Effects of a New Navigation Support Display on Human Performance

Qiao LIU*, Tadatsugi OKAZAKI**, Egil PEDERSEN*** and JUNJI FUKUTO****

Abstract

Collision avoidance is a crucial operative task in marine navigation. The process of information gathering, analyzing, decision-making and execution of evasive maneuver(s) in complex situations is tiresome and can be potentially error-prone. Pedersen et al have proposed a new kind of collision avoidance support interface display in which cone-shaped collision region CDS (collision danger sector) to target ships are visualized to help navigators to perceive collision-related information directly and take evasive actions well in advance of a developing situation. This display, referred to as CDS display, has been further developed and implemented on a ship-handling simulator in National Maritime Research Institute. Experimental studies were carried out to investigate the potential of this display. The experimental results showed that CDS display has the potential to improve navigators' collision avoidance performance and track-keeping performance. In addition, this display has the potential to enhance navigators' situation awareness and lessen their mental workload. Further study with many more participants is needed to provide the necessary statistical power to prove these benefits of this display. Keywords: collision avoidance, collision danger sector, direct perception display

1. Introduction

Marine accidents can be catastrophic since it may result in human and economic losses, as well as environmental pollutions. Navigation of large vessels is inherently difficult. Because of the ship's large inertia, maneuvering actions must be carefully planned well in advance. In addition, the process of information gathering, analyzing, decision-making is stressful and could be potentially error-prone, especially during complex situations (e.g., several vessels in collision courses with own ship).

Advanced Radar Plotting Aid (ARPA) systems were introduced some 30 years ago to replace the manual plotting of radar echoes and are now standard equipment on vessels of any appreciable size. In addition, new technologies such as Automatic Identification System (AIS) and ECDIS (Electronic Chart Display and Information System) have been introduced to the marine industry to further enhance navigational safety. The ARPA system is designed as a collision avoidance support system that provides a display of surrounded marine traffic flow and allows the navigator to track a number of targets automatically. It is a true or relative motion display (with true or relative vectors) providing graphical information about positions and heading of own ship and target ships. Furthermore, it alpha-numerically presents distance at closest point of approach (DCPA) and time to closest point of approach (TCPA), range, bearing, speed and course of selected targets. This graphical ARPA display augments human perceptual system and is particularly useful for navigators to

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understand surrounding traffic. However, ARPA does not provide graphical information that support navigators' maneuvering actions directly. A flashing symbol or aural alarm alerts navigators of coming danger when a target violates user selected setting of DCPA and/or TCPA, but information about what actions should be taken to avoid the danger can not be extracted from the display.

A typical procedure for collision risk assessment with utilization of ARPA is firstly to observe true vectors to get an idea of the actual traffic flow condition, then switch display to relative vector and turn on Trial Maneuver mode to try out the effect of a proposed course and/or speed change. The navigator then decides an evasive maneuver, switch off Trial Maneuver mode and once again observes the true vectors of targets before finally taking a maneuvering action. This "try-and-prove" procedure shows that the navigator actually lacks enough information to build up an updated mental model for problem solving. The situation is worsening when several ships are on collision courses with own ship in congested areas. In addition, for operation in congested waterways the use of Trail Maneuver function is generally too time-consuming to be practical.

The current ARPA display has a problem for direct perception\(^1\) of collision-related information for collision avoidance. The authors argue that it will be more helpful if the collision relationship of own ship with target ships are visualized geometrically in the interface and the navigator can plan suitable evasive maneuvers immediately instead of performing complex information processing activities.

Pedersen et al.\(^2\) proposed a new kind of collision avoidance display, in which CDL (collision danger line) and CDS (collision danger sector) is directly displayed in the interface. By monitoring the tip of own ship's velocity vector in relation with CDS/CDL, the navigator can understand the state of current traffic situations and plan feasible maneuvers to avoid collisions. The subjective evaluation of this play was positive\(^3\). In order to further evaluate the effectiveness of this display, the authors have further developed this display and implemented it on the ship-handling simulator of National Maritime Research Institute. Experiments have been designed to evaluate the performance of experienced navigators with this display. Section 2 will give an introduction about the updated CDS display. Section 3 introduced the experimental contents and procedures. The experimental results are then presented and discussed in Sections 4 and Section 5, respectively. Finally, conclusions are highlighted in Section 6.

2. Direct Perception Display for Collision Avoidance

Based on the algorithms to deriving CDL and CDS\(^4\), The authors have further developed this collision avoidance support display (hereafter, CDS display). An example of this display is shown in Fig.1.

The left part of CDS display is similar to ARPA's graphical display, except that it includes CDS to target ships when the predetermined criteria of visualizing CDS are satisfied. The velocity vector of own ship and acquired targets are drawn in different colors. Since collision risk is estimated by observing the tip of own ship's velocity vector in relation to the CDS of acquired targets, it is necessary to make the tip of own ship's velocity vector vivid in the interface. Therefore, the tip of own ship velocity vector is painted in red.

It is of prime importance to establish criteria to determine to which target CDS should be displayed and how. The CDS to an acquired target will be displayed when predetermined DCPA\(_\text{limit} \) and TCPA\(_\text{limit} \) are violated. Depending on the DCPA and TCPA to an acquired target \(i \), three alarm levels are adopted.

At the first level, when both the relations (2) and (3) are satisfied, the CDS and CDL to an acquired target will be drawn in the display. CDS and CDL are drawn with dotted lines that are easily distinguished from the velocity vectors of own ship and targets.

\[
DCPA_i \leq \kappa \times DCPA_{\text{limit}} \quad (2)
\]
\[
0 \leq TCPA_i \leq \beta \times TCPA_{\text{limit}} \quad (3)
\]

where the coefficients \(\kappa\) and \(\beta\) are greater than 1.0.

At the second alarm level, when both the relations (4) and (5) are satisfied, own ship will pass the target ship at a distance less than DCPA\(_\text{limit} \) and with a TCPA less than the TCPA\(_\text{limit} \). The CDS to this target is then painted to make it vivid in the interface.

\[
DCPA_i \leq DCPA_{\text{limit}} \quad (4)
\]
\[
0 \leq TCPA_i \leq TCPA_{\text{limit}} \quad (5)
\]

At the third alarm level, both relations (5) and (6) are satisfied. In addition to painting the CDS to target
ship $i$, its velocity vector will also be drawn in red solid line. This means that own ship is in great collision risk with this target and emergent evasive maneuvering action is necessary.

$$DCPA_i \leq \gamma \times DCPA_{\text{limit}}$$

(6)

where $\gamma$ is less than 1.0.

The right part of this interface alpha-numerically presents detailed information about own ship as well as target ships, such as DCPA, TCPA, range, speed and course. On the upper right part of the interface, “Collision Risk Indicator” is shown on three levels, where green signifies safe, yellow means potential collision risk and red means direct collision risk.

3. Experiment

3.1 Experimental design

Previous studies\(^2(3)\) have shown that the visualization of CDS in the display could lead to more homogeneous maneuvering actions. This experiment was designed to investigate more about the advantages and disadvantages of this display comparing to ARPA display.

A 2(two subjects)× 2 (two interface, ARPA and CDS display) design was adopted in this experiment. Both the ARPA and CDS display were installed on the ship-handling simulator of National Maritime Research Institute. This simulator is modeling a traffic flow model of Tokyo Bay, in which about 250 ships can be operated simultaneously during the peak hours. Given the hazardous nature of ship operations and traffic density in Tokyo Bay, it was assumed that the advantages of CDS display would be more obvious in this area. A daylight scene was created with landscape and ships visible. Own ship was a 100 metres long container ship with service speed of 15 knots. Scenarios were designed with consideration of the traffic density and reality of traffic situations. The scenario complexity was designed with up to 9 ships in one square mile. All target ships kept constant speed and designated course. To lessen the effect of memory recall, the collision scenes in all scenarios were designed slightly differently from each other.

3.2 Participants

Two experienced navigators were recruited for this experiment. One navigator (hereafter referred to...
Subject A) had nearly 40 years of navigational experience, and the other (Subject B) had 12 years. It was believed that the recruitment of navigators to evaluate the CDS display could make the evaluation more reliable and trustable. In addition, a graduate student was recruited as the operator. The task of this operator was to follow the captain's orders to change the course and speed of own ship.

3.3 Tasks
The subjects operated these scenarios in turn with ARPA or CDS displays. They were required to navigate safely and adhered to the intended track line. For all scenarios the intended track lines were identical, as shown in Fig. 2. Any course alternation should minimize the deviation from the intended track line. Subjects should also avoid sudden course change, speedup or slowdown.

3.4 Performance measures
Several parameters were adopted to measure subjects' performance, such as collision avoidance performance, track keeping performance, subjective workload and situation awareness.

Cross track error, which is given by the mean deviation of own ship from the intended track, is used to measure track-keeping performance. Collision avoidance performance was measured with number of ships violating DCPA$_{\text{limit}}$ and minimum DCPA to target ships. It was required that the minimum safe distance should be no less than 0.1 nm. In addition, the frequency and magnitude of rudder operations were recorded. It was anticipated that fewer and small magnitude of rudder operations were related to good navigational performance.

In addition, subjective workload was evaluated using NASA Task Load Index (TLX$^5$). The subjects were also asked to complete a single item measure of situation awareness (SA$^6$). They were asked to rate how well they were able to identify collision threats, and predict the development of the situation.

3.5 Procedures
Three distinct phases were consisted in this experiment: an introductory session, an experimental session, and a debriefing and commenting session.

In the introductory session, two subjects were firstly given an introduction about the purpose of this experiment, the overview of the ship simulator, and the experimental procedures. In addition, the functions and operating methods of ARPA and CDS display were introduced to subjects. Since the two subjects were quite familiar with ARPA display, CDS display was mainly explained to the subjects. The principle of CDS display as well as how to use CDS display was explained in detail. Then each subject performed one demonstration trial with ARPA and CDS display, respectively, to familiar them with this experiment and get used to operating the two displays.

In the experimental session, each subject performed one trial with ARPA display and one trial with CDS display in turn. These trials were executed without repetition. Each trial lasted about 1 hour. After the execution of each trial, the subject was asked to complete a questionnaire of NASA TLX and situation awareness. In addition, debriefing and commenting sessions were executed after each trail.

4. Results
4.1 Cross track error
For Subject A and B, the track lines of own ship with ARPA display as well as with CDS display are shown in Fig. 3 through Fig.6.

The data for cross track error are summarized in Table 1. For Subject A, overall track accuracy was very high with both ARPA display and CDS display, with a slight improvement of track error with the latter. As to Subject B, there was significant improvement on track accuracy with CDS display. The cross track error was 324.3m with CDS display, compared to 531.3m with ARPA display.
4.2 Minimum DCPA and number of ships violating $DCPA_{\text{limit}}$

For all target ships, DCPAs at $TCPA=0$ were recorded. The minimum DCPA is summarized in Table 2. The number of ships to which the minimum DCPA violated $DCPA_{\text{limit}}$ is shown in Table 3.

<table>
<thead>
<tr>
<th>Subject</th>
<th>ARPA Display</th>
<th>CDS Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject A</td>
<td>111.2</td>
<td>98.8</td>
</tr>
<tr>
<td>Subject B</td>
<td>531.3</td>
<td>324.3</td>
</tr>
</tbody>
</table>

Table 2 Minimum DCPA (nm)

<table>
<thead>
<tr>
<th>Subject</th>
<th>ARPA Display</th>
<th>CDS Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject A</td>
<td>0.05</td>
<td>0.15</td>
</tr>
<tr>
<td>Subject B</td>
<td>0.16</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Table 3 Number of ships with minimum DCPA < $DCPA_{\text{limit}}$

<table>
<thead>
<tr>
<th>Subject</th>
<th>ARPA Display</th>
<th>CDS Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject A</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Subject B</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

For Subject A, $DCPA_{\text{limit}}$ were violated with ARPA display and the number of target ships with minimum DCPA < $DCPA_{\text{limit}}$ was 3. On the contrary, there was no violation against $DCPA_{\text{limit}}$ with CDS display. For Subject B, there was no violation against $DCPA_{\text{limit}}$ with ARPA display, but 2 violations with CDS display.

4.3 Frequency and magnitude of rudder operations

As shown in Table 4 and Table 5, for Subject A, the frequency of rudder operations that are more than 5 degree was 14 with CDS display, less than that with ARPA display. In addition, the maximum rudder operation magnitude with CDS display was 23.5 degree, which was also smaller than that with ARPA display.

On the contrary, for Subject B, the frequency of rudder operations with CDS display was 16, a little more than that with ARPA display. Besides, the maximum rudder operation magnitude with CDS display was also higher than that with ARPA display. It was 35.0 degree with CDS display compared to 27.3 degree with ARPA display.
Table 4  Frequency of rudder operations

<table>
<thead>
<tr>
<th>Subject</th>
<th>ARPA Display</th>
<th>CDS Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject A</td>
<td>22</td>
<td>14</td>
</tr>
<tr>
<td>Subject B</td>
<td>14</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 5  Maximum magnitudes of rudder operations (degree)

<table>
<thead>
<tr>
<th>Subject</th>
<th>ARPA Display</th>
<th>CDS Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject A</td>
<td>27.4</td>
<td>23.5</td>
</tr>
<tr>
<td>Subject B</td>
<td>27.3</td>
<td>35.0</td>
</tr>
</tbody>
</table>

4.4  Subjective workload

The subjective workload of both subjects was measured with NASA-TLX method. The results are shown in Table 6.

Table 6  Subjective workload

<table>
<thead>
<tr>
<th>Subject</th>
<th>ARPA Display</th>
<th>CDS Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject A</td>
<td>1.47</td>
<td>1.20</td>
</tr>
<tr>
<td>Subject B</td>
<td>1.53</td>
<td>3.53</td>
</tr>
</tbody>
</table>

For Subject A, the overall workload (on a scale of 1-5, with 5 being highest) was rated slightly lower with CDS display. The overall workload with CDS display was 1.20, and 1.47 with ARPA display. For Subject B, the overall workload with CDS display was 3.53, significant higher than the value 1.53 with ARPA display.

4.5  Situation awareness

The rating results of situation awareness (on the scale of 1-5, with 5 being best) are shown in Table 7.

Table 7  The rating values of situation awareness

<table>
<thead>
<tr>
<th>Subject</th>
<th>ARPA Display</th>
<th>CDS Display</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject A</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Subject B</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

For Subject A, there was slight improvement on situation awareness with CDS display, which was rated 5 compared to the rated value 4 with ARPA display. On the contrary, the situation awareness was rated rather poor with CDS display for Subject B. It was rated 1 with CDS display compared to 3 with ARPA display.

5. Discussions

The principal research issue in this study is addressed to potential benefits of CDS display, as compared with traditional ARPA display. Cross track error was measured to analyse track-keeping performance. Number of ships violating DCPA_{limit} and minimum DCPA were adopted to evaluate collision avoidance performance. In addition, the frequency and magnitude of rudder orders were also recorded. Furthermore, the subjects’ workload and situation awareness were measured.

For Subject A, there was no violation against DCPA_{limit} with CDS display as compared to 3 violations with ARPA display. Besides, the use with CDS display led to smaller cross track error, fewer rudder operations and smaller magnitude of rudder orders. In addition, the subjective workload and situation awareness were also improved with CDS display. Visualization of the CDS to target ships with collision threats made it possible for Subject A to make a quick assessment of collision risk and take evasive maneuvers well in advance of the developing situation.

As to Subject B, there was no violation against DCPA_{limit} with ARPA display. However, the cross track error was large (531.3m). The on-site observation showed that Subject B was so busy in assessing collision risks and taking evasive maneuvers that he had to sacrifice track-keeping performance. On the contrary, though there was improvement on cross track error with CDS display for Subject B, there were 2 violations against DCPA_{limit} with CDS display. In addition, the subjective workload and situation awareness of Subject B were also rated very poor with CDS display. The case of one violation against DCPA_{limit} (DCPA at TCPA=0 was 0.03nm.) was taken as an example for explanation here. Data analysis showed that the CDS to the approaching target ship had already been visualized in the interface nine minutes before reaching the closest point of approach. However, Subject B ignored it until this target was approaching so near that a sudden course alternation (35.0 degree) of own ship had to be taken to avoid the collision. When noticing that collision was still unavoidable, Subject B finally had to make a sudden stop of own ship. Debriefing after this experiment
showed that Subject B had difficulties on understanding CDS display. It was anticipated that these violations against DCPA limit could be avoided if Subject B understood CDS display fully.

Because of the short introduction session, Subject B could not understand CDS display completely. He struggled to acquaint himself to CDS display even in the experimental session. The experimental results of Subject B showed that whether subjects have adapted to a new display (e.g., CDS display) or not had great influence on performance. If a subject does not have enough training before operating a new display, his performance will not be good and he will be easily frustrated. Since Subject B had not adapted to CDS display in the experiment, it may not be suitable to give a conclusion based on the experimental results of Subject B.

The performance results from Subject A showed that CDS display has the potential to improve collision avoidance performance, track-keeping performance. It also has the potential to enhance situation awareness and lessen workload. Because Subject A was a veteran navigator and was quite familiar with ARPA display, the performance improvement with CDS display was not very significant. If the subjects are novice navigators, it is expected that the benefits of CDS display would be more obvious.

6. Conclusions
Aiming at improving human performance for safe marine navigation, the authors have updated a display for direction perception of collision risk, i.e., CDS display, and implemented it on the ship-handling simulator of National Maritime Research Institute. By observing the tip of own ship's velocity vector in relation to the cone-shaped collision region CDS to acquired target ships, navigators can assess collision risks to multiple targets easily and identify feasible maneuvers to avoid collision. A simulator study of CDS display showed that it has the potential to improve navigators' collision avoidance performance and track-keeping performance if these navigators receive sufficient training on CDS display. In addition, CDS display has the potential to lessen subjective workload and enhance situation awareness, too.

Because of the small number of subjects who attended this experiment, it is not suitable to derive definitive conclusions. A large study with many more participants is needed to prove these benefits of CDS display.

Acknowledgements
The authors are grateful to Mr. Kunihiko Tanaka and Mr. Nobuo Arimura of National Maritime Research Institute for their kind support with this experiment. The authors would also like to thank the two captains and the student who kindly participated in this experiment.

References
Questions and Answers
Masao FURUSHO (Kobe University):
I am sure this research activity is significant and important for improving the navigational safety from the viewing point of human elements.
I have two questions as follows:
(1) Is there any difference among nationalities?
(2) Navigation instrument, such as ARPA, is more familiarized to the young officers. I think it might be difficult to judge (decide) that Subject A is better than Subject B. Could you show the clear difference between Subject A and B?

Qiao LIU:
Thank you very much for your comments and questions.
As to the first question, there has not yet been carried out a study to investigate if there is any variation in the performance among different nationalities. This study and previous experimental test programs \(^{(3)(4)(5)}\) all recruited Japanese nationals as subjects. Preferred ARPA display (relative or true) is known to vary somewhat with individual navigators, type of own ship, and possibly also nationality. Among Norwegian navigators the trend is to prefer true motion display among the younger professionals.

For the second question, the two subjects that were recruited were experienced navigators. Subject A and Subject B had about 40 and 12 years of at-sea experience as navigators, respectively. Both subjects were more than 70 years old. Subject A showed a performance improvement with CDS display. The main factor contributing might be because he was more familiarized with the CDS display than Subject B. Subject B had some difficulty in understanding the completeness of CDS display because of the short introduction session. It is to be expected that the performance of Subject B will improve if CDS display is fully understood.