ERGONOMICS, 2002, VOL. 45, NO. 15, 1078–1090

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A maritime navigation display that provides visual feedback to improve conning officers' ship-handling during low visibility environments

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Keywords: Maritime display; Navigation displays; Virtual environment.

Navigating a ship at night in close proximity to another vessel is a dangerous task. To improve conning officers' night time ship-handling performance, a visual navigation display is proposed that is mounted on the stern of the aircraft carrier that will help shipboard conning officers manoeuvre in a battle group formation. To test the effectiveness of the visual navigation display, the Nimitz-class aircraft and plane guard vessel, a Ticonderoga-class cruiser, were modelled in a virtual environment. A navigation display condition had significantly fewer navigational positional errors than a non-navigation display condition. The navigation display provided immediate feedback as to whether the aircraft carrier had changed bearing or speed, thus enabling the operator to initiate the appropriate input to maintain station astern of the carrier. Actual or potential applications of this research include the deployment of a maritime navigation display to assist conning officers' ship handling.

1. Introduction

For centuries, sailors used navigation aids, such as flags, smoke and lights, to signal and manoeuvre around ships and other obstacles. Early navigation aids date back to the Roman era, around 300 B.C., when lighthouses built near the mouth of the Nile were used to guide ships and assist with coastal navigation (Browning 1999). During the U-boat battles of World War I, convoys of 20 or more supply ships would transit the Atlantic Ocean in tight-knit packs at ranges as close as 750 yards. Radar had not yet been developed, so the conning officer viewed red and white lights mounted on the vessel to maintain a safe distance between ships. When engaging the enemy, British destroyers illuminated two red lamps spaced two metres apart horizontally on the port yardarm, and two red lamps on the starboard yardarm. Ocean vessels of today are equipped with advanced navigation systems such as radar, global positioning systems, and automatic pilot systems to enhance conning officers' situational awareness. Despite these advanced navigation systems, the United States Navy's surface fleet had 12 collisions between 1992 and 1996 (Lacy 1998). Moreover, within the past 12 months the United States Navy has had 10 ships collide or run aground (Cole 2001). Numerous causal factors were cited for each mishap (Lacy

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Ergonomics ISSN 0014-0139 print/ISSN 1366-5847 online
http://www.tandf.co.uk/journals
DOI: 10.1080/00140130210166979

1998); however, in every case, the crew had lost situational awareness of the surrounding area. To improve conning officers' night time ship-handling ability, a Tactical Vectoring Equipment (TVE) is proposed to be mounted on an opposing vessel's stern to help shipboard conning officers manoeuvre his or her vessel in a group formation (Evanoff 1999, Krebs *et al.* 2000).

A case study of a recent collisions at sea highlights the importance of night time ship-handling skills and the need for conning officers to be aware of nearby obstacles. On October 14 1996, the aircraft carrier USS Theodore Roosevelt and guided-missile cruiser USS Leyte Gulf collided while conducting training exercises in the Atlantic Ocean (Dorsey 1997). The accident occurred at night at approximately 0300hrs in calm seas with good visibility. The cruiser was on station approximately 3658 metres astern of the carrier. The carrier was conducting three significant events: testing a communications system; manoeuvring in a zigzag pattern; and conducting propulsion plant drills that included manoeuvring in reverse. At the same time, the cruiser's commanding officer was in the combat information centre assisting in the recovery of a helicopter. Due to communication problems between the two vessels, the cruiser was not aware of the carrier drills. A short time later, the aircraft carrier ceased zigzag manoeuvres, and without warning the aircraft carrier went to emergency back full. The two ships collided with a closing speed of 20 knots. The mishap investigation board stated that the collision was caused by a number of human-factor failures between both bridge teams, with the primary causal factor being failure to communicate intentions.

Fortunately, such events as the Theodore Roosevelt and Leyte Gulf mishap are rare; however, surface warfare officers often manoeuvre in close formation with an aircraft carrier, as a 'plane guard', which may increase the likelihood of a collision. During a plane guard task, the aircraft carrier is launching and recovering aircraft, while the surface combatant is positioned a few thousand metres astern of the carrier. The conning officer's attention is divided between gauging the location of the aircraft carrier, monitoring aircraft traffic, searching the water for other vessels and avoiding floating or submerged obstacles. To accomplish these tasks, the combatant's conning officer must estimate the aircraft carrier's distance and bearing by visual, auditory and radar information; however, in certain situations these cues may be ambiguous which may cause the conning officer to become disoriented. To reduce disorientation, it is proposed that a Tactical Vectoring Equipment (TVE) be mounted on the stern of the aircraft carrier to assist shipboard conning officers when manoeuvring in a battle group formation (Evanoff 1999, Krebs *et al.* 2000). The TVE will consist of six bi-colour red and white lights mounted several feet apart on the stern of an aircraft carrier. The TVE concept is analogous to the visual approach slope indicators (VASI) or the precision approach path indicators (PAPI) airport navigation displays. These airport navigation displays consist of a combination of multi-coloured lights that indicate the plane's vertical position in relation to a desired approach glide-slope angle to the runway. The light indicators change colour if the aircraft is too high or too low relative to the desired approach angle. These airport visual aids help pilots make fine critical adjustments to altitude and power just prior to landing.

The TVE will increase shipboard conning officers' ship-handling performance while manoeuvring in a group formation by providing additional visual cues of the leading vessel's spatial orientation relative to the escort's ship. Similar to the VASI and PAPI aviation displays, the TVE will illuminate different combinations of red and white lights to indicate the escort ship's relative position to the stern of the leading ship. For example, if the escort ship were left of station at 200° relative from the leading vessel, then the TVE display would illuminate one white and five red lights to indicate the approximate number of degrees off station—the desired station is 175°. The TVE should be an improvement on the current red port and green starboard navigation lights by providing instantaneous, continuous, and positive visual feedback of the leading vessel's position relative to the escort vessel.

The goal of the present research is to assess the benefits of the TVE display during a night time plane-guard task. Participants performed a plane-guard task while immersed in a virtual environment. During a plane-guard task, the aircraft carrier is launching and recovering aircraft while the surface combatant is positioned astern of the carrier. In experimental trials, participants viewed a Nimitz-class aircraft carrier from the forward bridge window of a Ticonderoga-class cruiser and were instructed to maintain station 175° astern of the carrier at a range of 274.3 metres. Two experiments, using a static navigation spatial localization task and a dynamic plane-guard task, were conducted to test whether the TVE display improves conning officers' ship-handling compared to the standard red, green and white aircraft carrier navigation running lights. It was predicted that the TVE would assist the conning officer in tracking an aircraft carrier significantly more than the normal shipboard lighting condition does. The TVE's red and white light configuration will enable the conning officer to easily discriminate range and bearing of the stern of the aircraft carrier in relation to the combatant ship. Thus, the TVE will increase conning officers' ship-handling during battle group formation.

2. General methods

2.1. *Apparatus*

The virtual environment was rendered on a Silicon Graphics Onyx Reality Engine. Software used to model the simulation were MultiGen Creator (version 14.5), Vega (version 3.2), Vega Marine module (version 3.2), and LynX graphical user interface (version 3.2) from MultiGen-Paradigm Inc. The dynamic simulation was presented through a Virtual Research Systems, Inc. V8 head-mounted active matrix display (HMD) with a field-of-view of approximately 60 degrees and resolution of 600×480 pixels. Head positions were tracked with a 3-space FastTrack Polhumus tracking system. The cruiser's direction and speed were controlled by a BG Systems FlyBox. Frame rate was fixed at 30 frames/second.

2.2. *TVE display*

The Tactical Vectoring Equipment (TVE) consists of a horizontal line of six bi-colour (red and white) lights spaced approximately 1.83 metres apart on the stern of the carrier (figure 1). In the computer simulation, the lights were mounted just below the aircraft carrier's flight deck, approximately 18.3 metres above the waterline. Each light was 45.7 centimetres in diameter, with a luminous intensity of approximately 12 candelas, which corresponds to approximately 24.1 kilometres of visibility.

The TVE will illuminate different combinations of red and white lights to indicate the escort ship's relative position to the stern of the carrier. The TVE will provide the conning officer with instantaneous, continuous, and positive visual feedback on the carrier's position relative to the cruiser, but remain invisible to carrier pilots approaching the aircraft carrier due to the downward position of the TVE lights only illuminating the combatant. For example, if the cruiser were 200° left of the stern of

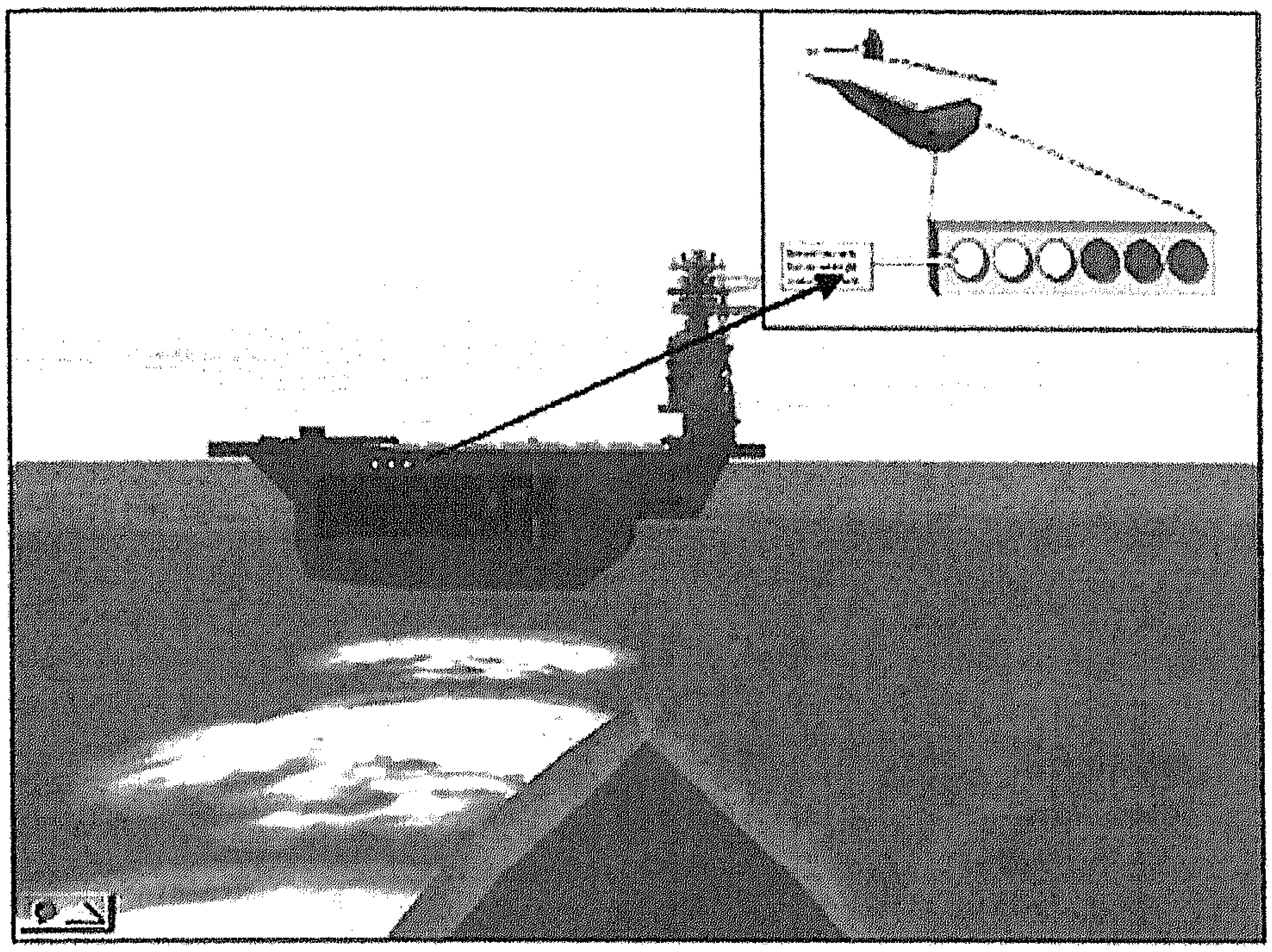

Figure 1. Computer generated view of the TVE on the stern of a Nimitz-class carrier from the plane-guard ship. The conning officer is at an approximate position of 175° relative, indicated by three red and three white lights.

the carrier, then the TVE display would illuminate one white and five red lights to indicate the approximate number of degrees off station (figure 2)—the desired station is 175°.

3. Experiment I

3.1. *Participants*

Thirty-four military participants with normal or corrected-to-normal vision volunteered for this experiment. There were two groups of participants: 17 designated as Surface Warfare Officers (SWO), and the remaining 17 designated from non-SWO communities (e.g., aviation). All participants provided informed consent.

3.2. *Procedure*

The subject was exposed to 10 practice and 30 experimental static images: two lighting schemes (normal shipboard lights or TVE light display), three ranges (205.7, 274.3, or 342.9 metres), and five bearings (135°, 165°, 175°, 200° or 225° relative). In each trial, the static stimulus appeared for three seconds on a 78.7 centimetres monitor, followed by a five-second blank screen. The participant's task was to indicate the direction (left, right, or behind the carrier) and distance (range close, range far, or range good) of the aircraft carrier relative to the

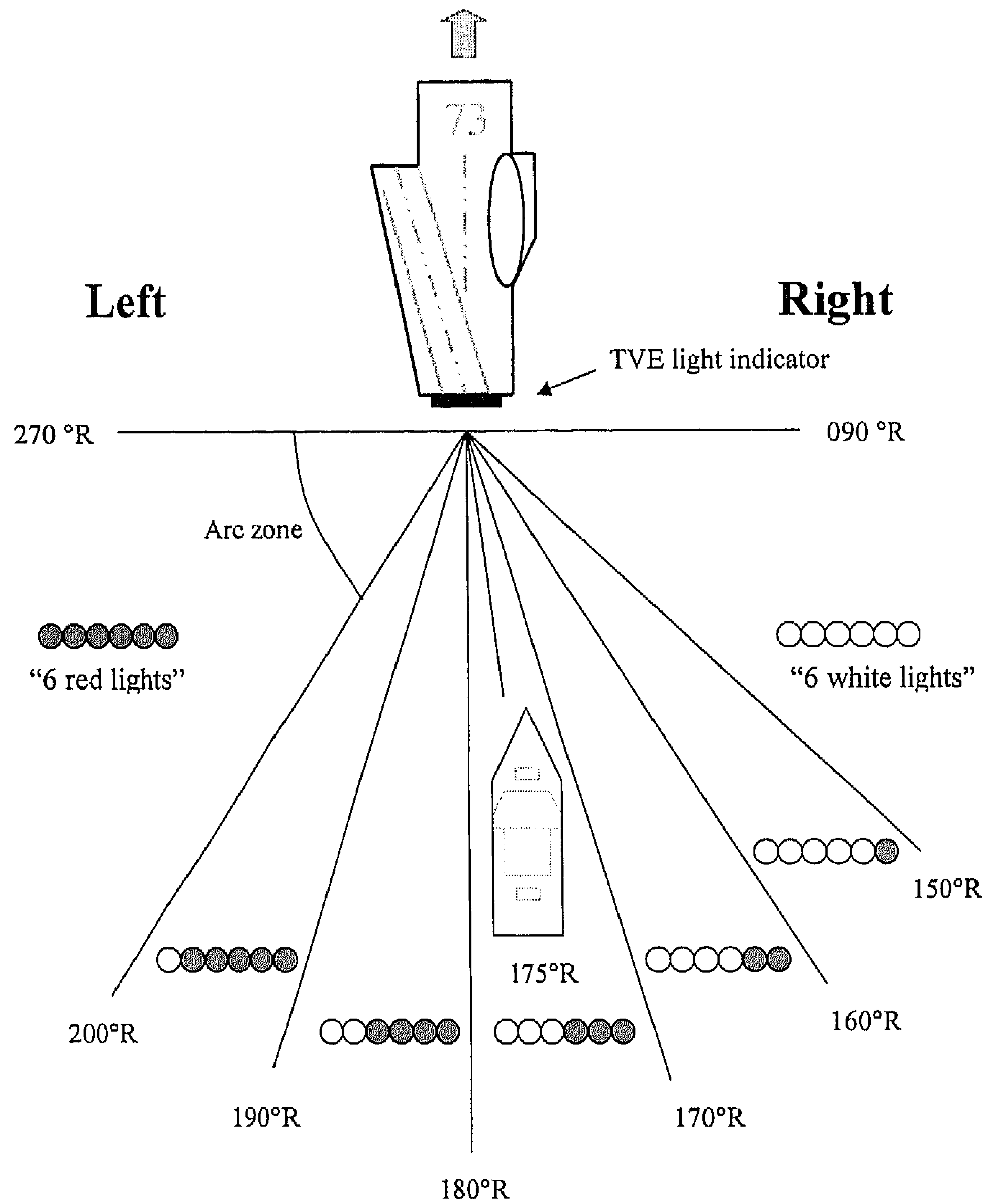

Figure 2. Overview of the TVE lighting scheme for a ship on plane-guard duty. Each bi-colour light changes based on ships' relative positions. As the combatant's position changes relative to the aircraft carrier's stern, the light display changes colour, indicating approximate degrees off station. For example, if the combatant were 200° right relative to the aircraft carrier, the conning officer would perceive one white and five red lights from the carrier's stern.

position of the astern ship during the five-second blank interval. The correct position of the combatant relative to the carrier's stern was 175° relative at 274.3 metres. Figure 3 illustrates the different locations of each distance by range location of the aircraft carrier relative to the participant's view from the combatant's bridge. After completing the 30 static slides, the subject participated in the dynamic experiment.

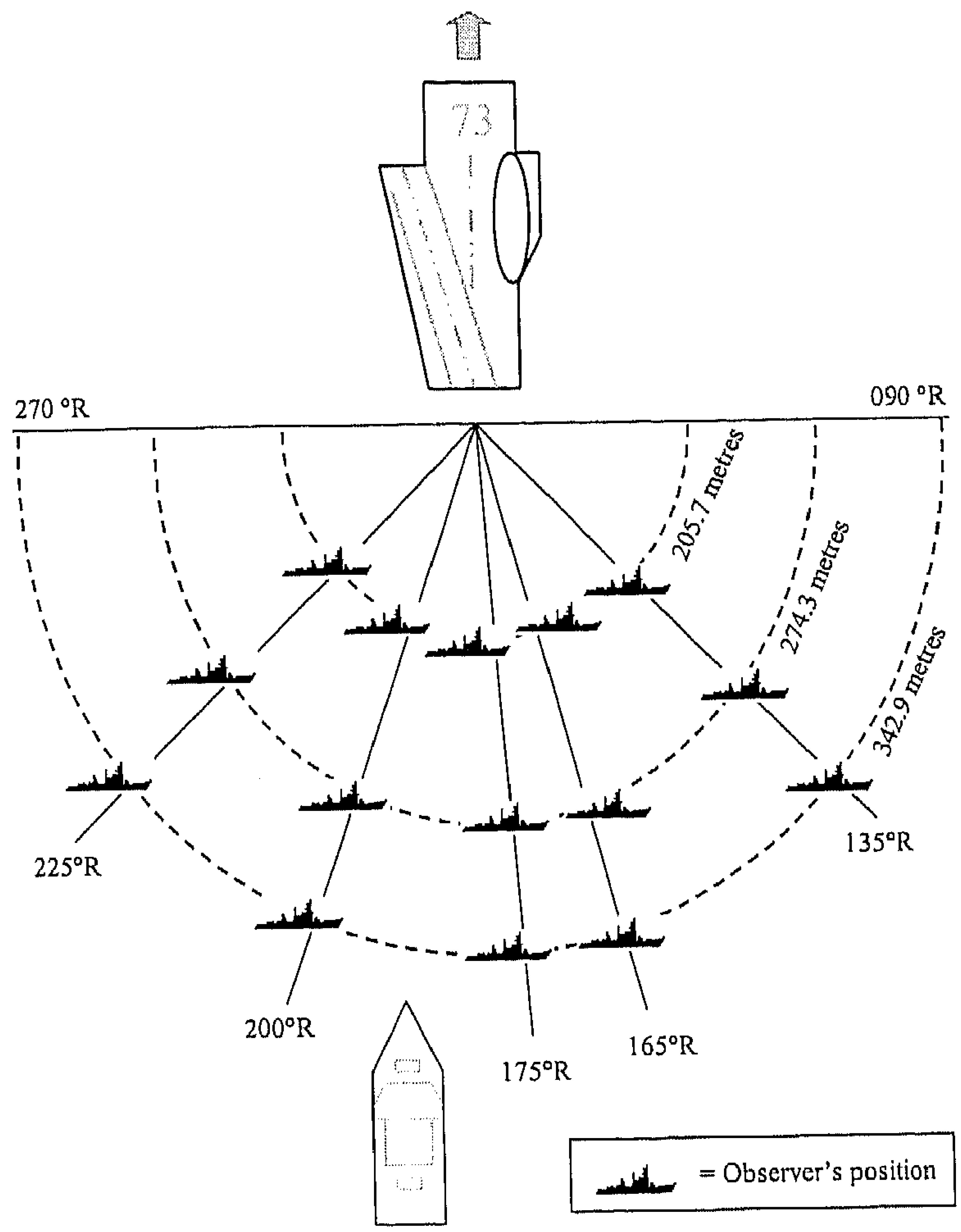

Figure 3. Summary of observer's relative positions from the carrier for static experiment.

3.3. *Results and Discussion*

A total of 1024 trials were collected from 34 participants; each participant viewed 15 TVE trials and 15 normal shipboard display trials. The number of incorrect trials for each display type served as the dependent measure. A 2 × 2 Multivariate Analysis of Variance (Group by Display) with bearing error and range error serving as the dependent measures showed participants performed significantly better using the TVE display compared to the normal shipboard display (Pillai-Bartlett Trace, F (2, 63) = 24.794, $p < 0.0001$). There was a non-significant difference between group (Pillai-Bartlett Trace, F (2, 63) = 0.324, $p < 0.724$) or group by display (Pillai-Bartlett Trace, F (2, 63) = 0.617, $p < 0.543$); this effect suggests that background experience had no effect on participants' ability to determine position or range.

Participants using the TVE display were significantly more accurate at estimating the carrier's position relative to the cruiser than they were using the normal lighting display condition ($F(1, 64)=38.325$, $p<0.0001$). When viewing the TVE display, participants had a bearing error of 2.2%, while, with the normal lighting display, they had a bearing error of 14.7%. Participants committed a total of 75 normal lighting display and 11 TVE bearing errors out of 510 trials for each condition. Six participants, of whom five were non-SWOs and one SWO, committed the 11 TVE bearing errors.

Participants estimated range significantly better using the TVE display than when using the normal lighting display ($F(1, 64)=11.62$, $p<0.001$). Overall, participants committed more range errors than bearing errors; however, participants were 56.7% correct (221 range errors out of 510 trials) using the TVE display, while with the normal lights, they were 48.2% correct (264 range errors out of 510 trials). Participants used the TVE lights to discriminate relative position from the carrier, but were unable to estimate the carrier's distance due to the lack of visual cues in the scene.

4. Experiment II

4.1. *Participants*

Same as experiment 1.

4.2. *Procedure*

The dynamic experiment consisted of five TVE display trials and five normal shipboard lighting display trials, with each display condition presented in five different carrier course tracks (20° port turn, 70° port turn, 20° starboard turn, 70° starboard turn, or a steady course heading with variable speed changes). The subject's task was to maintain station 175° relative at 274.3 metres astern of the aircraft carrier for each of the five course track changes (figure 3).

Realistic hydrodynamic effects were programmed into the Flybox controller and computer model to provide participants with the response and feel of an actual Ticonderoga-class cruiser. Input parameters for the virtual escort ship were based on the profile for a Ticonderoga-class cruiser and established maximum speed, acceleration, deceleration, advance, and transfer rates. Prior to experimental trials, participants were given three dynamic trials to practice verbal commands and to become familiar with the 'virtual ship' handling characteristics. In all trials, the participants manoeuvred the cruiser into station behind the aircraft carrier by issuing rudder and engine orders to the experimenter. Rudder commands consisted of 'Come Left,' 'Come Right,' and 'Steady.' Engine commands consisted of 'Engines Ahead,' 'Engines Back,' and 'Engines Steady.' The first trial was under day conditions, and the remaining two trials were at night, with the carrier displaying normal navigation lights and the TVE lights. Each practice trial lasted two minutes. After completing the practice trials, the subject was given a brief rest prior to the start of the experimental trials.

The experimental phase consisted of 10 four-minute trials (display by track). Participants were instructed to manoeuvre as necessary to maintain plane-guard station while the carrier executed a series of course and speed changes. At the start of each trial, the escort ship was repositioned on station behind the carrier at 175° relative at 274.3 metres. There was a five-second delay before the carrier manoeuvred so that participants could evaluate their surroundings and relative position. Trials were randomly ordered from a file of five predetermined carrier tracks. The carrier maintained a steady course or turned 20° to port, 70° to port, 20° to starboard, or

70° to starboard. The computer recorded the time, position and heading of both ships every five seconds and saved the information in a data file for follow-on analysis. The experiment ended when all 10 trials were completed.

4.3. *Results and Discussion*

Participants' ability to maintain station astern of the carrier was measured by position error (figure 4). Position error was defined as the distance from where the combatant was positioned to where the ideal position was located—on station behind the carrier at 175° relative at 300 yards.

$$\text{Position error} = \text{sqrt}(X^2_{\text{position error}} + Y^2_{\text{position error}}),$$
$$X_{\text{position error}} = X_{\text{combatant position}} - X_{\text{desired position}}$$
$$Y_{\text{position error}} = Y_{\text{combatant position}} - Y_{\text{desired position}}$$

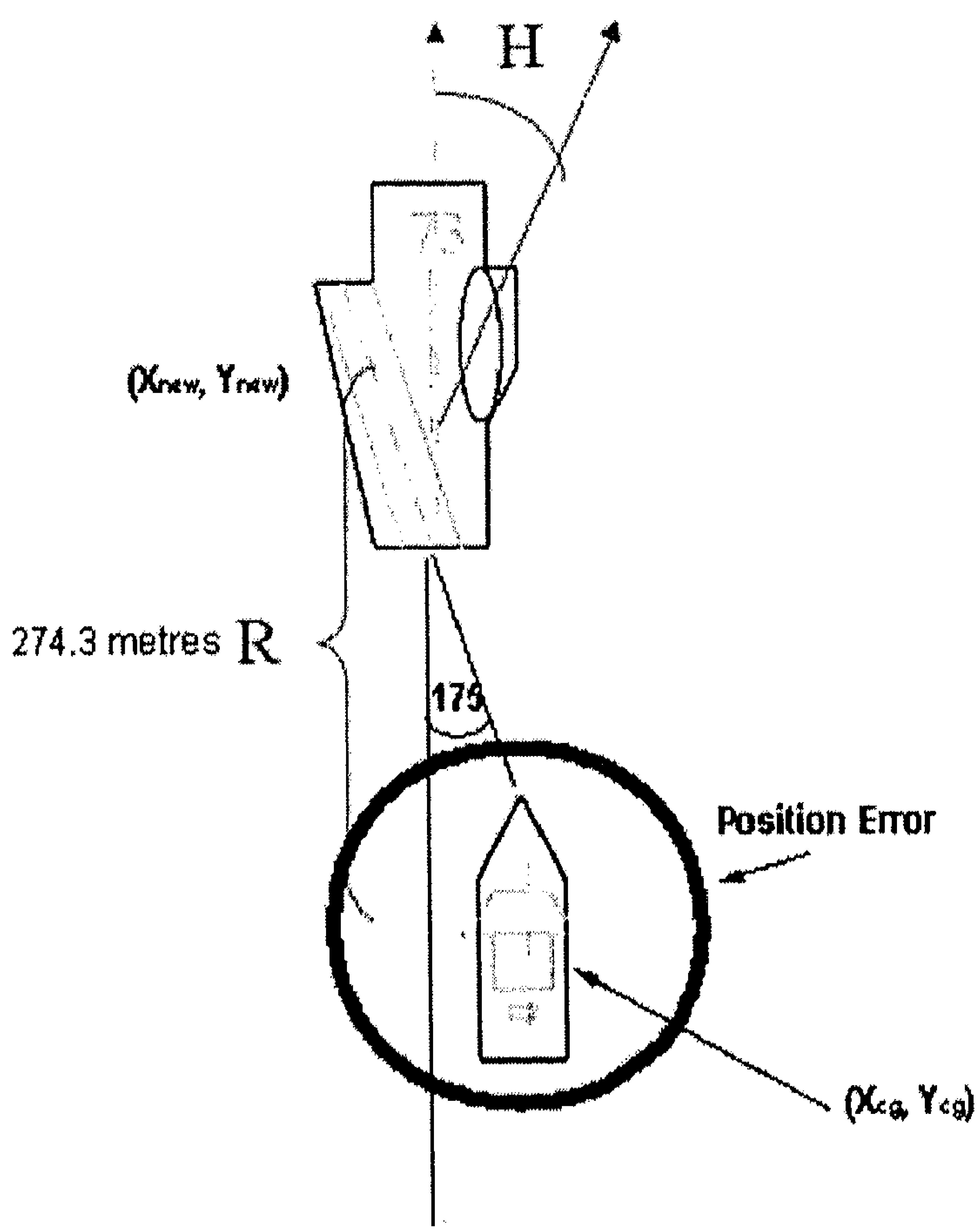

Figure 4. Position error was defined as deviation from the combatant's desired location of 175 degrees at 274.3 metres astern of the aircraft carrier. The solid bold circle surrounding the combatant illustrates the desired location. If the combatant's location was 175 degrees and 274.3 metres astern of the aircraft carrier, position error was zero; however, with any deviation from this desired position (outside the circle), the combatant's position error increased.

$$X_{desired\ position} = X_{new} + R^*\sin(\text{radians}(H + 175°))$$
$$Y_{desired\ position} = Y_{new} + R^*\cos(\text{radians}(H + 175°)),$$

where X_{new} and Y_{new} are the aircraft carrier's position, H is the aircraft carrier's heading, and R equals 274.3 metres which is the distance between the combatant and aircraft carrier.

A mixed three-factor within-subjects Group × (Display × Aircraft Carrier Course Tracks) Analysis of Variance design with position error serving as the dependent variable showed a non-significant difference between SWOs and non-SWOs while maintaining station astern of the aircraft carrier (F (1, 32) = 0.71, $p < 0.41$). Participants did significantly better when using the TVE display than when using the normal lighting display (F (1, 32) = 15.56, $p < 0.001$, with Geisser-Greenhouse (1958) correction) with 164.883 (S.E. = 4.64) and 186.96 (S.E. = 7.14) position error for the TVE and normal lighting display, respectively. Aircraft Carrier Course Tracks showed a significant effect (F (4, 128) = 121.68, $p < 0.001$, with Geisser-Greenhouse (1958) correction), and the interaction of Group by Aircraft Carrier Course Tracks was significant (F (4, 128) = 2.8, $p < 0.05$, with Geisser-Greenhouse (1958) correction). The 70° course tracks were significantly more difficult than the 20° and speed change course tracks; however, there was significant but inconsistent difference between the SWOs and non-SWOs across the 20°, 70° and speed change course tracks. The two-way interaction Display by Aircraft Carrier Course Tracks and three-way interaction Group by Display by Aircraft Carrier Course Tracks failed to reach significance.

Figure 5 illustrates a dynamic trial for a typical SWO observer. The experienced SWO using the normal shipboard lighting display was unable to track the carrier however, the same observer committed no errors when the TVE was used (figure 5). The observer's ship-handling skills were increased with the TVE.

The results suggest that SWOs and non-SWOs maintain station astern of the aircraft carrier significantly better with the TVE lighting system, as compared to normal shipboard lighting configurations. The confusion experienced at night due to a lack of visual cues appeared to significantly diminish with the TVE display. With normal lights, perception of the carrier turning was delayed, whereas with the TVE, participants had an immediate indication as to which direction the carrier was turning and how quickly.

5. General discussion

The confusion experienced at night due to a lack of visual cues appeared to significantly diminish with the TVE shipboard display. These studies suggests that this shipboard navigation display can enhance an observer's perceptual understanding of the relative motion between ships and improve a conning officer's ship-handling.

On the basis of the data collected, it was noted that significant differences between the two lighting schemes. During Experiment I, both subject groups performed better and made fewer range and bearing errors with the TVE. This helps support the notion that conning officers can more quickly and easily identify a ship's target angle and relative position, regardless of the amount of time their view of the carrier is interrupted. The implication is a better mental picture of the carrier's perceived motion and position.

The results during Experiment II were as expected. The use of the TVE significantly improved a subject's ability to maintain station on the aircraft carrier.

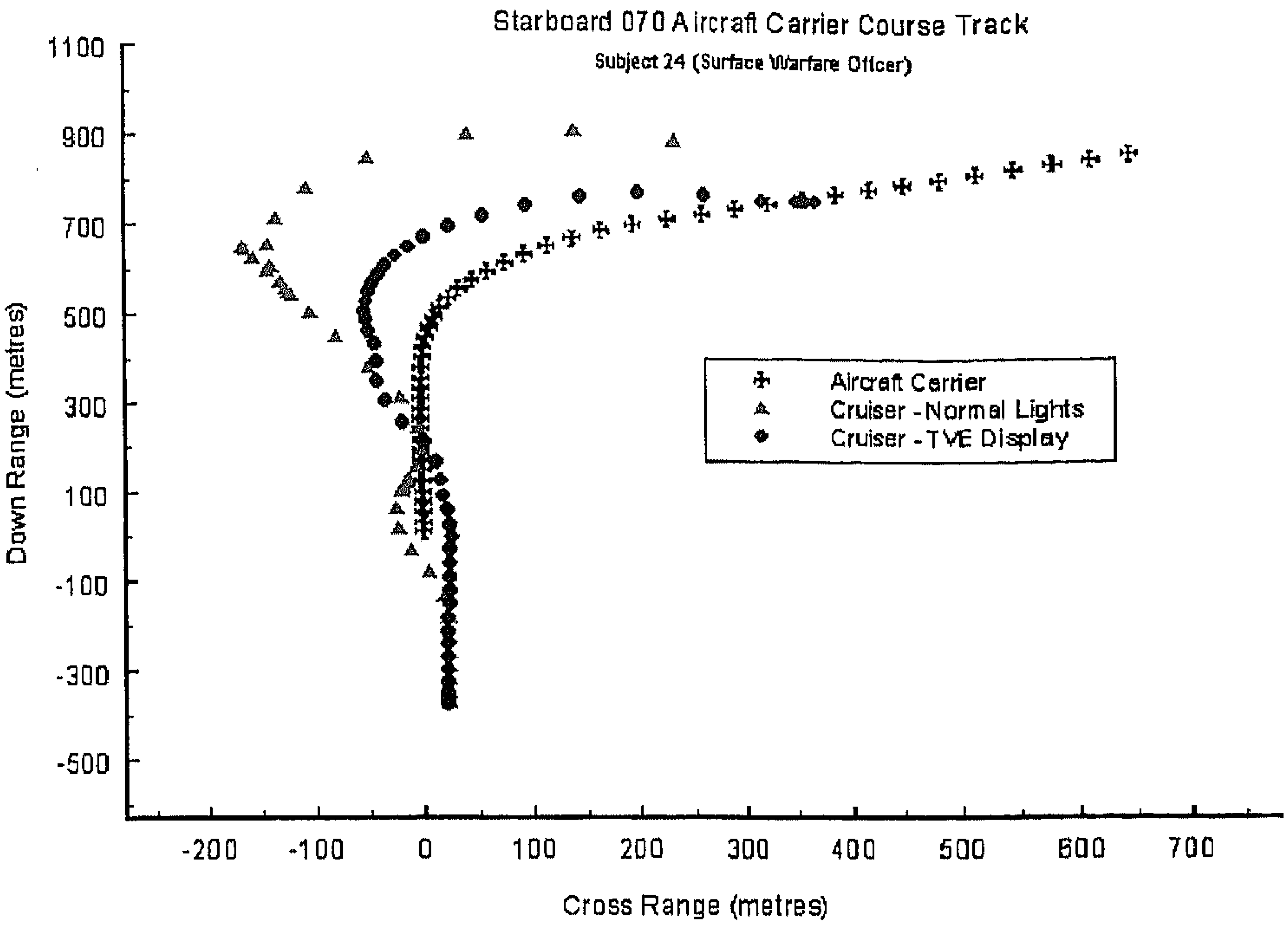

Figure 5. Illustrates a dynamic trial of the carrier turning 070° starboard (⊕). The SWO using the normal shipboard lights (▲) initially tracked the carrier, but became disoriented after the carrier started its turn. The subject, unsure of the carrier's movement, initiated a port turn, reversed engines, then initiated full forward momentum to catch the carrier. The SWO using the TVE display (●) immediately detected the carrier's starboard turn. The subject crossed the carrier's wake; stayed outside the wake until the carrier steadied on the 070° course heading, then proceeded back across the wake to regain plane-guard station. This was a textbook example of a proper ship manoeuvre when following a carrier.

The data showed that participants exhibited fewer errors in perceiving egocentric distance and location. Experience level evidently made a difference in ship-handling ability, with SWOs performing better than non-SWOs. This is important when considering the validity of the simulation. The different carrier ship tracks also affected the results. When the carrier executed large course and speed changes, it was more difficult for participants to maintain station.

An associated effect to consider is the impact of using this device to train inexperienced naval officers. Most conning officers will spend many hours on watch in order to develop an accurate understanding of how a ship turns and manoeuvres. This is because, for the most part, they are guessing how a carrier will turn and react at different speeds. Through trial and error, and under the careful guidance of their commanding officers, conning officers will eventually develop a sense of the relative motion between ships. What the TVE can provide is an immediate indication of how the ship is turning and the characteristics of the turn. For example, the faster the TVE lights change colours, the faster the carrier is turning. This gives the conning officer an immediate visual indication of the carrier's advance/transfer rates and its effect on relative position. Thus, the

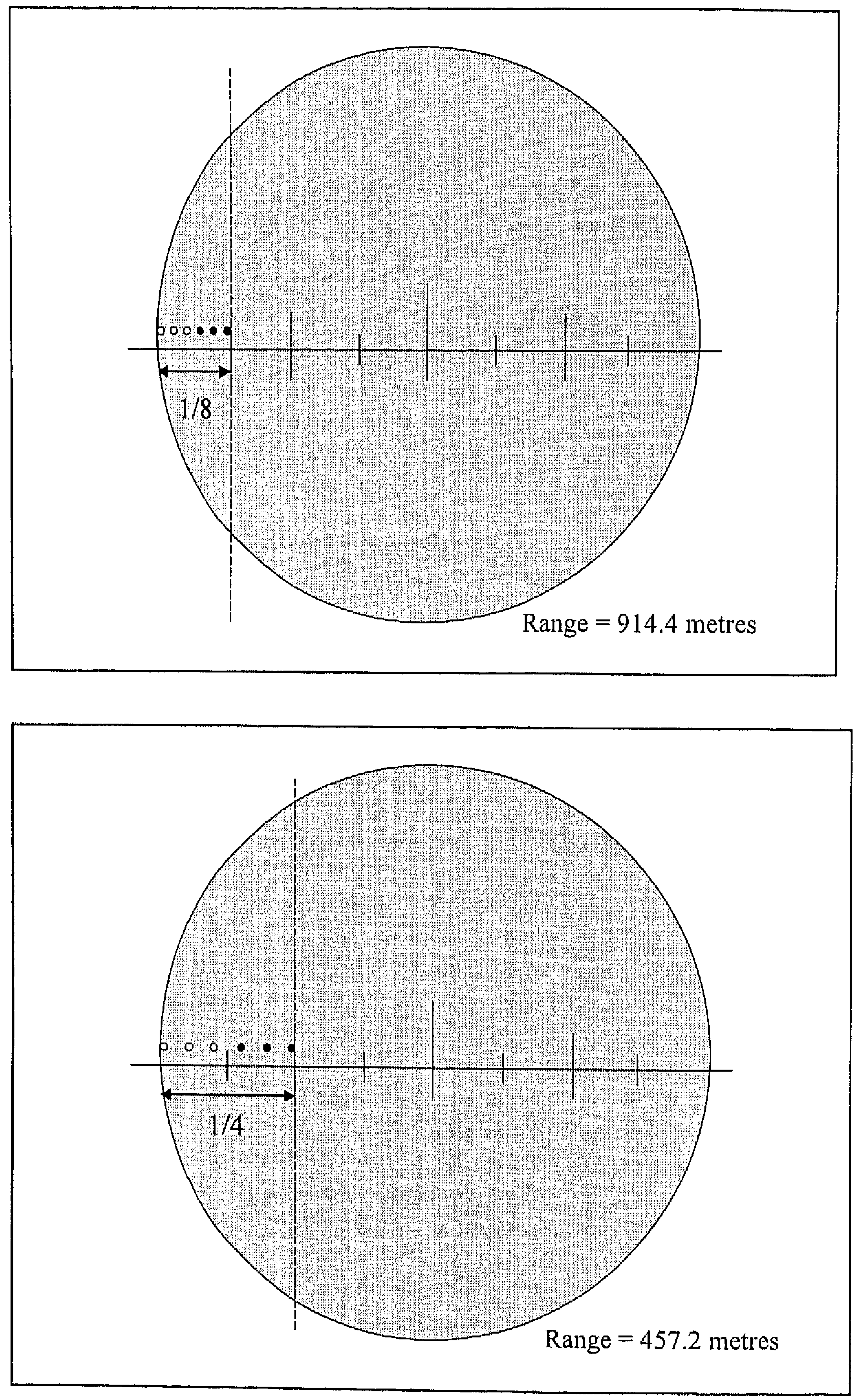

Figure 6. Simulated view of the TVE shipboard display seen through binoculars with reference grid overlaid on lens. The range from the observer to the aircraft carrier is 914.4 metres (top) and 457.2 metres (bottom).

TVE is a useful training aid that can develop and improve a junior naval officer's ship-handling skills more quickly.

Another useful visual application would involve connecting the TVE to the helmsman's ship control console. When a backing engine is ordered (throttles in the backing position on the ship's control console), a simple relay circuit could make the TVE lights flash in unison. This would provide an immediate warning signal to the plane-guard ship conning officer that the carrier is backing, decreasing speed more rapidly and may actually transit backwards. This type of warning system could have prevented the collision between the USS Leyte Gulf and USS Theodore Roosevelt in 1996.

With additional training, naval officers could use the TVE to determine approximate range to the carrier without the use of radar. A common technique used by naval officers involves using a set of binoculars and a ship's dimensions to determine range. At a given range, binoculars have a set field of view (FOV) across the lens. For example, a standard set of binoculars (7×50) at a range of 914.4 metres can have an FOV of 109.7 metres. This means an object that is 13.7 metres long would fill one-eighth of the binocular lens. At 457.2 metres the FOV is 54.9 metres. The same object that is 13.7 metres long now fills one-quarter of the binocular lens (figure 6). Using this example, each light would be positioned nine feet apart, so the total length of the TVE array is 13.7 metres. An approximate distance to the carrier can now be determined by applying this principle. This would provide immediate bearing and range information for conning officers, improving their ability to accurately form a mental picture of the carrier's heading and target angle.

In summary, this research confirmed that the Tactical Vectoring Equipment provided instantaneous, continuous and positive visual feedback to the conning officer. Participants demonstrated significant improvement in ship-handling skills and situational awareness. This is an effective, versatile, and inexpensive device that should be seriously considered for future development and implementation in Naval maritime operations.

Acknowledgements

A special thanks to Dr. Rudolph Darken at the Naval Postgraduate School for providing the resources to accomplish this study, Lt. Jim Patrey at Naval Air Warfare Center Training Systems Division in Orlando, Florida for the invaluable support and providing the ship models for the simulation. Finally, we thank Dr. Samuel E. Buttrey for ensuring that we used the appropriate statistical techniques. A special thanks to Dr. Joel Davis, Human Systems, Office of Naval Research who sponsored this research grant (ONR grant # N0001400WR20312). The TVE device has been submitted to the US Patent Office for review.

The views expressed in this article are those of the authors and do not reflect the official policy or position of the Department of the Navy, Department of Defense, nor the United States Government.

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