire

The post-exercise questionnaire consisted of 10 questions utilizing a Likert-type scale (5 = strongly agree, 4 = agree, 3 = neutral, 2 = disagree and 1 = strongly disagree). The mean for question #1, "I feel that North-Up display on both the radar and the ECDIS increased my situational awareness", was 4.32 (SD = 0.839), with 86% of agreeing or strongly agreeing. The mean for question #2, "I feel that Head-Up display on both the radar and the ECDIS increased my situational awareness", was 2.64 (SD = 1.136), with 55% of participants disagreeing or strongly disagreeing. The mean for question #3, "I feel that Head-Up display of the radar and North-Up display on the ECDIS increased my situational awareness", was 2.23 (SD = 1.152), with 73% of participants disagreeing or strongly disagreeing. The mean for question #7, "I feel the best combination is for radar and ECDIS to both be North-Up", was 4.09 (SD = 1.019), with 73% of participants agreeing or strongly agreeing. The mean for question #8, "I feel the best combination is for radar and ECDIS to both be Head-Up", was 2.09 (SD = 1.109), with 64% of participants disagreeing or strongly disagreeing. The mean for question #9, "I feel the best combination is for radar to be Head-Up and ECDIS to be North-Up", was 1.95 (SD = 0.950), with 77% of participants disagreeing or strongly disagreeing.

4. Discussion

Because of the small sample size, few things in the study were found to be statistically significant and, therefore, may not be generalized. However, the general trend of the data provided some interesting results.

The pre-exercise survey indicates that, prior to the exercise, the participants did not feel comfortable using either radar or ECDIS in the Head-Up mode but they were very confident in their ability to navigate using those devices in North-Up. This is not surprising because throughout their maritime training at the Academy their instructors have emphasized the use of North-Up display modes. Prior to this study, the participants had little, if any, prior experience navigating in Head-Up.

The mean cross-track error by display mode data revealed that those teams navigating with radar and ECDIS both in Head-Up achieved the best navigational accuracy (mean XTE = 0.0514 nm), followed by North-Up / North-Up (mean XTE = 0.0534 nm) and Head-Up / North-Up (mean XTE = 0.0604 nm). These differences are not large; the mean difference between Head-Up / Head-Up and North-Up / North-Up was 0.002 nm (3.7 meters) and the difference between Head-Up / Head-Up and Head-Up / North-Up was 0.009 nm (16.7 meters). Nonetheless, the data suggests that having both radar and ECDIS set to the same display mode increases navigational accuracy and that mariners should avoid navigating with the radar in Head-Up orientation when the ECDIS is North-Up. A 16 meter increase in cross-track error could make the difference between a vessel running aground or navigating narrow waters safely.

The mean cross-track error by direction of travel was surprising. Navigational accuracy was the best when proceeding on the southerly route (mean XTE = 0.0528 nm), followed by the northerly route (mean XTE = 0.0545) and the westerly route (mean XTE = 0.0580). The differences were small and not statistically significant, yet the trend of the means was unexpected. When traveling in a northerly direction, all three display orientations (North-Up / North-Up, Head-Up / Head-Up and Head-Up / North-Up) are approximately the same. Features to the north of the vessel can be seen visually ahead of the vessel and near the top of the display screen. No mental reorientation is required to correlate the view out of the bridge window, the electronic chart and the radar. Traveling in a southerly direction requires the most mental reorientation when the radar or chart is in the North-Up mode. It was expected, therefore, that the mean XTE would be least for the vessels traveling towards the north and the greatest for those traveling towards the south.

There are several ways that the differences in mean cross-track error by direction might be explained. The teams navigated the northerly route first. Perhaps they learned from mistakes made during the first exercise and applied corrections during the second exercise that resulted in increased navigational accuracy when traveling to the south. But, the fact that they performed worse on the third exercise indicates that probably is not the case. Perhaps the participants were aware that navigating in a southerly direction can be challenging and therefore were more diligent on that route. An appropriate survey question might have been enlightening, but, unfortunately, that question was not asked. Perhaps the teams performed worst on the westerly route because it was the last exercise conducted and they were tired and less alert. An appropriate survey question might have answered that question as well. Most likely, though, the reason the mean cross-track error was different for the three routes was because the routes were not equivalent. Although each route required the same number of turns (5), the degree and direction of the turns were not the same in all cases. Also, the land features around the vessel were not consistent between routes. On Route #1, there was land on both sides of the vessel. On Route #2, there was land on the starboard side and ahead of the vessel. The vessel navigating Route #3 had land only on the port side. Because the routes were not equivalent, it is not appropriate to compare mean cross-track errors obtained and no conclusions can be drawn from those data.

The mean cross-track error by direction and display mode provided a statistically significant difference. When navigating Route #3, the teams using Head-Up / Head-Up performed significantly better than those teams using Head-Up / North-Up and North-Up / North-Up. Head-Up / Head-Up was also the most accurate display mode for vessels navigating Route #2, though the difference was not statistically significant. This finding was consistent with the research conducted by Porathe [2] and Norris' contention that using Head-Up on both the radar and ECDIS is a sensible choice [3]. The data from Route #1, however, indicate that Head-Up / North-Up was the best display combination when navigating toward the north. But, because Head-Up and North-Up displays are essentially the same when traveling north, it is likely that the small differences in the mean cross-track error are largely due to the small sample size.

The post-exercise questionnaire also provided interesting data. Though the cross-track error data indicate that the participants navigated most accurately when they used Head-Up / Head-Up mode, 86% perceived that their situational awareness was highest when radar and ECDIS were set to North-Up. In addition, 73% of participants reported that they feel that North-Up is the best mode setting for both radar and ECDIS. Perhaps this apparent discrepancy between perception and performance is due

to the fact that throughout their brief maritime careers, their instructors have routinely taught them that North-Up is the "proper" display mode.
There are several opportunities for future research in this area. This study should be repeated with a larger sample size. This would likely provide more statistically significant results. It could also be repeated with more professional mariners to see if greater experience affects the results. Because navigation isn't the only use of marine radar, it would also be important to examine the effect of radar display mode on collision avoidance decision making.

5. Conclusion

Although most of the findings in the study were not statistically significant, the data appear to indicate that use of radar and ECDIS in the Head-Up display mode contributes to increased situational awareness and navigational accuracy. The difference in navigational accuracy between those using the Head-Up display mode and those using the North-Up display mode was very small. But, few of the participants in the study had much previous experience operating radar or ECDIS in Head-Up and, as indicated by the pre-exercise survey, they felt more comfortable operating North-Up. Despite this, the best navigational accuracy was achieved by those that used Head-Up. It seems likely that if maritime cadets are given more opportunity to practice navigating using Head-Up, the level of accuracy and comfort would further improve.

It is suggested that maritime educators should no longer teach that North-Up is the "only proper display mode". Although most professional mariners routinely use the North-Up mode, Head-Up could, indeed, be a "very sensible choice" [3] for the bridge watchstander. Use of radar in Head-Up and ECDIS in North-Up, however, should be discouraged.

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