Direct perception biases with maritime navigation displays of collision risk

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Abstract: Maritime navigation systems need to assist judgments about safe separations and avoidance manoeuvres. Collision Danger Sectors (CDS) are a proposed visualisation for radar displays intended to support the direct perception of impending traffic separation violations. We report an evaluation of the CDS display format in a laboratory study of navigation decision-making involving judgments of safe separations. Contrary to prediction, the CDS display did not bias decision making towards neglecting rules about track crossing. The CDS display did encourage excessive avoidance manoeuvres at higher angles of approach. A marked increase in response time with angle of approach was also evident, indicating a need for decision-aiding.

The ship's bridge has been transformed by the introduction of digital technologies and so also has the task of maritime navigation. Automatic radar plotting systems, electronic chart systems and global positioning systems provide navigators with access to data of an unprecedented quantity and quality. These systems are now able to actively assist navigators in assessing collision risks and choosing avoidance manoeuvres (Lee and Sanquist, 2000). Some advanced radar displays visually render projections of vessels' minimum safe passing distances (HSE, 2007). Liu and Pedersen (2004) have proposed a visualization of this safety envelope projected in time relative to the own ship's speed and heading. This visualization has the appearance of a cone (Figure 1) and is termed a 'collision danger sector' (CDS). If the tip of the vector extending from the navigator's own vessel enters the cone, a collision risk is indicated and an avoidance manoeuvre will be necessary.

The potential benefits of the CDS display can be foreseen through the distinction between perceptual and analytic decision-making. Liu and Pedersen argue that an effective visual display enables the user to make decisions directly from the information presented and the way in which it is represented. This perceptual processing contrasts with a more analytic processing involving a more extended and conscious reasoning process. Vicente and Rasmussen (1992) similarly claim that 'direct perception' is able to out-perform analytical reasoning in terms of speed and error reduction. However direct perception will result in worse decisions and errors if the display omits relevant variables. Vicente and Rasmussen (1992) find evidence for this issue of perceptual displays across all kinds of complex systems control (citing studies by Hollnagel (1981); Smith (1989) and Fischoff (1978)). This was also an issue with trainee operators as reported by instructors at marine academies (Lee and Sanquist, 2000).

By making explicit the predicted risk of a separation violation, the CDS display encourages perceptual processing in deciding whether two vessels are at risk of collision and choosing an avoidance manoeuvre. However the display does not represent an important feature of the navigation situation – the 'rules of the road' (COLREGS) governing sea borne traffic (e.g., vessels crossing from the right have priority). Tam, Bucknell and Greig (2009) have predicted that the CDS display may encourage navigators to ignore the COLREGS.

We report a study of the effect of a simulated CDS display on decision-making in a simplified and abstracted navigation task. The study examined decision making with the CDS display in comparison with the standard radar display. In particular, the study aimed to verify the claim that the CDS display would encourage participants to ignore the COLREGS, as claimed by Tam, Bucknell and Greig (2009) and similarly implied in a more general sense by Vicente and Rasmussen (1992). The study also examined the relative effects of the CDS and standard radar display on collision avoidance decisions.

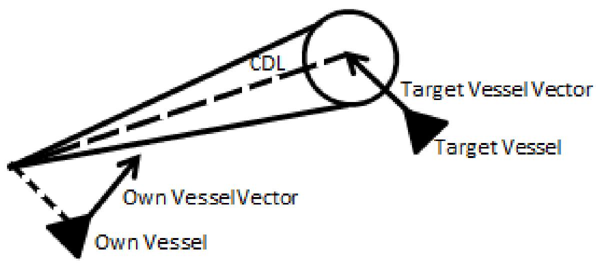

Figure 1. Construction of a collision danger sector (CDS).

METHOD

A matched set of collision risk decision-making trials was created for CDS and standard radar forms. The trials consisted of still images of the display in which the own ship and another potentially conflicting vessel is present. The vessels are in close proximity to increase the effect of rule-following behaviour on the risk of a collision.

CDS Trials

The CDS trials were created using the geometrical construction method described by Liu and Pedersen (2006). Each scenario defined the position, heading and speed of a 'target' other vessel relative to the navigator's own vessel. A velocity vector was added both to the own and target vessels in their current locations, representing its speed and heading. The target vessel velocity vector length and heading were used to define the position of the CDS cone tip during the trial construction (dotted line in Figure 1). The dotted line protruding from the centre of the own vessel would not be visible during trial presentation.

The CDS is defined as the conical area projected from the tip of this velocity vector and bounded by the tangents to a circle representing the minimum separation distance of the target vessel (centred on the tip of the target vessel's velocity vector). If the tip of the own ship's vector enters the

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CDS, a collision risk is present and a manouevre must be made that will maintain the tip outside of the CDS. If the tip of the own ship's vector is lying on the central dashed line of the CDS then the two vessels are predicted to collide.

Each CDS trial consisted of a single snapshot image. Figure 2 is an example where the target is seen approaching at an angle of 30 degrees and the tip of their own ship vector is inside the CDS. Participants needed to choose a soft turn manouevre to move the tip outside the CDS and remove the collision risk.

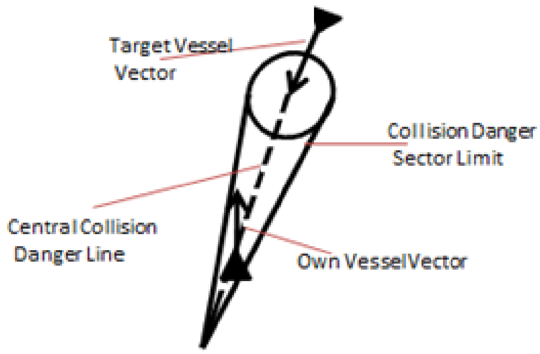

Figure 2. Example of a CDS trial with another vessel approaching at 30 degrees, the tip of the own ship vector is within the CDS indicating a collision risk.

A variant of the CDS was created as a separate display factor, referred to as CDS-X. These trials showed the own ship's vector extending across the CDS with the tip outside of the sector. In each such CDS-X trial, the CDS indicates that no infringement of safe separation if the own ship continues on its course, passing in front of the oncoming vessel. However a separate COLREG, as described below, forbids crossing the path of another vessel even when minimum separations are not infringed. The CDS-X trials would therefore examine whether additional non-displayed rules were ignored, and therefore whether such an effect was generally operative, rather than being simply an aspect of the CDS graphic.

Twenty unique trials were created for both the CDS and CDS-X. Both CDS and CDS-X were replicated to produce forty trials for each factor. The total number of trials in this stage of the investigation therefore numbered eighty and the order of presentation was randomised.

Radar trials

The Radar trials presented a circular display with the own ship iconified as a small triangle at its centre and concentric circles marking separation intervals.

The direction of travel of the own ship icon would always be vertical (the radar showing motion relative to the own ship, therefore the own ship icon is static and centered in the display). In each trial a target vessel on an approaching course was visible, iconified by a short directional line. Each trial consisted of a sequence of two snapshot images with the target vessel changing position. Participants would therefore perceive the target approaching on a constant bearing.

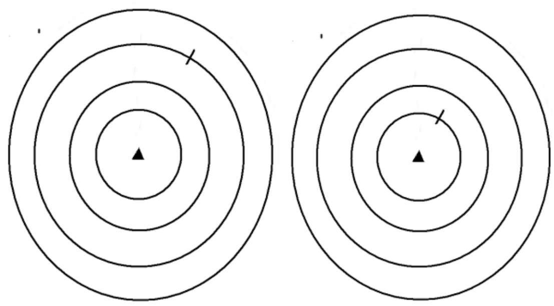

Figure 3. Example of a Radar trial. The images were presented in sequence, another vessel is approaching on a constant bearing of 30 degrees.

Procedure

The collision decision-making task was defined in relation to a set of rules, some of which applied separately to the different display types and some that were common to both. Participants were briefed on these rules prior to the trials and were given training in order to ensure they had learnt them sufficiently.

Rules for Radar and CDS: For both CDS and Radar displays, participants told they must not cross the path of a target vessel. Participants were informed that their responses would be limited to five options. Their options would consist of a soft left or right turn which would rotate the own ship icon by 45 degrees and a hard left or right turn that would rotate their ship by 90 degrees. The final option was 'no turn, speed up' which participants were told was only appropriate if there was no possibility of crossing a target's path.

The trajectories on which a target would be approaching would be 10-40 degrees from the vertical, where the soft turn response would be appropriate as this rotates the own ship icon by 45 degrees, which is enough to avoid a collision for all 10-40 degree approach trajectories. The hard turn 90 degree response was appropriate for the hard turn trajectories where the target was approaching at 50-80 degrees from the vertical. In these cases the soft turn response of a 45 degree turn would never suffice to take the own ship out of a collision situation or a situation where the own ship broke the rules by crossing target's path.

Rules for CDS display. If participants were presented with an image where the tip of their vector was inside the CDS they would be forced to choose one of the options to rotate the own ship icon so as to take the tip of the vector out of the CDS. In the case of the CDS-X trials the vector of the own ship icon would be crossing the CDS with the tip of the vector protruding out from the other side of the CDS. Although the tip of the vector in the CDS-X display is outside the CDS which means that own ship can continue on it path without danger of collision, remaining on the same path would result in crossing target's path which is against the rules.

Rules for Radar. The target other vessel would be approaching the own ship icon on either a constant bearing trajectory, which would result in a collision, or moving across the display on a path that posed no threat to the own ship. Participants were informed that as target was approaching on a constant bearing they had to make a response in order to avoid a collision situation.

Rotation manouevre penalties. Participants were told that a soft left or right turn would incur a delay of one hour while a hard left or right turn would incur a two hour delay. The 'no turn, speed up' option would improve progress by one hour. Where participants erroneously under-rotated, resulting in crossing a target's path or not turning hard enough to avoid a collision, an extra four hours of delay would be added to the existing delay that their option incurred. Participants were encouraged to abide by all the rules and avoid collisions.

Training

Participants were presented with five CDS training trials to cover all possible response options where the tip of the vector was inside the CDS and five trials when the tip of the vector was protruding out of the CDS, which are referred to as the CDS-X trials. Five CDS and CDS-X trials were initially aided followed by five unaided CDS and CDS-X trials. The same process was used with the Radar trials. After each response participants were requested to give the reasons for their decision so as to ascertain whether they were using the rules of the game correctly to inform their decision making process. Any errors made were corrected and the reasons as to why their response was not appropriate were communicated. Out of the twenty four participants, seven were not able to reach proficiency at the end of both the CDS and CDS-X trials. For Radar, three were not able to reach proficiency by getting all the unaided training trials correct. In these cases the aided and unaided training trials were repeated and all seven participants were able to reach proficiency by the end of the second round of training. Participants were informed that they had four seconds to respond in each trial in which they must decide whether a collision risk was present and what manoeuvre was necessary.

Experiment

Participants were presented with the single image for the CDS and CDS-X factors while for the Radar Factor a two image sequence was presented. In each factor the target vessel approached at all eight angles ranging from 10-80 degrees from the vertical and from both the left and the right hand side. The total number of unique trials where participants had to make a soft or hard turn response numbered 16 in total, and an additional four trials, where the 'no turn, speed up' response would be appropriate. The twenty unique trials were replicated to increase the statistical power of the experiment, resulting in each factor (CDS, CDS-X and Radar) being comprised of forty trials presented to participants in random order.

Measures

Participant responses were logged and erroneous responses categorized as crossing errors, over-rotating errors and under-rotating errors. A crossing error was logged if the participant selected an option that caused the own vessel to cross the target's path. Participant's reaction times were measured with a stopwatch and recorded within 0.1s. Task load was measured using the NASA-TLX task load evaluation instrument. Participants were provided with tally cards to assess the relative importance of the six factors in determining how much workload they experienced and a list containing six workload factors and an unmarked 20-point, equal interval scale.

RESULTS

Crossing Errors: Friedmans ANOVA. No effect was demonstrated of the three conditions on number of crossing errors. D(2) F =2.8, p>0.2

Radar, CDS and CDS-X Post Hoc Wilcoxon Signed Rank pair wise comparisons. No significant differences arose for the comparisons highest Z > -1.155 and lowest p>.2

Over-Rotating (OR) and Under-Rotating (UR) Errors. Crossing errors will not be included in this analysis.

Friedmans ANOVA for OR, UR error scores. No significant effect of condition on the number of errors D(2) F =5.0, p>0.05 although the p-value lies close to significance at 0.082.

Post Hoc Wilcoxon Signed Rank pairwise comparisons. Means communicate participant Mean Error. CDS (Mean 1.35) produced fewer errors than Radar (Mean 1.64) Z= -2.47, p<0.05. The remaining two comparisons were not significant.

Post Hoc Wilcoxon Signed Rank pair wise comparisons between same angles of approach for the three conditions. Pairs comprised of same angles of approach for CDS, CDS-X and Radar. All angles of approach are included in the analysis.

10-40 Degrees Pairs**:** all except two pairs of the 10 to 40 degrees were not significant. Pairs with significant differences: CDS-X 40 (Mean 1.9) - R-40 (Mean 1.3) Z=-2.151, p< 0.05 and between CDS-40X (Mean 1.9) - CDS-40 (mean 1.7) Z= -2.236, p<0.05.

50 degrees Pairs**:** pairs with significant differences: CDS 50 (Mean .7500) - R-50 pair (Mean 1.6667) and the CDS-X50 (Mean .5833) – R-50 (Mean 1.6667) pair the highest Z=-3.589 and the lowest p< 0.001. No significant difference was uncovered between the CDS-X50 and the CDS-50.

60 degree Pairs: significant differences were uncovered in R-60 (Mean 1.0833) compared with CDS-X60 (Mean .4167) Z= 3.119, p<0.01. No significant difference was uncovered between the R-60 and CDS-60 nor CDS 60 and CDS-X 60.

70 Degree Pairs**:** no significant differences were uncovered between any of the pairs, highest Z= -.577 and lowest p>0.5.

80 Degree Pairs**:** no significant difference between any of the pairs, highest Z= -0.905 and lowest p>0.05.

Reaction Time Results: A three way ANOVA uncovered a significant effect of display on participants RT's (D2) F=41.1, p<0.001.

Post-Hoc comparisons t-test**:** RT of CDS and CDS-X both significantly higher than Radar. CDS (M=2.9, SE=0.11)–

Radar (M=1.9, SE=0.7, t(23)= -8.66, p< 0.001) CDS-X (M=3, SE=0.9) –Radar (M=1.9, SE=0.7, t(23)= -10.37, p< 0.001). No significant difference in the mean RT's of CDS and CDS-X.
T-test results (RT 10 Degrees – RT 80 Degrees): RT within each condition significantly longer at 80 Degrees rotation than 10 degrees rotation. Data provides evidence of mental rotation. Radar 10 (M=1.5, SE=0.7) Radar 80 (M=2.5, SE=0.16, t(23) = - 5.471, p<0.001) CDS 10 (M= 2.3, SE=0.18) – CDS 80 (M=3.4, SE=0.23, t(23) = -3.7, p<0.001) CDS-X 10 (M=2.4, SE=1.4) – CDS-X 80 (M3.7, SE=0.36, t(23) = -2.8, p<0.01).

NASA-TLX Results The CDS and CDS-X are the same display method therefore in this case they will be labeled as CDS. The paired sample t-test compared the two sets of weighted scores for the Radar (M=48.71, SE=2.55) – CDS (M=54.94, SE=2.87, t(23)= -1.99, p=0.59) and a marginally non-significant result was indicated.

Retrospective think-aloud: CDS-X and CDS display gave the impression that a greater degree of own vessel rotation was necessary to not cross target vessel path.

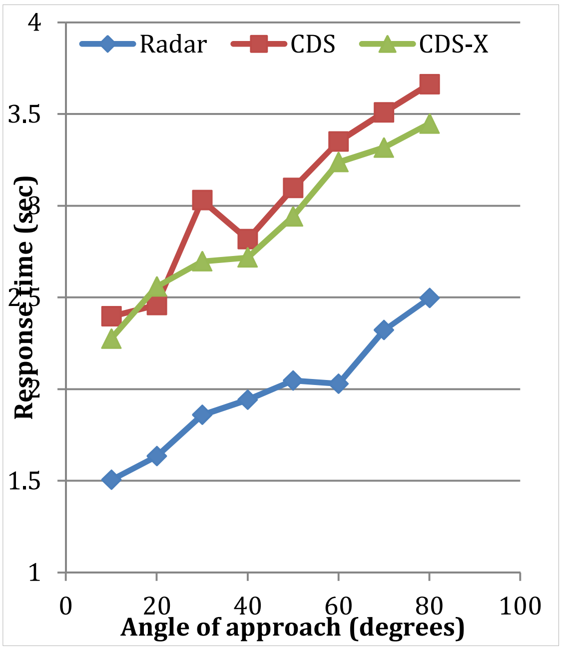

Figure 4. Response time with increasing angle of approach in CDS (Collision Danger Sector), Radar, and variant CDS-X conditions.

DISCUSSION

Response times and task load

The CDS display is intended to assist prediction of separation violations and decisions about avoidance manoeuvres. Hence it would be expected that participants' response times would be lower with the CDS displays than with the Radar. The results of this study do not support this hypothesis and a significant difference was found in the opposite direction. The greater time to make a decision using the CDS display with the CDS display is to be explained by its relative visual complexity and participants' limited training, also reflected in the greater difficulty recorded by the NASA-TLX. Implications of these results for user interface design include keeping the visual design as simple as possible and selectively and progressively reducing visual clutter as traffic congestion increases.

Mental rotation

The data show a clear linear increase in response time with angle of approach of the target vessel. This effect can be explained by participants mentally rotating their own ship icon to identify a conflict, rather than using recognition to guide their choice of hard or soft turn. Participants appear to continue to mentally rotate their own ship even at the most extreme angles of rotation, such as approach headings of 80 degrees, where the hard turn manouevre is the most probable response. Mental rotation clearly adds significantly to a navigators task load when judging potential collision risks. Rather than allowing response time to be affected by mental rotation, it would be preferable and possible for the system to suggest the required degree of turn manoeuvre for a specific target vessel, which the navigator could then choose to accept.

Crossing errors

The study did not find significant differences between the displays in terms of number of crossing errors. The number of crossing errors recorded was extremely low in all conditions, indicating that participants were using their conceptual knowledge while interacting with all displays.

The study therefore did not support the prediction made by Tam et al (2009) that the perceptual salience of the CDS display will cause participants to ignore the COLREG rules that forbid crossing in front of another vessel. In discussing the factors affecting levels of cognitive control, Vicente and Rasmussen (1992) identify lack of experience and skill as affecting the likelihood that the operator will rely on lower levels of cognitive control (skill-based behaviour, rule-based behaviour) where the perceptual salience of the display would be expected to have an increased effect. The limited training of the participants in our study would have meant they were operating with a higher level of cognitive control (knowledge-based behaviour), making it more likely that they would incorporate their knowledge of the traffic rules including the crossing rule.

Rotation errors

The majority of rotation errors were of turns made in the right direction but too hard or too soft. Comparisons made at each angle of approach where a soft turn response was appropriate, indicated that when participants used the CDS and CDS-X displays compared to the Radar display, their performance regarding incorrect hard rotations was not significantly different for the majority of the comparisons. However, participants in the CDS-X condition at the high proximity, 40 Degrees angle of approach, incorrectly chose the hard turn response significantly more than the when using Radar at the same angle of approach. Further significant differences were uncovered for both CDS and CDS-X when compared to Radar at 50 degrees and CDS-X and Radar at 60 degrees, both angles are also in close proximity to the threshold between hard and soft turns. It appears that the perceptual salience of the CDS display biased judgments towards a harder turn than is required. This finding is in line with the retrospective think-aloud data in which participants reported that if “the arrow” was protruding through to the other side of the CDS (i.e., the CDS-X trials) then it was assumed that a hard turn was more appropriate compared to a soft turn to bring the tip back through the CDS and out of the other side in order to avoid crossing the target’s path.

This finding has implications for the use of the CDS display in congested waters where navigators will need to make accurate changes of course. Excessive and unnecessary turns will affect progress in the voyage and increase fuel consumption. A better display would advise the navigator on an optimal turn manoeuvre taking account of the COLREGS. Communication of a navigator’s intended route to other vessels in the area would significantly improve this decision making, particularly if that route was superimposed on the navigation displays of those other vessels.

CONCLUSION

This study is the first evaluation of the effect of the proposed CDS maritime radar display on navigators’ decision-making. The study did not find evidence for the effect anticipated by Tam et al (2009) of the CDS causing navigators to forget or ignore important factors in the task (the ‘rules of the road’) that were not visible in the display. The study needs to be repeated with a more highly featured and genuinely continuous navigation task to determine whether the expected effect is present. The study did find evidence of negative effects of the CDS in judging the correct avoidance manouevre in terms of a significant bias towards a harder turn than required. The data also show an increase in the difficulty of judging collision risks at higher angles of approach, an effect that was found across display forms.

The most visible finding was the general increase in response time with the CDS displays compared with the simple radar display, forcing some reflection on the notion of direct perception. Direct perception displays encourage intuitive, surface processing rather than a more analytic processing. They are able to do this because they present a visualized abstraction of key attributes of key domain objects in relation to task goals, translating and filtering low level and second order data into a simplified abstraction. Operators are therefore able to directly perceive the state of the task domain and respond appropriately and rapidly. However the addition of the cone and vectors in the CDS displays appears to have increased visual complexity relative to the simple radar display, at least in the limited scenarios used in this study, increasing the time taken to predict separation violations. Visual complexity is a distinct factor to be accounted for in designing direct perception displays.

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