Evaluation of the effects of field-of-view in augmented reality for marine navigation

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ABSTRACT

Augmented reality (AR) has potential for increasing safety in marine navigation, but current-generation AR devices have significantly limited field-of-view, which could make them impractical for such usage. We developed a virtual reality ship simulator that displays AR navigation overlays across variable fields-of-view. This paper presents a human factors study, in which participants (including experienced boaters) piloted a virtual vessel while navigating using combinations of a traditional electronic chart display and AR overlays presented at various fields-of-view. Eye movements were tracked to discover how AR and restricted fields-of-view effect navigational target finding, safety, and situational awareness. The results indicate that AR provides significant benefits that can promote safer marine navigation, and that the field-of-view of an AR device has some significant and predictable effects on its usefulness for navigational tasks. Increasing field-of-view capabilities in future AR hardware is expected to improve AR's usefulness for marine navigational tasks, however, this research shows that current-generation AR hardware (such as HoloLens 2) may already be suitable for this application, as most of the significant benefits were gained by providing AR overlays regardless of their field-of-view.

Keywords: Augmented reality, field of view, evaluation, marine, navigation, ECDIS, electronic charts

1. INTRODUCTION

Augmented reality (AR) technology has potential for aiding marine navigation by displaying critical navigational information directly on top of mariners' real-world view. AR can display information such as navigational markers otherwise not visible due to darkness or fog, predicted ship tracks for surrounding traffic, and underkeel/airgap clearances for precision navigation in tight waterways. By displaying such information in a heads-up manner, it keeps mariners' eyes off display screens and on the water, which is the most important factor in avoiding ship collisions.

Furthermore, such first-person or perspective presentation of marine navigational information has been shown[1] to require fewer cognitive spatial translations than traditional track-up electronic charts, which increases the speed at which users can locate targets, and can reduce errors and overall cognitive load.

However, current AR devices have significantly limited field-of-view (FoV), which could potentially hinders their application in marine navigation tasks. To evaluate the effects of limited AR FoV in marine navigation, we developed a virtual reality ship simulator for conducting human factors studies. The simulator provides a pilotable copy of our research vessel and the surrounding harbor, and generates AR navigation overlays at variable FoV values, which allows it to simulate a range of potential AR devices, from the narrow (35° diagonal) Microsoft HoloLens, up to the full 110° diagonal capability of our head mounted display. An integrated eye tracker provides data on where users are looking, which can be mined to understand how they use the AR overlays to navigate.

This paper presents the design, implementation details, and results of a study in which participants were tasked with piloting a virtual vessel (using a force-feedback steering wheel and throttle) from waypoint to waypoint, using combinations of a traditional electronic chart display and AR overlays presented at various fields-of-view. The results are then analyzed to explore the potential usefulness of AR for aiding safe marine navigation. Finally, conclusions are made from the results about how although FoV plays a role in the usefulness of AR for such tasks, and advancements in future AR hardware will certainly improve performance, even current-generation AR hardware may provide sufficient FoV for aiding safe marine navigation.

2. RELATED WORKS

The approach of using virtual reality to simulate a range of augmented reality devices for evaluation purposes is not new[1], and has been experimentally validated[2] to produce comparable results to identical experiments run on actual AR hardware. This is possible because virtual reality hardware is currently more advanced in terms of resolution and field-of-view than AR hardware. It has the benefits of not requiring development targeting multiple hardware platforms, and avoids complications from registration and latency issues. It also avoids issues of brightness, such as how most current AR devices are not bright enough to be used outside on a sunny day. Finally, for our application domain of marine navigation, it is far easier and safer to run participants through a ship simulation in virtual reality (VR) than to allow them to pilot an actual vessel. It is also much less expensive than full-scale physical simulators.

Ware and Arsenault[3] conducted a marine navigation study that compared performance in target-finding tasks between traditional track-up chart displays and spatially aware handheld displays. These handheld displays showed perspective views of the chart and targets, and were held outstretched by participants in such a way that they effectively provided a first-person perspective view similar to an AR overlay, only it was offset slightly (usually held just below wherever they were looking in the simulator). They found that presenting the information in this perspective, which matches a user's viewing perspective, eliminated the spatial transformations required when using a track-up chart display, and reduced the overall cognitive load of the target-finding task. Their results found this perspective display enabled faster target finding, and reduced the number of errors made by novice navigators (enabling them to maintain low error rates similar to expert navigators).

Kishishita et al.[4] studied the effects of wide-field-of-view augmented reality on divided attention search tasks by conducting an experiment in which participants solved puzzles while monitoring a number of potential targets surrounding them. Occasionally while solving the puzzles, a target would have an AR annotation placed over it, and participants would indicate when they noticed these AR annotations. Targets were distributed horizontally, and the horizontal-FoV values they used ranged from 36° to 100°. They tested both "in-view" annotations, which were displayed on the periphery of the AR FoV area for targets that were outside the AR FoV, and "in-situ" annotations, which were only displayed when the target was within the AR FoV. The in-situ condition of their experiment is very similar to our experimental task, and here they found that the 100° FoV condition resulted in significantly higher target detection rates than the 36° FoV, especially for targets at wider angles from the center of view (puzzle). This suggests that in our experiment we should see an effect in which wider AR FoV result in targets away from the ship's heading are more readily found solely using the AR overlays and without viewing the electronic chart display. Furthermore, Kishishita et al. report their linear regression detecting a turning point at approximately 133° FoV, indicating that increasing FoV beyond this value presents significantly diminishing returns as content is then displayed in the user's peripheral vision, where it can go unnoticed.

In a previous study[5], Kishishita et al. conducted an experiment on users walking through a maze while wearing either a VR simulated see-through display and an actual wide-field-of-view AR display. They tracked how many "information source" targets users noticed, which were prompted using annotations on the periphery of the AR display's field-of-view. These annotations indicated that a target was off-screen in a particular direction. They found that at very wide fields-of-view (81° and wider), users actually noticed fewer targets, because the annotations became less noticeable due to being displayed in the user's peripheral vision. However, locating them here in the periphery was reported to be more comfortable to users than locating them in the center of the visual field. They also found that adding motion to these peripheral annotations increased their perception. These findings again indicate that, although a wider field of view certainly allows users to see more digital information, any information displayed in the periphery can go unnoticed. Thus, even on a device with a wide field-of-view, urgent/important content outside the center of view should be emphasized with movement, connecting lines, etc.

Ren et al.[6] examined the effects of presenting simulated AR content at different field-of-view values inside a full-surround, spherically projected virtual reality system. Their scene consisted of a stereo panoramic photo of temple ruins, with three AR annotations: a map, a photograph, and a chart, each rendered very large and floating above/around the scene, and connected/linked to objects in the ruins with 3D lines. They tested two FoV conditions: 108°x82° and 45°x30°. Tasks involved following links to/from objects and annotations, such as finding an object in the scene when prompted by a number that the chart, which would have a link to it, and finding objects prompted by a letter that was a label on the map with a link to the object. Ren et al. found the wider 108° AR FoV resulted in significantly faster task completion times than the constrained 45° AR FoV. Notably, Ren et al. drew a black border line around their simulated constrained FoV, explicitly informing participants of the boundaries of the AR content, while our experiment kept these boundaries invisible, which is the case in modern AR devices such as HoloLens and Magic Leap. They note that their black border may have been responsible for an unexpected slight increase in correctness for the constrained FoV condition, as participants reported that “they were more careful with the small field of view, and the black border helped them concentrate.”

Trepkowski et al.[7] studied the effects of AR FoV on visual search tasks (specifically finding target text labels, and finding target symbols by color and shape) at different information densities. They used both a tiled wall display and a Microsoft HoloLens for displaying stimuli, and used a range of FoV values (14°, 23°, and 35° diagonal) that were notably much lower than those used in the previously mentioned studies and in this paper. They found that when using the HoloLens, higher FoV values significantly improved text and symbol search task performance, and that the low FoV condition led to significantly more targets being missed. They concluded that increasing AR FoV led to a search performance increase of “7–28% over the next smaller FOV.”

Finally, while there are of course many solutions involving “in-view” AR annotations that alert and draw attention to targets located outside the AR FoV, we specifically wanted to study “in-situ” AR annotations, i.e. those only displayed when their targets are inside the FoV. For our particular domain of marine navigation, any real-world application would likely have too many simultaneous annotations to support in-view solutions without disruptive clutter or complex filtering, as well as expansive features (e.g. boundaries & fairway lanes) that do not translate well to single locations.

3. EXPERIMENT

This experiment was designed to study how users gather spatial information, locate targets, and navigate while using an augmented reality marine navigation aid presented across a range of field-of-view conditions, with a goal of determining AR’s usefulness for marine navigation tasks, and ideal FoV requirements for AR devices in this application.

3.1 Simulation interface design

This experiment was conducted using a custom virtual reality ship’s bridge simulator, shown in Figure 1. The simulator uses an HTC VIVE Pro Eye head mounted display (HMD), which provides a resolution of 1440x1600px to each eye, for a total resolution of 2880x1600px spread over a total field-of-view of 110°, and refreshes at 90Hz. The HMD has an integrated eye-tracker, which provides gaze direction with an accuracy of 0.5°-1.1°, at an update rate of 120Hz.

Figure 1: The experimental setup. Participants wear a head mounted display while interacting with physical boat controls (wheel and throttle). A television provides a mirror view that allows experimenters to monitor subjects’ performance.

The simulator is controlled using a Logitech G920 force feedback steering wheel modified with a large stainless steel ship's wheel, and a Logitech G Saitek Pro Flight throttle with a custom 3D printed handle. These controls are mounted together on platform that is tracked by a VIVE Tracker, such that the virtual models of the controls appear in the simulation exactly where they are in the real world.

The software for the simulation was developed using the Unity 3D game engine. The simulation consists of a ~64km² copy of Portsmouth harbor, New Hampshire, with physics-simulated water and shoreline models generated from digital elevation models and draped satellite photos, supplemented by high-resolution textured 3D models generated using structure-from-motion. Users are placed in a copy of the bridge/cabin of our research vessel, within which the VIVE's wide-area tracking allows them to freely move around. See our previous systems paper[8] for more details and in-depth discussion regarding this simulator and its capabilities.

3.2 Task and procedure

Participants were tasked with piloting a virtual boat from buoy to buoy along a pre-determined course. The course consisted of two starting buoys (intended to ensure participants began the main course at full speed and headed in a consistent direction) followed by four sub-courses with 24 buoys each. Each sub-course was designed to present buoys at a range of offset angles from participants' expected heading, as shown in Figure 2. There were four target buoys for each of the lesser angular offsets (10°, 20°, 30°, 40°, 50°) and two target buoys for each of the wider (and more disruptive) angles of 60° and 100°. Offset direction was equalized in terms of the number of right and left turns for each angle. Order of the angles was random and varied by sub-course.

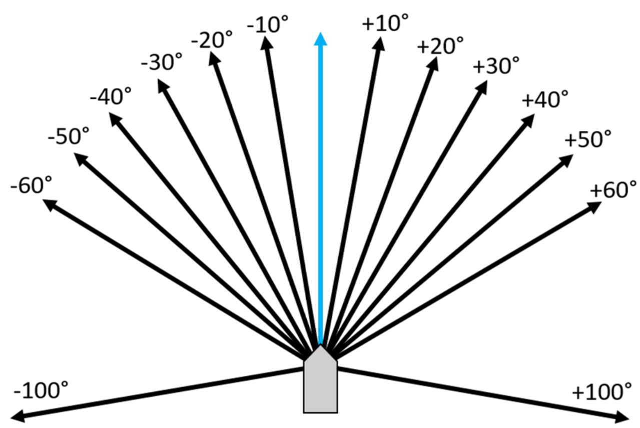

Figure 2: Angular distribution of target buoys in relation to the ship's heading at the start of each trial.

The distance between each buoy was consistent, and this distance was chosen based on pilot studies to give participants enough time to locate the next target buoy, adjust the boat's heading towards it, and then continue straight towards it for a few more seconds (which helps maintain predictable boat headings at each buoy). While a throttle to control speed was provided, participants were instructed to always keep the throttle at maximum forward speed, except when they made a mistake and needed to significantly correct their course. This maximum forward speed was chosen based on pilot studies to make navigating the course a simple, relaxed steering exercise, and not a task that would require quick reaction times or driving/boating skills.

To keep participants engaged with the steering task, the boat simulation included the forces of water currents. These currents caused the boat to drift in the direction of the current (with forces dependent on boat angle relative to current) and caused it to rotate towards the upstream direction. These currents were tuned based on pilot studies such that some active steering input was required from participants to maintain heading towards targets, but were kept subtle enough as to not increase the difficulty to the point any actual skills were necessary.

At all times during the study, participants are able to look up and view a traditional electronic chart display and information system (ECDIS) that is displayed on a virtual monitor located just above the boat's windows (as shown in Figure 3). The

ECDIS shows a track-up electronic chart (shown in detail in Figure 4) generated using OpenCPN open-source charting software. It consists of a standard electronic nautical chart, which pans and rotates automatically to keep an icon of the boat in the center and pointed upwards. The current target buoy is indicated by a yellow buoy icon, and the straight-line path from the boat's position to the buoy is drawn with a red line. Because we are interested in detecting when participants look at the ECDIS, the screen is blanked out unless the eye-tracker explicitly reports that they are looking at it. This prevents false-negatives that could result from participants reading the ECDIS using their peripheral vision. The position of the ECDIS and the eye-tracking detection area around it was tuned during pilot studies to eliminate false-positives.

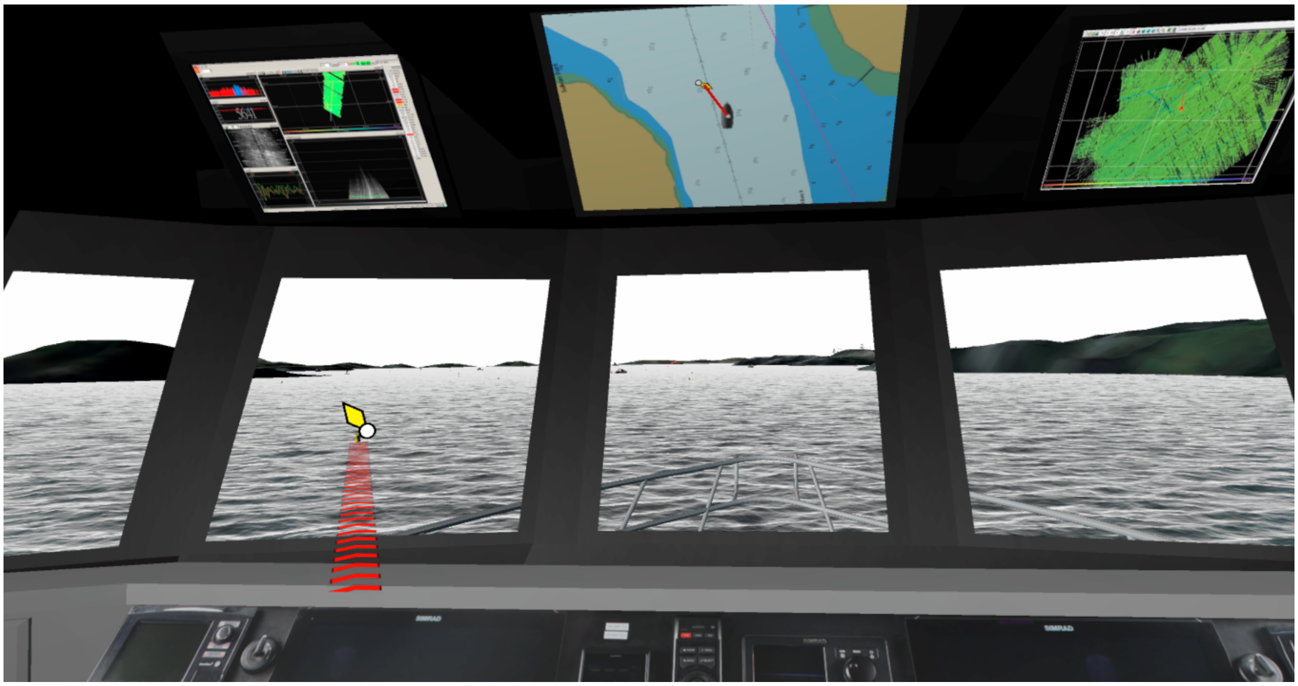

Figure 3: Example view inside the simulation, showing a wide field-of-view augmented reality overlay of a yellow icon over the target buoy and a red line connecting it to the ship's current position. Visible above and center is the ECDIS displaying the same information in track-up chart form.

Figure 4: Detailed view of the track-up ECDIS display in the simulation, showing target buoy (yellow icon) and connecting line (red) between boat and target. The chart automatically pans and rotates to keep the boat in the center and facing upward.

During each of the four sub-courses, participants experienced one of four different viewing conditions. Three viewing conditions provided the simulated augmented reality overlays at different field-of-view values, while one condition did not provide any AR overlay and thus required participants to rely solely on the ECDIS to navigate. The first FoV condition is the narrowest, and emulates the HoloLens 2 with a 52° diagonal at a 3:2 aspect ratio. The second FoV condition is 60° diagonal at a wider 16:9 aspect ratio, chosen to be roughly halfway between the FoV of the original HoloLens and the third FoV condition, which is 90° at 16:9. It is important to note that although the diagonal FoV value is only 8° larger from the first to second condition, the aspect ratio is much wider, which results in a 21% increase in horizontal field-of-view (and a 73% increase in horizontal FoV from narrowest to widest). For our study, these horizontal FoV values are significantly more important than the vertical values, as targets are distributed across the horizontal, and AR content was not permitted to draw over / occlude the ship's instrument panels just below the windows. A comparison of these FoV values is shown in Figure 5.

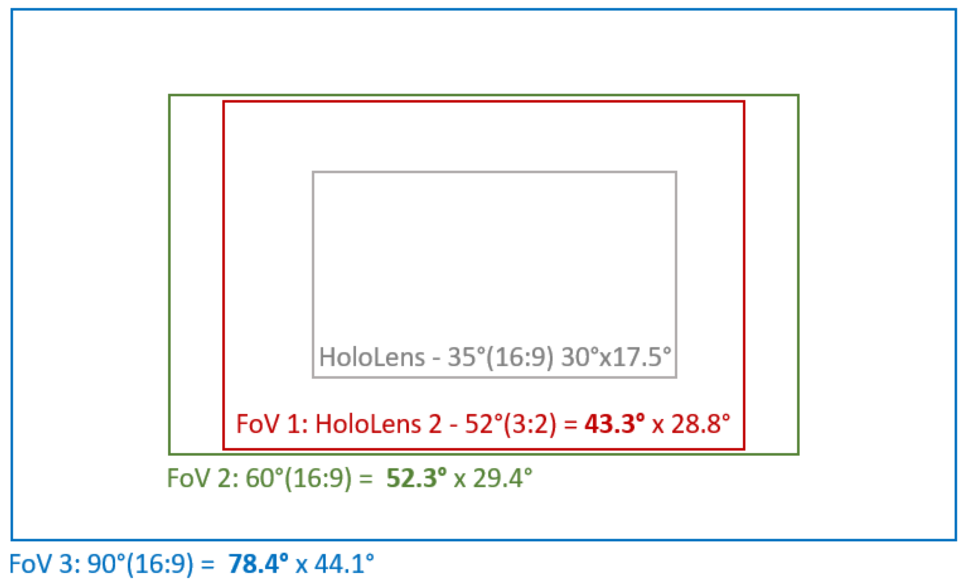

Figure 5: The three field-of-view conditions used in this experiment. The original HoloLens FoV is provided for reference.

Similar to the ECDIS's presentation, in each of the AR viewing conditions, the AR overlay draws the same yellow buoy icon directly over the 3D location of the target buoy. This icon is billboarded such that it always directly faces the viewer, and is scaled to maintain a consistent visual size, subtending a visual angle of 5°. The path from the boat's current position to the target buoy is indicated by a red line, dashed with a chevron pattern. This dashed design was developed to enhance perception of the line's direction and length. An example of this overlay can be seen in Figure 4.

To ensure that participants did not just head for the next visible buoy, and instead had to use either the ECDIS or the AR overlay to find the next target buoy, the harbor was littered with many distractor buoys. Furthermore, the meandering course often doubled-back on itself, and thus previous and upcoming buoys also played a distractor role.

There were 20 participants total, consisting of 8 experienced boaters and 12 novices, 16 male / 4 female, ranging in age from 18 to 79 (mean age: 31.3). Participants were volunteers from an ocean mapping research center and students recruited from the wider university community, who were paid $20 compensation for their participation.

Each participant began the study by filling out a consent form and undergoing vision tests. A standard eye chart was used to ensure at least 20/20 corrected vision, and a random-dot stereogram test was viewed through a stereoscope to verify ability to perceive stereoscopic 3D. Participants then put on the HMD, and it was adjusted to fit their head comfortably while keeping the optics properly centered over their eyes. The VIVE Pro Eye's calibration software was then used to assist adjusting the HMD's interpupillary distance, and to calibrate the eye tracking for each participant.

Participants were first provided with a separate training course, in which they learned how to pilot the boat from buoy to buoy, and were familiarized with how to understand and use both the AR overlays and the traditional electronic chart (ECDIS) to find the target buoys. Once participants showed sufficient proficiency and agreed that they had practiced enough and fully understood the task, they began the study on the actual buoy course. The 98-buoy study course took approximately 25 minutes to complete.

Participants were randomly assigned to a standard 4x4 Latin Square group to counterbalance any learning effects arising from the order in which the participant saw the AR conditions. Expert boaters were equally distributed among the groups.

4. ANALYSIS

For each trial, the navigational task can be broken down into three sub-tasks: Locating and visually acquiring the target buoy, adjusting course / steering towards it, and maintaining course toward it. In AR-enabled conditions, low-angle targets can be immediately visible in the AR overlay. Higher-angle targets that are outside the immediate AR FoV are found either by visually scanning left/right, or by looking up at the ECDIS to determine which direction to look. The choice of which of these strategies to employ varied from participant to participant (explored later in Section 4.4), and was dependent on learning and ordering effects (Section 4.3). No-AR conditions required the ECDIS strategy for every trial. Finding a target using the ECDIS requires participants to cognitively translate spatially between the track-up chart and the scene. Ware and Arsenault[3] provide a detailed explanation of this visual cognitive loop.

After the target has been located, participants steer the vessel towards it. In AR-enabled conditions participants generally maintained eye-contact with the target itself, as the constant-visual-angle AR marker over the target buoy is easy to see at a distance. However in no-AR conditions, participants were often observed keeping their eyes on the ECDIS as they turned, lining the ships heading up with the line connecting it to the target. This was likely because without AR markers, the buoys can be difficult to see at a distance, and distractor buoys increased the challenge of determining which buoy is the target.

Finally, once the correct heading has been established, participants head straight towards the target, with only minimal steering required to maintain the course. During this phase participants would either keep their eyes fixed on the target, look around the scene (e.g. at the coastline or surrounding ship traffic), or check the ECDIS.

4.1 Visually acquiring the target

The augmented reality markers over target buoys are most useful when they are immediately seen at the start of a trial (i.e. without scanning). As illustrated in Figure 6, the immediate visibility of AR markers for each of the three field-of-view conditions is predictable: In the narrowest 43° FoV condition, only 10° targets will always be immediately visible, while 20° targets would be expected to fall on the periphery, somewhat cut-off, but mostly visible. In the medium 52° FoV condition, 10° and 20° targets are well within the FoV, while 30° targets are entirely outside. Finally, for the widest 78° FoV, all 10°, 20°, and 30° targets should be immediately visible, while 40° targets are just barely within the periphery. Targets predicted to be just within the periphery of the FoV or slightly outside it will often be immediately seen if the participant happens to be looking slightly off-center in that direction as the trial begins.

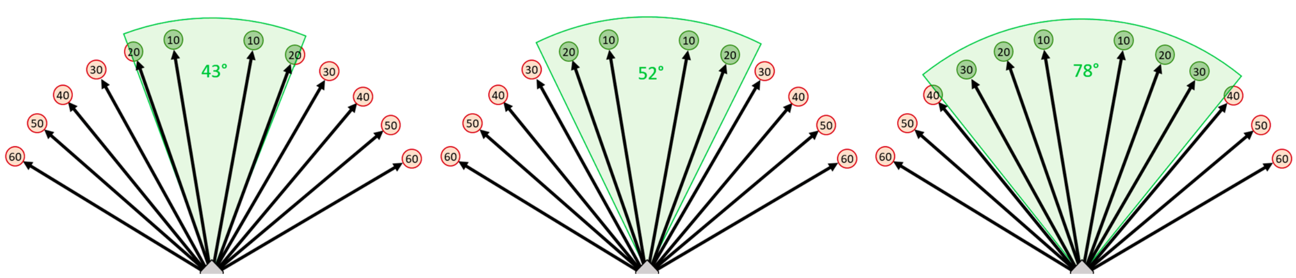

Figure 6. Predicted visibility of AR markers on angular targets during the three different field-of-view conditions. Note that AR markers subtended five degrees, i.e. a target at 20° would be visible starting from 17.5° to 22.5° off center from the viewing direction.

Looking at the elapsed times to visually acquire the target buoy (shown in Figure 7), it can be seen that wider AR FoV values generally led to participants getting their eyes on the target sooner. As predicted, the medium- and wide-AR conditions appear to help users find target buoys faster in lower-angle conditions (10º-30º), but perform similarly at higher angles where scanning is required regardless of FoV. As expected, the no-AR condition resulted in significantly longer times to visually acquire targets, as users had to first consult the ECDIS to gather information about where to look for the target. Predictably, the angle of the target relative to the current heading had a significantly effect on the time to acquire targets: the further off to the right or left of the current heading, the longer it took participants to find the target.

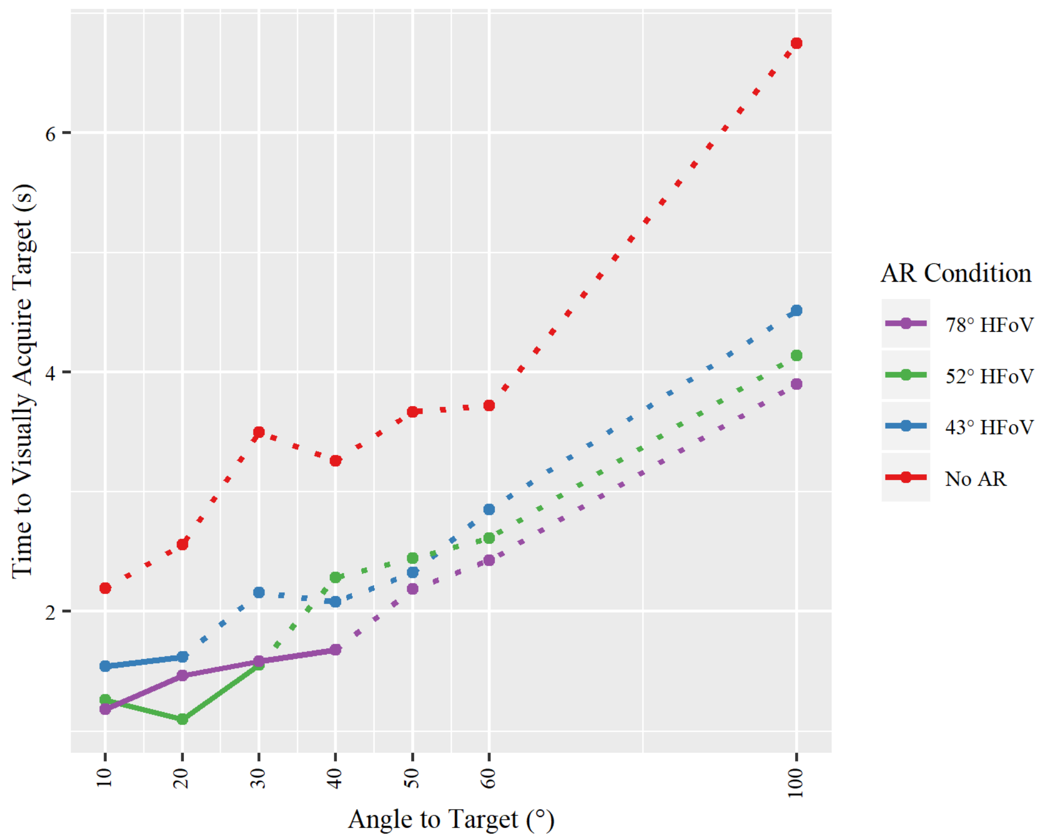

Figure 7: Time to visually acquire target buoy by AR condition and target angle. Solid portions of the lines indicate angles at which targets should always be immediately visible. Notice times in AR-enabled conditions rising beyond these angles (dashed portions).

In AR-enabled conditions, when the target is not immediately visible, it does not take long for participants to realize this and either start scanning or consult the ECDIS. Scanning the immediate area in front of the boat is a very quick process. This is revealed by looking at trials with extremely off-course 60º and 100º targets (bottom right of Figure 8), where participants scan but do not see a target, then fall back to the strategy of viewing the ECDIS, all in under a second.

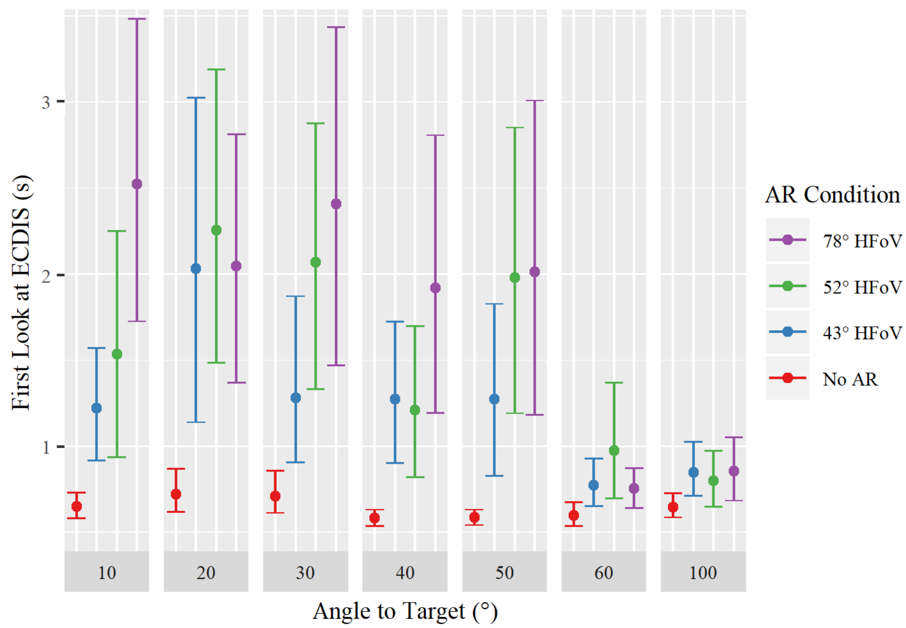

Figure 8: For trials in which the ECDIS was viewed, the time when participants first looked at the ECDIS.

Analyzing how often target buoys were visually acquired before a participant looked at the ECDIS shows that the AR overlays were effective at presenting navigational waypoints while keeping mariners eyes on the water. As visible in Figure 9, across all AR-enabled conditions, low angle targets were visually acquired around half the time without first viewing the ECDIS. As 10° targets should almost always be immediately visible, the half of trials in which participants looked at the ECDIS first represents participants (1, 11, & 18 in Figure 16) who preferred a strategy of checking the ECDIS at the start of each trial, as well as participants who looked at the ECDIS at the end of the previous trial and maintained eye contact with it through the start of the next trial. (In retrospect, to prevent this specific behavior which confounds our analysis, it may have been helpful to blank out the ECDIS screen at the start of each trial until users looked away.)

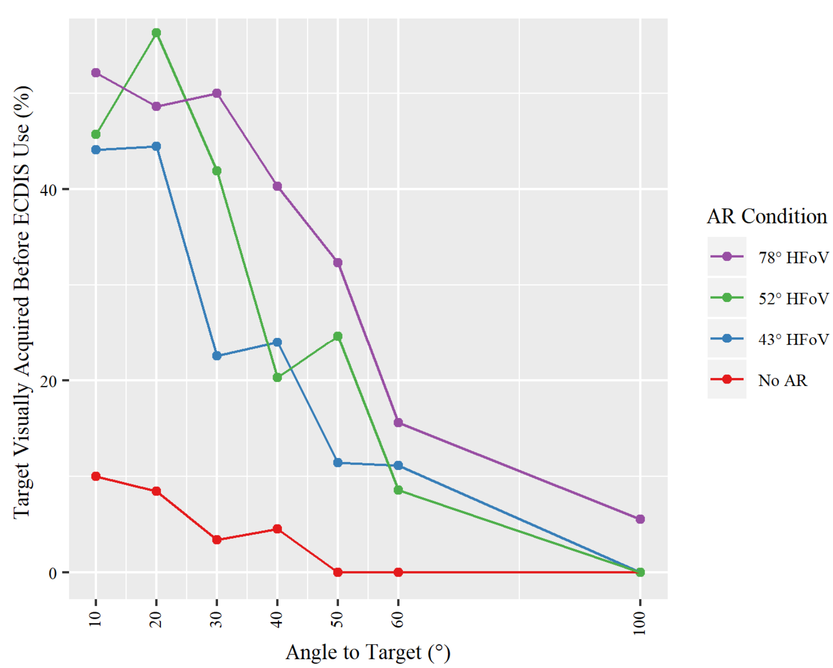

Figure 9: Percent of trials where targets were visually acquired before viewing the ECDIS.

As target angles increased, participants were less likely to find them without first consulting the ECDIS. Predictably, the angle at which this fall-off in performance occurred was directly related to the AR FoV. This effect can be seen in Figure 9, where each progressively wider FoV condition's performance curve is about 10° better than the narrower condition. Performance converges after angles become very wide (60°+) and exhaustive scanning would be required to find targets.

4.2 Keeping mariners' eyes on the water

The most important factor in avoiding ship collisions is keeping mariner's eyes on the water. Thus, we were interested in learning how AR and different FoV affected how often participants took their eyes off the water to look at the ECDIS. As expected, without AR overlays, users had to rely on looking at the ECDIS. They did so both more frequently, and for longer periods of time. As shown in Figure 10, participants looked at the ECDIS 225% more frequently during no-AR conditions than AR-enabled conditions, which were remarkably consistent regardless of FoV differences.

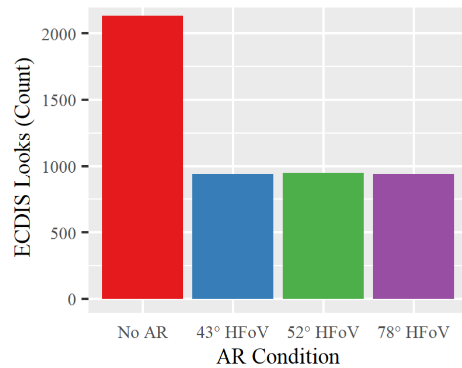

Figure 10: Number of times participants looked at the ECDIS by AR condition.

During no-AR trials, participants not only looked at the ECDIS more frequently, they looked at it for longer as well. This can be seen in Figure 11, where participants spent approximately 14% of the time viewing the ECDIS when no-AR was provided, as opposed to only approximately 6% of the time when AR was provided. FoV had no effect. This provides strong support for the use of augmented reality for aiding safer marine navigation, as it can help keep mariners' eyes on the water much more consistently, even when using devices with a narrow FoV.

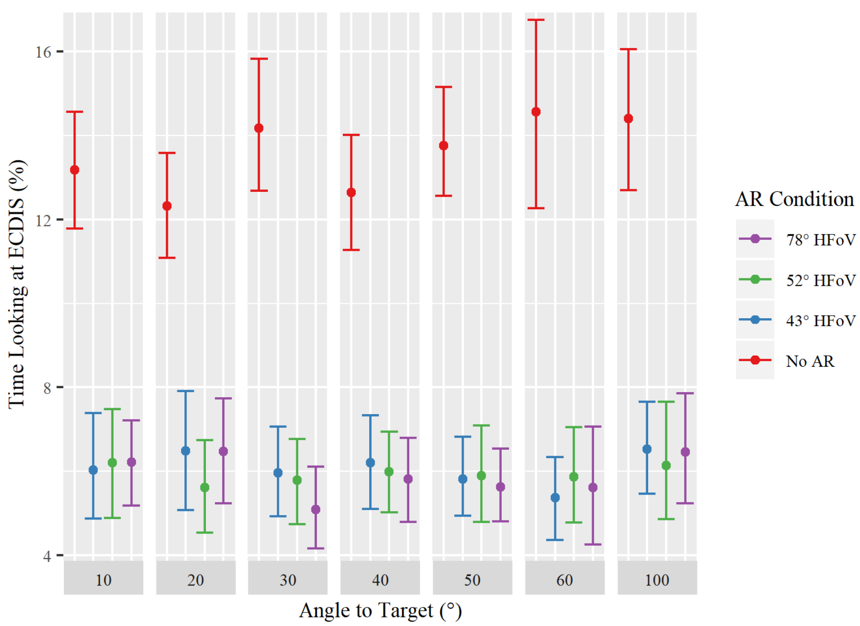

Figure 11: Time spent looking at the ECDIS by AR condition and angle to target.

We further examined ECDIS look counts at the individual participant level, and found that they were noticeably consistent between users across all AR conditions. In Figure 12, participants are plotted by how often they looked, and how long they looked each time (dwell time). This reveals the range of preferences/strategies. Generally, those who look more often dwell for shorter periods than those who look less frequently. Expert boaters tended towards more frequent, shorter looks.

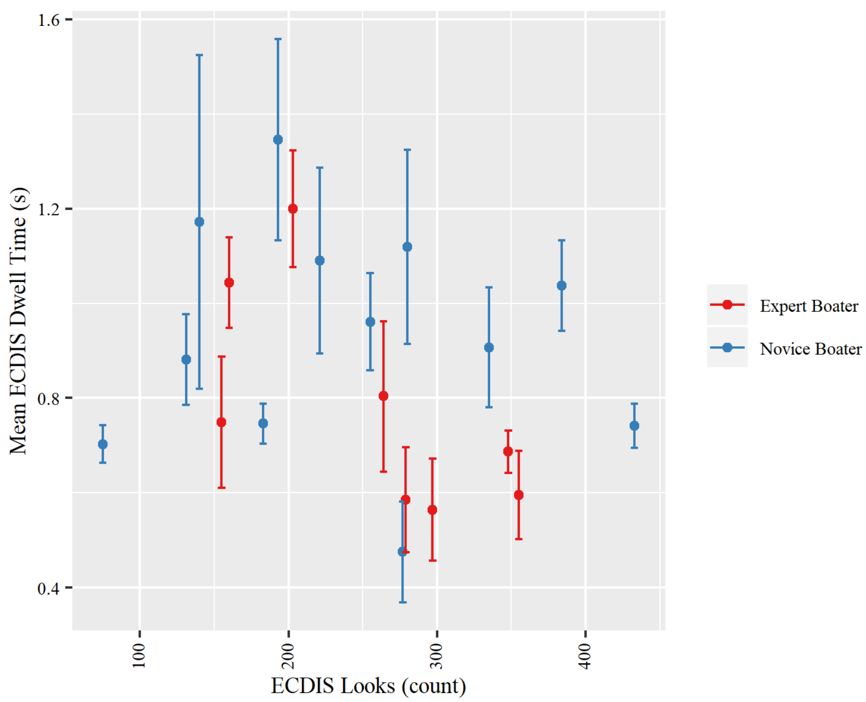

Figure 12: Participants plotted by how number of ECDIS looks and mean dwell time.

4.3 Ordering effects

Our study was designed to minimize ordering and learning effects (as described at the end of Section 3.2), however there were some significant ordering effects present in our results.

There was no evidence for learning effects on time spent looking at the ECDIS in the no-AR condition, but there were ordering effects for the three AR-enabled conditions. As can be seen in Figure 13, participants in Group C spent significantly less time looking at the ECDIS in all FoV conditions, while Group D looked at the ECDIS significantly more during the two narrower FoV conditions.

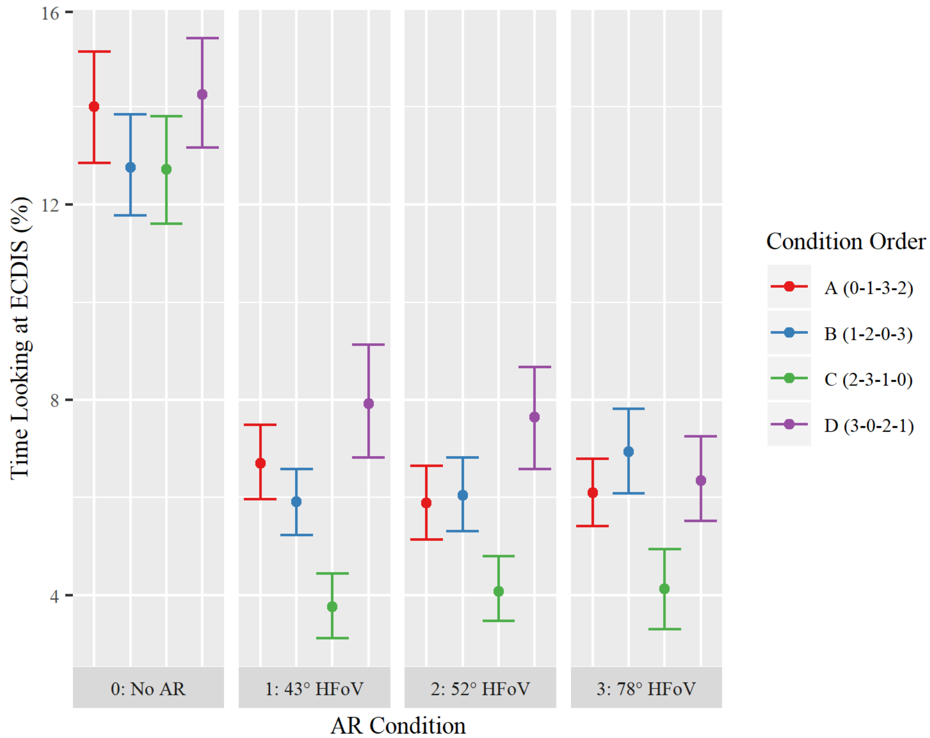

Figure 13: Time spent looking at the ECDIS, by AR condition and ordering group. Note that Group C spent significantly less time looking at the ECDIS in AR-enabled conditions.

This can be explained by the order in which they experienced the conditions. Group C began with the most useful AR-enabled conditions: medium-FoV AR followed by the widest-FoV AR. Only during the final block of trials were they forced to resort to using the ECDIS to find targets due to a lack of AR. This caused them to learn to rely more on using the AR than other groups, which experienced the no-AR condition earlier, exposing them to the strategy of just using the ECDIS.

This effect is especially pronounced in Group D, which began with the widest-AR, followed by no-AR. After this, they experienced the less-useful medium- and narrow-FoV AR-enabled conditions, so it is not surprising that they might be more likely to employ a strategy of looking at the ECDIS in these later blocks than other groups, which experienced the conditions in a different order.

4.4 Situational awareness

Situational awareness is difficult to measure; many researchers do so by repeatedly pausing a simulation and asking participants questions. We attempted to automatically measure awareness by keeping track of how often people looked at surrounding ship traffic and if they noticed kayakers that came dangerously close to their boat.

Overall, participants spent little time (5-6%) looking at surrounding ship traffic. We expected that traffic would be viewed less often in no-AR conditions, as participants had to take their eyes off the water to view the ECDIS, but this did not appear to prevent them from glancing around in between. We did not provide any AR markers over any surrounding ships, but it is likely that even simple AR markers would draw more attention to them.

AR and FoV did however have significant effects on if, and how quickly, participants noticed kayakers dangerously close to their boat. As seen in Figure 14, kayakers were missed most often in the no-AR condition, which was predictable, as participants had to take their eyes off the water to look at the ECDIS. Unexpectedly, there was an inverse relationship between AR FoV and kayaker sightings: Kayakers were spotted most often in the narrowest-FoV condition.

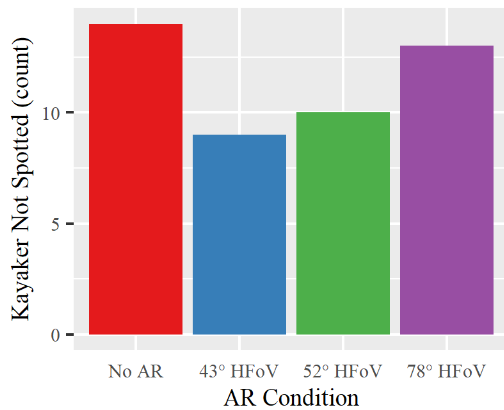

Figure 14: Number of kayakers missed during each AR condition.

Similarly, considering the cases when kayakers were spotted, the lowest FoV condition also performed best, with participants spotting the kayakers significantly faster. AR did seem to provide a benefit to sighting times, as the no-AR condition resulted in significantly worse times. These times are shown in Figure 15.

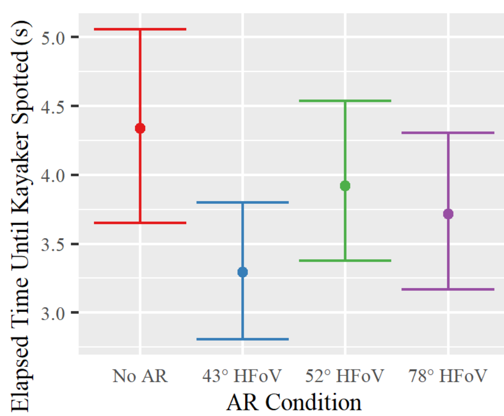

Figure 15: Time elapsed until kayaker spotted, by AR condition.

This inverse relationship could be explained by how lower FoV AR overlays can cause users to scan their environment more thoroughly than wider-FoV AR overlays, which generally help users find targets faster, after which they tend to fixate their gaze on them instead of looking around the scene. Indeed, this hypothesis can be supported by breaking the participants into two groups: scanners and non-scanners, and comparing their kayaker spotting performance.

We did this by first calculating mean scanning times for each participant. Scanning time was the time elapsed from the start of each trial until users either visually acquired the target, or abandoned their visual search by looking at the ECDIS. As can be seen in Figure 16, some participants (e.g. 1, 11, and 15) choose to almost always rely on the ECDIS rather than the AR overlays, and some (e.g. 2, 3, 5, 18) preferred to exhaustively search the scene using the AR overlay before resorting to using the ECDIS. We defined “scanners” as those who scanned their environment more than the mean scanning time. As shown in Figure 17, “scanners” were significantly more likely to spot kayakers than “non-scanners”, who missed twice as many kayakers.

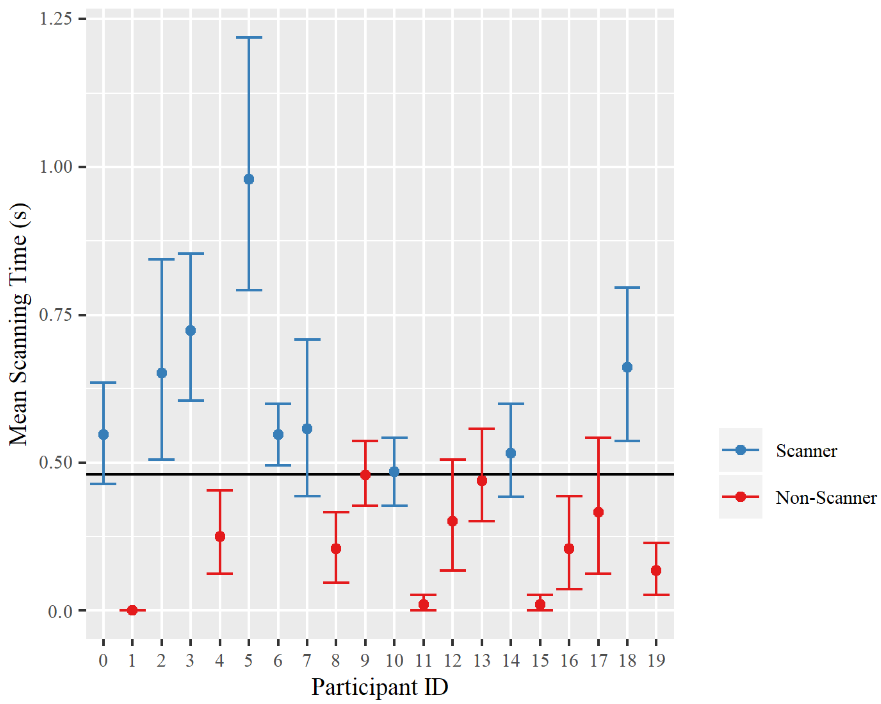

Figure 16: Mean scanning time by participant, with cutoff line for scanner/non-scanner groups. Notice that participants 1, 11, and 15 almost always preferred to look at the ECDIS at the start of each trial rather than scan for a target using AR.

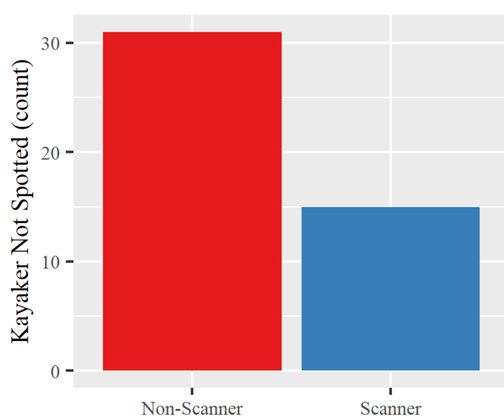

Figure 17: Kayakers missed by scanner grouping. Scanners missed half as many kayakers as non-scanners.

4.5 Expert boaters

After breaking the analysis apart by boating experts versus non-experts, there were surprisingly few significant differences between the two groups. Experienced boaters noticed more of the kayakers, whereas novices missed more of them. Experienced boaters were also more frequently able to locate wider-angle (60°+) targets across all AR-enabled conditions without using the electronic chart at all. Similarly, in the narrowest-AR condition, experts looked at the ECDIS significantly less than non-experts.

While these differences appear to suggest a preference for exhaustive scanning to find targets using the AR overlays, as opposed to taking their eyes off the water to look at the ECDIS, we did not see significantly higher scanning times, nor were expert users significantly more likely to fall into the “scanner” group. However, it is possible that experts scanned at faster angular rates than non-experts.

5. CONCLUSION

Based on the results of our study, we can conclude that augmented reality technology has potential to play a significant role in aiding safe marine navigation. AR presents mariners with navigational information in a heads up manner that keeps their eyes off computer screens and on the water, which helps maintain situational awareness, and is the most important factor in avoiding ship collisions.

Our experiment showed that, compared to a traditional ECDIS, AR overlays help mariners visually acquire targets significantly faster, both because they remove the need to look at a chart, and do not impose the cognitive load of translating between locations on the chart and the real world.

Our results also showed that AR overlays are effective in keeping mariners' eyes on the water: When AR was enabled, participants looked at their ECDIS significantly less frequently and for significantly shorter amounts of time. Participants who preferred to use the AR overlays to find their targets were able to find most targets without taking their eyes off the water at all.

Measuring situational awareness is difficult, and only our kayaker-spotting test found an effect for AR: Participants missed kayakers most often, and spotted them latest, when they did not have AR overlays. Interestingly, the field-of-view of the AR overlays had an inverse effect, where narrow-FoV AR actually resulted in the most and earliest kayaker spottings. This was likely due to the increased scanning behavior that was necessary to find targets with the more restrictive FoV AR conditions. Adding AR markers to surrounding ship traffic or objects detected via marine radar or thermal cameras would likely be very effective at drawing attention to them, and should be a subject for future studies.

In general, wider AR FoV values were associated with slightly better target-finding performance: Lower-angle targets were spotted significantly faster in the two wider-FoV conditions than the narrowest, and wider-FoV conditions enabled more targets to be found without needing to look at the ECDIS. However, for most of our other metrics, FoV was not a significant factor: All FoV conditions performed similarly in terms of how quickly participants could find targets that were far off from (60°) or behind (100°) the boat's heading direction (as these all required exhaustive scanning to find). FoV had no effect on how often or how long users chose to look at the ECDIS, nor did it have any effect on their observation of surrounding ship traffic.

In conclusion, our findings show that while increasing the field-of-view of AR devices would be beneficial for their application to marine navigation tasks, the effects of additional FoV (to our task) are actually much less significant than expected. The most important benefits that we found AR to provide were significant regardless of which FoV they were presented at. This indicates that current-generation AR devices like the Microsoft HoloLens 2 (which matches our narrowest-FoV condition) may already be suitable for application to marine navigation tasks, at least in terms of their FoV (there may still be other issues, e.g. brightness).

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