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ABSTRACT

Real-time information is essential for effective operator decision making and performance in safety-critical systems, as operators must make crucial decisions quickly, utilizing relevant information to monitor, assess and respond. Research examining the impact of multimodal displays with augmented reality (AR) on operators performing safety-critical work has shown improved operator situation awareness, but mixed results with respect to performance and workload. Multiple-resource theory (MRT) posits that individuals will experience different performance impacts when information is received using different modalities, compared to when the information is communicated using a single modality. Earlier work provides a theoretical basis for expectations about the impacts of multimodal displays, but does not address the costs or impacts of digital layers of AR imagery in multimodal displays with small viewscapes, a gap our research addresses in safety-critical systems such as Arctic search and rescue and maritime navigation.

Keywords

Operator performance, augmented reality, multiple resource theory, visual displays

INTRODUCTION

Real-time information is essential for effective operator decision making and performance in safety-critical systems. Operators in such settings must make crucial decisions in real time, utilizing relevant information to monitor, assess and respond to critical incidents in settings as diverse as aviation (Stanton, Plant, Roberts and Allison, 2019), healthcare (Cobus, Heuten and Boll, 2017), and emergency and disaster response (Treurniet and Wolbers, 2021). Relevant real-time information is available to operators in many forms, including multimodal decision support systems that display information from visual, audio, haptic and experiential channels (Levulis, DeLucia and Kim, 2018).

Real-time information in context is critical to ship's officers navigating ferries and passenger vessels, who must maneuver large vessels that sometimes stretch to 1000' in length in restricted waters with heavy traffic, with hundreds and sometimes thousands of passengers aboard, often in challenging conditions, including limited visibility; extreme temperatures; rain, snow, hail and thunderstorms; navigational hazards and sometimes ice in the waterway. Ferry accidents, which numbered 4,515 between 2012 and 2021, with 2,340 lives lost (Lloyds List Intelligence, 2021), have been attributed to a lack of situation awareness (Lindblom, 2014), distraction (NBCNews.com, 2008), as well as to an inability to interpret information in sufficient time to make appropriate decisions (Washington State Board of Inquiry, 2013). In a motivating event for this research, in 2003, the *Andrew J. Barberi*, a Staten Island Ferry in New York City, collided with a pier and killed 11 people and injured 70 people, due in part to the assistant captain's medical issues, and the ferry captain's insufficient situation awareness and performance (National Transportation Safety Board, 2005).

Multimodal technologies that incorporate visual, aural and sometimes haptic sensors have been introduced to assist mariners in ship navigation; these systems also incorporate input from the automated identification system, which uniquely identifies and tracks vessels on the waterway, and can connect to augmented reality (AR) systems that project computer-generated images on views of the 'real world'.

Recent research examining the impact of multimodal displays with augmented reality on operators performing safety-critical work has shown improved situation awareness with such displays, but mixed results with respect to operator performance and workload (Rebensky, Carroll, Bennett and Hu, 2022). Multiple-resource theory (MRT) has been used to examine the effectiveness of multimodal displays, suggesting that individuals will experience less information processing resource competition when information is received using different modalities, compared to when the same information is communicated using a single modality (Wickens, 2002). Earlier work provides a theoretical basis for expectations about the impacts of multimodal displays on operators, but does not address the information processing costs or impacts of digital layers of AR imagery in multimodal displays with small viewscapes, a gap our research addresses in safety-critical systems such as Arctic search and rescue and maritime navigation.

MULTIMODAL DECISION SUPPORT

Multimodal decision support systems distribute tasks and information across different sensory modalities in order to provide large amounts of information to users without increasing their cognitive workload. Studies of the impacts of multimodal displays on operator performance have shown benefits and costs, improving operator performance (Stanton, et al., 2019) and situation awareness (Rebensky, et al., 2022), but also raising questions of operator overload and distraction (He, McCarley, Crager, Jadliwala, Hua and Huang, 2018), and attention capture, all of which can have dire consequences in safety-critical systems.

Multimodal displays with overlaid and augmented reality (AR) imagery have shown a similar mix of overlay benefits and/or or display clutter effects (Wickens, 2021). The current research extends previous work examining the proximity-compatibility principle in display layout and design (Peng, Wang and Wu, 2019; Wickens and Carswell, 1995), focusing on layering effects in multimodal displays with small viewscapes, such as Google Glass and other AR Platforms, and their impact on operator performance and perceptions in safety-critical systems. New to this research is consideration of the impacts of display and overlay clutter in mobile, small viewscape displays in multimodal systems, and assessment of the contributions of microtasks such as geofencing—creating areas to be avoided around floating debris, logs or kayakers in the water -- in safety-critical systems. This work also responds to calls to assess the relative benefits and costs of superimposing layers of digital and AR images (Wickens, 2021).

RESEARCH MODEL

Our research model is shown in Figure 1. Following proximity-compatibility principles in display layout and design, the impacts of overlaid AR imagery in a mobile, small viewscape multimodal display will be assessed for display and overlay clutter, and the contributions of the digital layers and the various modalities to operator performance, situation awareness and perceptions will be studied. The hypotheses associated with these impacts are presented in the next section.

HYPOTHESES

Multiple resource theory holds that two tasks that both demand similar resources (e.g. two tasks requiring visual perception) can be expected to impact performance more than two tasks that demand separate resources (e.g. one visual, one auditory) (Wickens, 2002). Hypothesis 1 explores operator performance impacts when manual and verbal responses are required, necessitating resource sharing. In this setting, the manual responses are both spatial (vessel trackkeeping, steering, engine speed adjustments through joystick movements) and verbal (Wickens and Liu, 1998; Wickens, 2002).

Previous research showed that manual control can impact operator performance, imposing additional demands on spatial working memory (e.g. driving, or navigating a vessel), whereas voice controls may impact operator performance when heavy verbal demands are required (Wickens, 2002). Given the heavy demands for manual control of navigation equipment aboard ships, we expect that operator performance would be impacted less when verbal responses are required—at a VTS or ship pilot check point-- at the same time that ship navigation and collision avoidance tasks are competing for cognitive resources.

We also explore two aspects of visual processing, focal and ambient vision, in H1. Focal vision is utilized for detail and pattern recognition (e.g., reading text, identifying small objects), while ambient vision involves peripheral vision, and is used for sensing orientation and motion (Gabbard, Mehra and Swan, 2019; Wickens, 2002). In H1, we explore whether operator performance is impacted when utilizing focal and ambient vision when using small viewscape multimodal displays in safety-critical settings:

H1: Operator performance when utilizing small viewscapes on multimodal displays will be enhanced when using (1) vocal vs. manual processing *codes*, (2) visual vs. auditory perceptual *modalities, (3)* focal vs. ambient visual processing *channels, (4)* across the information processing *stages* of perception, cognition and response, (5) utilizing both *focal* and *ambient vision.*

Situation awareness (SA) can be enhanced with the provision of visual and auditory cues. In H2, we explore the impacts of requiring manual (through equipment) or verbal response while developing, maintaining and responding to settings requiring situation awareness. We would anticipate that the added requirement for a ship's officer to acknowledge their location or estimated time of arrival (a demand response), through an Automated Identification System (AIS) response or vocally, will have less of an impact on their ability to maintain an accurate mental picture of the waterway (a perceptual cognitive demand) than will a response requiring manual effort.

In H2, we also examine the impact of cross-modal perceptual cues as part of operator situation awareness. Two competing visual channels, if they are far enough apart, require visual scanning between them, which incurs an added cognitive cost. If they are too close together, they may produce confusion and masking, just as two auditory messages may mask one another if they arrive at the same time (Wickens, 2002). The degree to which cross-modal task performance (audio-visual, rather than audio-audio or visual-visual) is impacted by these cues is not clear, especially since cross-modal information does not always produce better performance (Wickens and Liu, 1988).We explore these notions in H2:

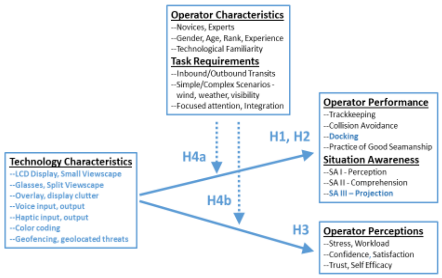

Figure 1. Research Model

H2: Operator situation awareness when utilizing small viewscapes on multimodal displays will be enhanced when (1) providing manual vs. vocal response *codes*, (2) in visual-auditory vs. auditory-auditory vs. visual-visual perceptual *modalities,* (3) across the information processing *stages* of perception, cognition and response, (4) utilizing both *focal* and *ambient vision.*

The technology-to-performance chain (TPC) proposes that operator performance with technology is based on operators' perceptions of compatibility among task, technology, and operator characteristics, known as task-technology fit (TTF) (Goodhue and Thompson, 1995). Self-efficacy (Agarwal, Sambamurthy and Stair, 2000), stress (Hancock, 1989) and trust (Merritt, Heimbaugh, LaChapell and Lee, 2013) have been linked in TTF studies (Shu, Tu and Wang, 2011), showing that improved operator performance with novel technologies has been positively associated with self-efficacy and trust (Merritt, et al., 2013), and negatively associated with workload (Wickens, 2008) and stress (Shu, et al., 2011). In earlier work, operators reported significantly increased self-efficacy, workload and propensity to trust when using small viewscape multimodal interfaces, but did not report significantly reduced stress (Rowen, Grabowski and Rancy, 2019), suggesting that operators using the technology may in fact balance workload but experience stress.

In H3, this research explores how operator and technology characteristics influence operator performance, processes, and perceptions in a safety-critical system. Previous work showed that the use of mobile wearable displays improved operator performance (Rowen, et al., 2019) and enhanced SA (Hong, Andrew and Kenny, 2015). Our research model explores these relationships in H3, proposing that:

H3: Operator perceptions will positively impact performance and SA when using small viewscapes on multimodal wearable displays.

Links between technology and performance, workload and SA, and self-efficacy and task-technology fit have been studied (Merritt, et al., 2013), but no model has been proposed that explores these links together. Our research model addresses these gaps by expanding the TPC model to consider such factors such as self-efficacy, workload, stress, and trust, as well as operator processes such as SA.

Previous work also suggests that mobile augmented reality display impacts on operators may be moderated by operator age, gender, and experience (Rupp, Michaelis, McConnell, and Smither, 2018), as well as by perceptions of self-efficacy, workload, stress, and trust (Gabbard, et al., 2019); Hypothesis 4 explores the moderating impact of operator characteristics on operator perceptions when using a small viewscape multimodal display with augmented reality:

H4: Operator characteristics will moderate operator perceptions when using small viewscapes on multimodal wearable displays.

METHOD

Several metrics will be used to examine the impact of small viewscape AR imagery on operator performance, situation awareness and perceptions in marine transportation. Operator performance will be assessed using traditional measures in ship navigation, namely *cross-track error* (XTE*)* or deviation from the vessel's intended track; distance from and time to collision with a nearby vessel or object, known as its *closest point of approach* (CPA) and *time to CPA* (TCPA); and adherence to standards of navigation and ship maneuvering, known as the *'practice of good seamanship'* (National Research Council, 1994). *Situation awareness* will be assessed using the Situation Awareness Global Assessment Technique (SAGAT, 2022) and observation of subjects using the U.S. Coast Guard-certified Navigation Skills Assessment Program (NSAP), as well as audio and video analysis of operator performance during vessel transits in the Staten Island Ferry's Class A ship simulator. *Operator perceptions* will be assessed using pre- and post-transit surveys. The variables and operationalizations for each hypothesis are shown in Tables 1 and 2.

SETTING

This work is set in the complex, safety-critical world of marine transportation, in which ship operators must anticipate the movements of their own and other ships and enact decisions in real time to avoid collisions (National Research Council, 1994). This setting requires that operators gather and synthesize information from several fixed displays around the vessel and the ship's bridge, including distributed information displays (Sauer, Wastell, Hockey, Crawshaw, Ishak and Downing, 2002), while integrating views of the environment outside the bridge windows and information from other agents (Figure 2). Some of the objects of concern in a ship transit are close to the vessel, in the near view; others may be on the horizon and more distant. In addition to scanning the environment for hazards and threats, ship operators must simultaneously

Hypothesis & Measure	Dependent Variable	Variable Operationalization	Data Collection
H1	**Operator Performance**		
H1A, XTE	Trackkeeping	Mean cross-track error (XTE). Smaller XTE = better performance	Simulator
H1B, XTE	Trackkeeping variability	Mean cross-track error (XTE). Smaller variability = better performance.	Simulator
H1C, XTE	Docking	Mean cross-track error (XTE). Smaller variability = better performance	Simulator
H1D, CPA	Threat avoidance	Closest Point of Approach (CPA). Larger CPA = better performance.	Simulator
H1E,CPA	Threat avoidance variability	Closest Point of Approach (CPA). Smaller variability = better performance.	Simulator
H1F, NSAP	Practice of good seamanship	Observations of qualitative ship management skills from the Navigation Skills Assessment Program (NSAP). Higher scores = better performance.	Transit observation with validated NSAP instrument.
H2	**Situation Awareness (SA)**	SA-1 Perception (Endsley, 1995)	Transit Observation
H2B		SA-2 Comprehension from the Situation Awareness Global Assessment Technique (SAGAT) & Navigation Skills Assessment Program (SNAP)	
H2C		SA-3, Projection of events or action in the future based on SA1 & SA2. Higher scores = better SA;	
H3	**Operator Perceptions**		
H3A	Self-Efficacy	New General Self Efficacy (NGSE) survey. Higher scores = better perception.	Post-Transit Survey
H3B	Workload	NASA Task-Load Index (TLX). Lower scores = better perception.	Post-Transit Survey
H3C	Stress	Short Stress State Questionnaire (SSSQ). Lower scores = better perception.	Post-transit Survey
H3D	Confidence	Contextual inquiry and Survey – Open-ended coding Analysis	Inquiry & Post-transit Survey
H3E	Satisfaction	Contextual inquiry and Survey – Open-ended coding analysis	
H3F	Propensity to trust	Propensity to Trust Scale (PTS). Higher scores = better perception.	Post-Transit Survey
H4A	**Operator Characteristics**	Novices vs. experts; Gender, age, rank, experience, technological familiarity	
H4B	Task Requirements	Simple vs. complex navigational scenarios; Inbound vs. outbound transits	H1a – H1f

Table 1. Dependent Variables and Operationalizations

Hypothesis & Measure	Independent Variable	Variable Operationalization	Data Collection
H1a & H2a	**Augmented Reality** (Mobile small viewscape, split screen) (Hoehle & Venkatesh, 2015)	Mobile, small viewscape display vs. traditional bridge equipment = Higher or lower SA score.	Audio, video; simulator output Mobile small viewscape and Transit Observation
H1b & H2b	**Voice Querying (Input)** (Levulis et. al, 2018)	Mobile small viewscape display with voice vs. without voice = Higher or lower SA score.	Audio, video; simulator output Mobile small viewscape voice-log and transit observation response + simulation log.
H1c & H2c	**Color Encoding Elements** (Naujoks et. al, 2017) (Sonderegger & Sauer, 2010)	Mobile small viewscape display with color-coding vs without color coding = Higher or lower SA Score.	Audio, video; simulator output Mobile small viewscape observation & post-transit survey
H1d & H2c	**Geo-Fencing/Location** (Carsten & Martens, 2019)	Mobile small viewscape display with geo-fencing vs no geo-fencing = Higher or lower SA score.	Audio, video; simulator output Haptic Sensor + mobile small viewscape display stream /Observation

Table 2. Independent Variables and Operationalizations

manage vessel navigation, bridge administration, weather and voyage planning, as well as safety tasks, while operating their vessel according to international law and the practice of good seamanship (International Maritime Organization, 1972). The cognitive challenges of ship navigation in close waters are significant, and require operators to process significant amounts of multimodal information in real time, balancing safety, efficiency and procedures (Wickens, Williams, Clegg and Smith, 2020).

The experimental setting for this study is the challenging and time-critical 5.2 mile long ferry transit from the southern tip of Manhattan, in New York City, to the St. George Ferry Terminal in Staten Island, a transit undertaken with 25 million passengers yearly every 30 minutes on a 24 x 7 x 365 day a year schedule by the masters and mates of the Staten Island Ferry (New York City Department of Transportation, 2022). Aside from the inherent dangers associated with high levels of traffic in one of the busiest ports in the world, the Staten Island Ferry transit is also beset with wind, weather, visibility and

Figure 2. Staten Island Ferry Simulator, View Approaching Manhattan

navigational hazards, making a twice an hour vessel transit with 5200 passengers aboard a challenge that requires vigilance and constant attention to the navigational transit.

TECHNOLOGY

Traditional maritime navigation displays distribute critical decision support information throughout the ship's bridge (Figure 3). In contrast, the technology utilized in this work integrates the information available from traditional bridge navigational displays onto a mobile multimodal display

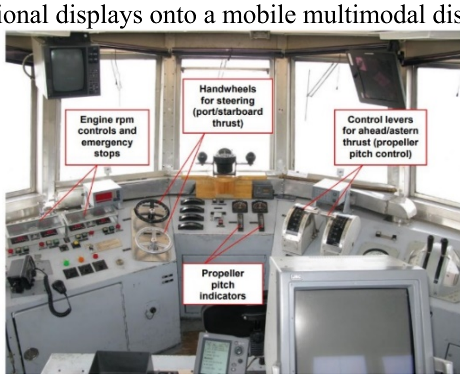

Figure 3. Bridge Display Consoles Aboard Typical Staten Island Ferry, *Andrew J. Barberi (NTSB, 2012)*

with a small viewscape running GlassNav™, a Google Glass (Version 2, 2016) application. GlassNav™ was developed by Le Moyne College researchers with support from the McDevitt Foundation. GlassNav™ displays a subset of critical navigational information aggregated from the ship simulator radar, electronic chart display and information systems, and helm panels in real-time, adding visual information about equipment status (i.e., 'GPS FAIL') to audible alarms in the conventional display (Figure 4). This information is superimposed over, but not registered to, views of the environment, travels with an operator's head, and is displayed on the Google Glass™ small viewscape.

Figure 4 shows own-ship bearing (BRG) to a radar target in degrees True (T); own-ship speed over the ground (SOG) in knots; own-ship engine speed in revolutions per minute (RPM); own-ship rate of turn (ROT) displayed by 1 to 3 dots, indicating low (1 dot) to high (3 dots) rates of turn, an indication of how fast the vessel is swinging during a turn; vessel mode ('docking mode'), indicating whether

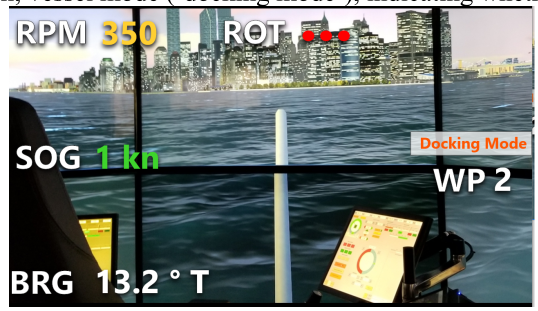

Figure 4. GlassNav® Display

the vessel is in transit or preparing to dock or undock; and WP2, a waypoint or a pre-defined point of reference to a geo-located position. The information on the GlassNav® glasses was identified by Staten Island Ferry subject matter experts as critical to the ship navigational task, and is linked in real time from the ship's radars, electronic charts and conventional bridge displays.

PROCESS

Earlier work (Rowen, Grabowski and Rancy, 2021) provided a basis for the current work. In the earlier study, subjects (n = 211) were U.S. Coast Guard-licensed Merchant Marine ship navigational officers attending federally mandated training courses at the Maritime Institute of Technology and Graduate Study – Pacific Maritime Institute (MITAGS-PMI) in Baltimore, Maryland, who volunteered to participate following their daily training. All operators had considerable experience at sea (M = 13.56 years, SD = 11.29) and in the simulator (M = 65.67 hours, SD = 138.57) at the time of participation.

In the current work, we extend the earlier findings and examine small viewscape and digital layering questions with a similar transit in the Staten Island Ferry's ship simulator in Manhattan, with a different subject group. Mates and Captains sailing aboard Staten Island Ferry vessels (n=60) will participate in the study after completing their mandatory yearly training in the Staten Island Ferry ship simulator.

In the experiment, operators are tasked with performing a typically rigorous 30-minute northbound or southbound Staten Island Ferry training transit in the simulator, using either the small viewscape display or the conventional bridge displays. Technology introduction will be varied to avoid order effects (Rebensky, et al., 2022), and transit conditions will vary from simple (no wind, no weather impacts, clear visibility, no traffic, no equipment failures) to complex (wind, weather, restricted visibility, vessel traffic, equipment failures). Layering effects of digital AR imagery will be studied, along with the impacts of the various modalities available in the system.

PRELIMINARY RESULTS

Earlier research showed both performance improvements and costs associated with the use of mobile multimodal AR displays (Table 3). Improvements to operator trackkeeping performance and situation awareness were attributed to the display's integration of data from several sources in a small viewscape (Stanton et al., 2019) and perhaps to the operator's inability to ignore salient information. This helped operators synthesize information and balance resource demands (Wickens, 2002), improving situation monitoring and decision making. Mobility with the mobile small viewscape display was shown to improve operator situation awareness, but was coupled with decreased threat avoidance performance, which suggested distraction and attention capture from highly salient information (He et al., 2018; Wickens, 2021).

TABLE V
HYPOTHESIS 1 RESULTS: OPERATOR PERFORMANCE AND SA

Measure	Data Source	Method	Test Statistic	*p*-value	Finding
H1a Trackkeeping	Simulator XTE	KS-test	$D = 0.178$	$p = 0.088$	Trackkeeping performance was not significantly improved with WARD use.
H1b Trackkeeping variability	Simulator XTE	F-test	$F = 0.177$	$\mathbf{p = 0.004}$	Trackkeeping performance variability was significantly improved with WARD use.
H1c Threat avoidance	Simulator CPA	KS-test	$D = 0.179$	$p = 0.096$	Threat avoidance performance was not significantly improved with WARD use.
H1d Threat avoidance variability	Simulator CPA	F-test	$F = 1.15$	$p = 0.486$	Threat avoidance performance variability was not significantly improved with WARD use.
H1e Practice of Good Seamanship	NSAP	Hotelling's T^2-test	$T^2 = 5.056$	$p = 0.081$	The practice of good seamanship was not significantly improved with WARD use.
H1f Perception (SA-1)	NSAP & SAGAT	t-test	$t = 3.302$	$\mathbf{p = 0.001}$	SA-1, perception, was significantly improved with WARD use.
H1f Comprehension (SA-2)	NSAP & SAGAT	t-test	$t = 2.893$	$\mathbf{p = 0.004}$	SA-2, comprehension, was significantly improved with WARD use.

Table 3. Previous Results (Rowen, et al., 2019)

NEXT STEPS

Analysis of the earlier multimodal small viewscape display data is complete and additional data collection in support of the layered AR imagery study and geofencing tasks in the Staten Island Ferry ship simulator is scheduled for Fall 2022 and Spring 2023.

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