Applied Ergonomics 80 (2019) 17–27

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Impacts of Wearable Augmented Reality Displays on operator performance, Situation Awareness, and communication in safety-critical systems

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ARTICLE INFO

Keywords:
Augmented reality
Communication
Information displays

ABSTRACT

Wearable Augmented Reality Displays (WARDs) present situated, real-time information visually, providing immediate access to information to support decision making. The impacts of WARD use on operator performance, Situation Awareness (SA), and communication in one safety-critical system, marine transportation, were examined in a real-time physical simulator. WARD use improved operator trackkeeping performance, the practice of good seamanship, and SA, although operator responsiveness decreased. WARD users who used more closed-loop communication and information sharing showed improved threat avoidance, suggesting that operators can avoid accidents and failure through WARD use that promotes sharing and confirming information. WARD use also promoted information source diversity, a means of developing requisite variety. These operational impacts are important in safety-critical settings where failures can be catastrophic.

1. Introduction

Operators in safety-critical systems increasingly face a proliferation of displays (Coutts et al., 2018), with more information available and retrievable (Klueber et al., 2019). These complex and capable displays include mobile, situated displays (Stanton et al., 2016) that provide in-context information in a wearable form factor, making available ubiquitous, real-time information. The impact of wearable, situated displays (Stewart and Billinghurst, 2016) on operator performance, communication, and Situation Awareness (SA) is little explored. Operator performance in safety-critical systems may depend on operator communication (Park and Kim, 2018) and SA, an operator's ability to perceive, comprehend, and project system states (Endsley, 1995). This research is motivated by unanswered questions about the contribution of these displays. The results of a study of 211 experienced subjects performing safety-critical tasks in a real-time operational simulator while utilizing mobile, situated displays and conventional displays are presented. The next section describes previous work that underlies the research model and hypotheses. The following sections then present the data, methods, procedure, setting, analysis, and results of the study. Conclusions and recommendations for future work are provided in the final section.

1.1. Operator communication in safety-critical systems

Operator communication, a crucial conduit through which information is shared, acknowledged, confirmed, and acted upon, is essential to effective performance in safety-critical systems (Park and Kim, 2018; Sutcliffe et al., 2017) such as medicine (Tiferes and Bisantz, 2018), aviation (Lassalle et al., 2017), air traffic control (Sharples et al., 2007), and firefighting (Jahn and Black, 2017). Operator communication in High Reliability Organizations (HROs) – organizations that either don't or can't make mistakes (Bigley and Roberts, 2001; Roberts, 1990) – has common elements: communication is timely (Park and Kim, 2018), rapid and frequent (Caldwell, 2008; Dunn et al., 2002), and task-relevant (Kim et al., 2010), with discernible patterns that support the operator's goals (Jahn and Black, 2017). Effective communication in these systems is often standardized (Leonard et al., 2004) and closed-loop (Hägerstam et al., 2013), providing task-relevant information (Sexton and Helmreich, 2000). Effective communication can improve operator performance (Svensson and Andersson, 2006) and SA (Parush et al., 2011), supporting the development of requisite variety, the capability to match operator skills and performance to the mix of situational demands (Weick, 1987), in increasingly complex safety-critical systems (Coutts et al., 2018). Protocols for structured communication have been developed (Barbour and Gill, 2014; Leonard et al., 2004) on the premise that effective communication contains

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https://doi.org/10.1016/j.apergo.2019.04.013
Received 28 December 2018; Received in revised form 22 March 2019; Accepted 26 April 2019

Abbreviations

ARIMA	Auto-Regressive Integrated Moving Average
BRG	Bearing
CCF	Cross-Correlation Function
COG	Course Over Ground
CPA	Closest Point of Approach
HDG	Heading
HRO	High Reliability Organization
MANOVA	Multivariate Analysis of Variance
MITAGS-PMI	Maritime Institute of Technology and Graduate Studies – Pacific Maritime Institute
NSAP	Navigation Skills Assessment Program
SA	Situation Awareness
SAGAT	Situation Awareness Global Assessment Technique
SOG	Speed Over Ground
TCPA	Time to Closest Point of Approach
WARD	Wearable Augmented Reality Display
XTE	Cross-Track Error

information that is timely, complete, and relevant (Wadhera et al., 2010), and closes the loop with feedback acknowledging or confirming receipt (Caldwell, 2008; Nonose et al., 2015). Closed-loop communication ensures that information is delivered properly (Kim et al., 2010), and has been associated with reduced error and improved performance (Härgestam et al., 2013).

Timely information is valuable and relevant in dynamic situations (Barbour and Gill, 2014; Janssen et al., 2010); timely information communicated early in a time-critical task may allow operators time to assess the situation and respond appropriately (Bigley and Roberts, 2001; Kim et al., 2007), preventing problems from compounding (Janssen et al., 2010), while less timely information shared later limits reaction time and time to seek additional information (Barbour and Gill, 2014). Similarly, communication responsiveness, the time between a request for information and a response, can affect decision making (Seppänen and Virrantaus, 2015). Higher responsiveness can aid decision-making performance (Caldwell, 2008; Dunn et al., 2002).

Unsolicited information sharing has also been identified as an aspect of effective communication (Sexton et al., 2018), which can contribute to effective operator performance and decision-making that depends on shared information (Kim et al., 2007). Information shared preceding any specific request for that information may indicate that operators are communicating effectively and anticipating system needs (Zhang and Sarcevic, 2018), improving performance in time-critical settings with high operator workload and stress (Entin and Serfaty, 1999). More shared information has been linked to higher responsiveness, reduced task duration, and reduced cognitive load (Sexton et al., 2018). Information sources differ in richness, with personal communication providing richer information than text. Despite operator preferences for verbal information in safety-critical systems, text displays are used when tasks are routine (Daft and Lengel, 1986). In complex situations, richer information sources can improve performance and operators may seek information from more diverse sources (Jahn and Black, 2017).

1.2. Technology impacts in safety-critical systems

Operators in safety-critical systems can face a complex array of displays and technology that are ostensibly provided to assist in operator decision-making and improve operator performance (Stanton et al., 2016; Svensson and Andersson, 2006). New technology displays in safety-critical systems have both improved (Klueber et al., 2019; Stewart and Billinghurst, 2016) and degraded (He et al., 2018) operator performance, as well as improved SA (Stanton et al., 2016), the operator's ability to perceive, comprehend, and project the state of the system into the future (Endsley, 1995). Displays of task-relevant information have improved performance (Grabowski and Sanborn, 2003; Hong et al., 2015) and SA (Klueber et al., 2019), but have increased workload (Hong et al., 2015) and reduced communication, although primarily in routine, low-workload conditions (Grabowski and Sanborn, 2003; Müller and Giesa, 2002). Displays may improve an operator's ability to access and process information, improving operator performance (Kim et al., 2019), or distract the operator from task requirements by overloading them (He et al., 2018). In safety-critical systems, experienced operators may be capable of selecting and processing relevant information while filtering and ignoring extraneous information (Kim et al., 2018; Prytz et al., 2018). Media richness theory (Daft and Lengel, 1986) suggests that more information is contained in rich, multi-channel face-to-face communication; less rich displays may help operators prevent overload with simplified presentations of relevant information (Kim et al., 2007), while preserving access to a variety of media channels.

Calls to match operator capabilities with needs to manage the complex array of technology and displays in increasingly complex systems – the notion of requisite variety (Weick, 1987) – have increased with the proliferation of increasingly capable and sophisticated displays (Schneider et al., 2017). When limits of requisite variety are breached, failure is likely (Oliver et al., 2017). To prevent failure, operators may increase their capabilities to absorb and process information and to manage situational complexity by sharing and integrating information from a variety of sources, a central characteristic of HROs (Jahn and Black, 2017; Roberts, 1990). Mismatches in requisite variety could lead operators to behave as if the system was less complex, leading to inadequate responses to change (Schneider et al., 2017). Operators may improve requisite variety by using additional sensory channels (Klueber et al., 2019; Riggs et al., 2017) or by increasing the diversity of information sources (Jahn and Black, 2017). HROs often have numerous technological and human information sources (Roberts, 1990) that can increase requisite variety while improving operator capability to handle this variety (Schneider et al., 2017). The result may be improved reliability, and higher rates of task completion (Chadwick and Fallon, 2012).

Mobile situated displays such as Wearable, Augmented Reality Displays (WARDs) provide operators with visual information superimposed on the real world (Azuma, 1997), situated near the relevant physical entity (Willett et al., 2017). WARDs have the potential to impact operator performance and SA in safety-critical systems (Klueber et al., 2019; Stanton et al., 2016) in several ways: they may provide timely, relevant information to operators anywhere within the workspace, but may also distract or overload operators. WARD use may reduce information retrieval effort and increase information salience, possibly also increasing cognitive load and introducing a source of distraction (He et al., 2018) or discomfort (Aaltonen and Laarni, 2017). WARD use has been observed to improve performance and SA (Klueber et al., 2019; Stewart and Billinghurst, 2016) by letting users spend time with eyes on the task (He et al., 2018); however, costs include increased workload and possible distraction (Stanton et al., 2016). The mixed results of prior work leave it unclear what the impacts of such displays may be (Kim et al., 2019; Klueber et al., 2019), and no study has explored WARD impacts on operator communication, despite widespread recognition of the importance of communication in safety-critical systems.

1.3. Research model

The literature reviewed suggests several unanswered and under-explored questions about the impacts of mobile, situated displays on operators in safety-critical systems. Using the lens of HRO and requisite variety research, a research model and hypotheses are proposed to address these questions (Fig. 1):

H1. WARD use will improve operator communication.

Display technology has been shown to improve operator communication when that communication is timely (Janssen et al., 2010), responsive (Caldwell, 2008), task-relevant (Sexton and Helmreich, 2000), and in safety-critical systems, closed-loop (Härgestam et al., 2013) and from diverse sources (Jahn and Black, 2017). H1 explores the impact of WARD use on these aspects of communication in safety-critical systems.

H2. WARD use will improve operator performance and SA.

Mobile, situated displays provide operators access to timely, relevant information in close proximity to the physical entity to which the information pertains (Willett et al., 2017). Earlier examinations of similar displays have suggested that this access may improve operator perception (SA Level I) and comprehension (SA Level II) (Klueber et al., 2019). Operator performance, measured in marine transportation as trackkeeping, threat avoidance (Hockey et al., 2003), and the practice of good seamanship (International Maritime Organization, 1972), and SA (Gould et al., 2009), may benefit from improved information access provided by WARDs (Stanton et al., 2016). H2 examines this premise.

H3. Operator communication when using WARDs will improve performance and SA.

Communication is crucial to performance (Park and Kim, 2018) and SA (Parush et al., 2011) in increasingly complex systems. Timely (Janssen et al., 2010), responsive (Caldwell, 2008), closed-loop (Härgestam et al., 2013) information, shared with (Kim et al., 2007) and sourced from, diverse system elements (Jahn and Black, 2017) may support improved operator performance and SA (Zhang and Sarcevic, 2018). H3 explores the impact of operator communication on performance and SA when using WARDs.

H4. WARD impacts on operator performance and SA will be moderated by communication.

Improved access to salient information (Willett et al., 2017) may improve (Klueber et al., 2019; Stewart and Billinghurst, 2016) or degrade (Aaltonen and Laarni, 2017; He et al., 2018) operator performance and SA. Operator communication can support operator performance and SA (Leonard et al., 2004; Sexton et al., 2018), or may moderate display impacts on operator performance and SA (Sharples et al., 2007), a notion H4 examines.

H5. WARD impacts on operator communication will be moderated by operator characteristics and perceptions.

Display impacts on communication may be moderated by operator perceptions of technology (Huttunen et al., 2011) and task factors (Lassalle et al., 2017), as well as by individual characteristics (Lawry et al., 2019; Rupp et al., 2018). Operator perceptions of self efficacy with and trust in technology have been observed to affect technology impacts (Rupp et al., 2018), and perceptions of workload and stress have been shown to impact communication (Huttunen et al., 2011). Similarly, operator role (Jahn and Black, 2017), age (Li et al., 2019), experience (Prytz et al., 2018), gender (Walton and Politano, 2014), and technology familiarity (Lawry et al., 2019) have each been suggested as moderators of technology impacts. Operator trust in technology may influence the diversity of information sources consulted (Merritt et al., 2013), while workload, stress, or operator experience (Prytz et al., 2018) could impact when and how information is shared. H5 explores these hypotheses.

2. Experimental design

The experiment tested three types of subjects (77 Masters, 115 Mates, and 19 Pilots) in one of two treatment conditions (140 using WARDs, 71 using conventional displays) in a 3 × 2 between-subjects design. Data were gathered during a 30-min simulated transit on a weekly basis for 18 months. No subject was observed more than once.

3. Method

This research considered impacts of WARD use on operator performance, SA, and communication in one safety-critical system, marine transportation (Fig. 1). 211 volunteer expert subjects participated in a simulated ship transit task in a real-time operational ship simulator. Variables, operationalizations, and data sources are shown in Table 1. Questions addressed included whether WARD use impacted operator communication (H1), performance and SA (H2); and how operator communication impacted performance and SA directly (H3) and as a moderator (H4). Also considered were moderating effects of operator characteristics and perceptions on operator communication when they were using the technology (H5).

3.1. Setting

The study was conducted in the safety-critical setting of marine transportation, where ship operators are responsible for safely navigating their vessel and coordinating with other ships and with shoreside

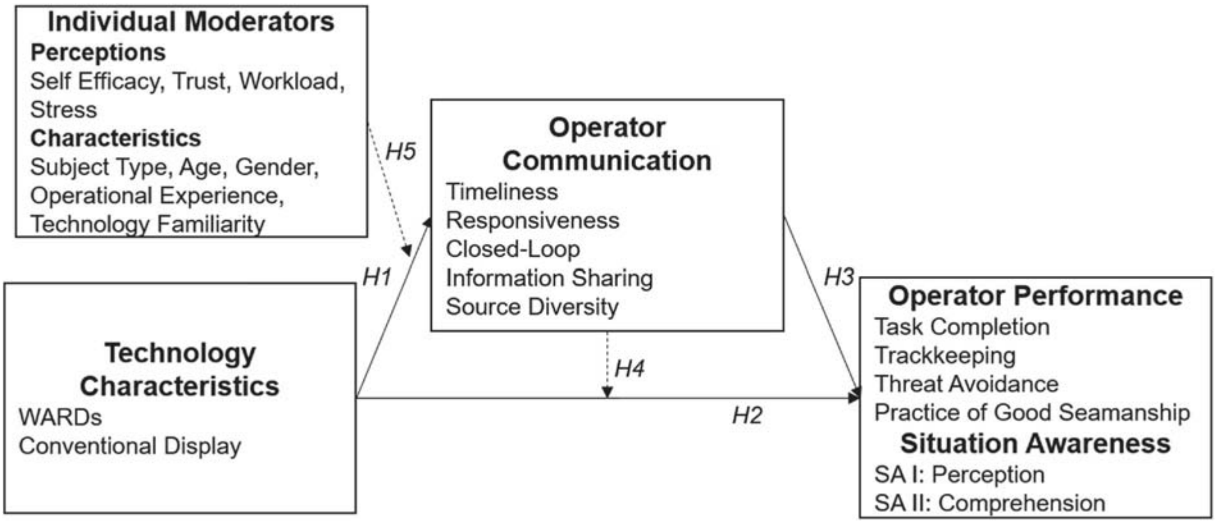

Fig. 1. Research model.

Table 1
Definition, operationalizations, data collection methods, and measurements of variables.

Dependent Variables	Variable	Definition	Operationalization	Data Source
H1				
Operator Communication	Timeliness	Earlier communication of key information (Janssen et al., 2010)	Cross-correlation of communication time series	Coded audio data
Operator Communication	Responsiveness	Time between information requested and supplied (Caldwell, 2008)	Time elapsed in response to a request in seconds	Coded audio data
Operator Communication	Closed-loop communication	Confirmation or acknowledgement of information (Härgestam et al., 2013)	Ratio of Assertions, Acknowledgements, and Requests to total utterances	Coded audio data
Operator Communication	Information Sharing	Unsolicited Assertions of information (Kim et al., 2007)	Assertions of information not preceded by a request	Coded audio data
Operator Communication	Source Diversity	Number of information sources consulted (Jahn and Black, 2017)	Number of different information sources in response to Assertions, Requests, or Commands	Coded audio data
H2, H3				
Operator Performance	Task Completion Percentage	Percentage of key tasks completed during transit	Navigation Skills Assessment Program (NSAP) items 1, 6, 10, & 16	Transit Observation
Operator Performance	Trackkeeping	Deviation from intended track (Grabowski and Sanborn, 2003)	Average cross-track error (XTE) in feet measured at one-second intervals	Simulator
Operator Performance	Threat Avoidance	Maintenance of safe passing distances (Hockey et al., 2003)	Closest point of approach (CPA) in feet to another vessel	Simulator
Operator Performance	Practice of Good Seamanship	Norms and practices of ship management (International Maritime Organization, 1972)	Navigation Skills Assessment Program (NSAP) items 5 &7	Transit Observation
H2, H3				
Operator SA	SA Level I: Perception	Perception of situation elements (Endsley, 1995)	Situation Awareness Global Assessment Technique (SAGAT), NSAP items 2 & 14	Transit Observation
Operator SA	SA Level II: Comprehension	Comprehension of situation elements (Endsley, 1995)	Situation Awareness Global Assessment Technique (SAGAT), NSAP items 3 & 15	Transit Observation
Moderator Variables	Variable	Definition	Operationalization	Data Source
H4, H5				
Operator Perception	Self Efficacy	Belief in operator's capability to be empowered to use resources to meet situational demands (Chen et al., 2001)	New General Self Efficacy survey (NGSE); 3 items	Post transit survey
Operator Perception	Workload	Task demands on resources to achieve performance (Hart and Staveland, 1988)	NASA Task Load Index (TLX); 6 items	Post transit survey
Operator Perception	Trust	Belief in operator's attitude that an agent will help achieve performance (Merritt et al., 2013)	Propensity to Trust Scale (PTS); 3 items	Post transit survey
Operator Perception	Stress	Perception that situational demands task or exceed resources (Helton and Näswall, 2015)	Short Stress State Questionnaire (SSSQ); 6 items	Post transit survey
Operator Characteristics	Subject Type	U.S. Coast Guard License level	Self-reported license level	Pre-transit Survey
Operator Characteristics	Age	Age of subject	Self-reported age	Pre-transit Survey
Operator Characteristics	Gender	Gender of subject	Self-reported gender	Pre-transit Survey
Operator Characteristics	Experience	Years of operational experience	Self-reported years of experience	Pre-transit Survey
Operator Characteristics	Technology Familiarity	Familiarity with mobile, wearable, and Bluetooth devices	Self-reported familiarity with technologies	Pre-transit Survey

authorities as governed by the International Rules of the Road (International Maritime Organization, 1972). Ship navigation requires operators to retrieve and share information (Orlandi and Brooks, 2018) as they move about the bridge, often beyond the visible range of fixed displays (Fig. 2).

This work was undertaken in a Class-A, full mission ship's bridge simulator at the Maritime Institute of Technology and Graduate Studies – Pacific Maritime Institute (MITAGS-PMI) in Linthicum Heights, Maryland. Licensed mariners – Masters, Mates, and Pilots – navigated a simulated 725-ft, 35,000 deadweight-ton container ship into or out of New York harbor (Fig. 3). The simulated transit lasted approximately 30 min, and included vessel traffic, weather, and equipment conditions that were both routine and non-routine.

3.2. Technology

The WARD evaluated was a software application named GlassNav™, developed by Le Moyne College researchers, running on Google Glass Version 2 (2016) (Fig. 4). GlassNav™ provided a real-time display of navigational information gathered from bridge equipment, not registered to the environment (Azuma, 1997), thus providing information situated near a physical entity when the operator looked at it (Willett et al., 2017). Fig. 5 shows the WARD information superimposed on a user's view of the navigation situation, displaying information repeated from the conventional bridge displays: deviation from the intended track (XTE) in feet, own-ship heading (HDG) in degrees, bearing of a radar target (BRG) in degrees, own-ship Course Over Ground (COG) in degrees, own-ship Speed Over Ground (SOG) in knots, Closest Point of Approach to another vessel (CPA) in nautical miles, and Time to Closest Point of Approach (TCPA) in minutes. The status of other equipment was also shown (i.e. ‘GPS FAIL’). The information displayed on GlassNav™ was basic navigational information required by national licensing authorities, was selected as critical to the ship navigation task, and was available on the conventional fixed displays that were dispersed around the ship's bridge (Fig. 2). The WARD information was available on different displays on the bridge but not was presented together on one fixed conventional display.

3.3. Subjects

Subjects were U.S. Coast Guard-licensed ship Masters, Mates, and Pilots attending training courses who volunteered to participate following their regularly-scheduled and federally-mandated training ($n = 211$). All subjects had substantial experience in the simulator ($\bar{x} = 65.67$ hours) and at sea ($\bar{x} = 13.56$ years) prior to volunteering. Table 2 presents the characteristics of operators by subject type.

3.4. Procedure

Subjects were exposed to one technology treatment (WARD or conventional displays), in one navigational transit, either inbound to or outbound from New York Harbor, a typically rigorous transit used for U.S. Coast Guard certification and licensing, shown in Fig. 3. Each transit lasted approximately 30 min and consisted of three legs demarcated by buoys. The first leg of the transit was routine, with clear visibility, minimal currents, functioning bridge equipment, and vessel traffic that followed the International Rules of the Road. The second leg was a transition from a routine to a non-routine transit. The third leg of the transit presented subjects with non-routine occurrences including reduced visibility, high currents, bridge equipment failures, and unpredictable behavior from other vessels. These factors increased both the range of complexity and the realism of the simulated task. Learning effects across subjects were minimized, as subjects participated in the exercise after their regular training was completed, and they were not able to confer with other participants before their transit.

Following an explanation of the purpose of the work, subjects gave consent, completed a pre-transit background survey, and were led to the simulator bridge. There, they were given time to orient themselves to the bridge equipment and instructed in the use of the WARD when applicable. The operational situation was explained, and the simulation commenced when subjects accepted navigational responsibility. During the transit, subjects stood and moved about the bridge; manipulated conventional navigational equipment, including radars, chart displays, and paper charts as shown in Fig. 2; gave commands to a helmsman present in the simulator; and communicated by radio with the Master, other vessels, and shoreside authorities. Following the simulated transit, subjects completed a post-transit survey and interview.

3.5. Data

Data were gathered from five sources: pre-transit surveys; simulator data capturing operator performance measures during the transit; audio recordings of verbal communication on the bridge; in-transit observations of operators captured with a validated U.S. Coast Guard-approved navigational exercise assessment tool, the Navigation Skills Assessment Program (NSAP) (Murphy, 2015); and post-transit surveys and interviews (Table 1). Pre-transit surveys collected operator background information. Data collected during the transit included simulator measurements of operator navigational performance and SA, as well as observations captured by the NSAP. Communication data were coded from audio recordings. Perceptions were measured using validated instruments included in post-transit surveys.

Fig. 2. Simulated bridge showing conventional displays.

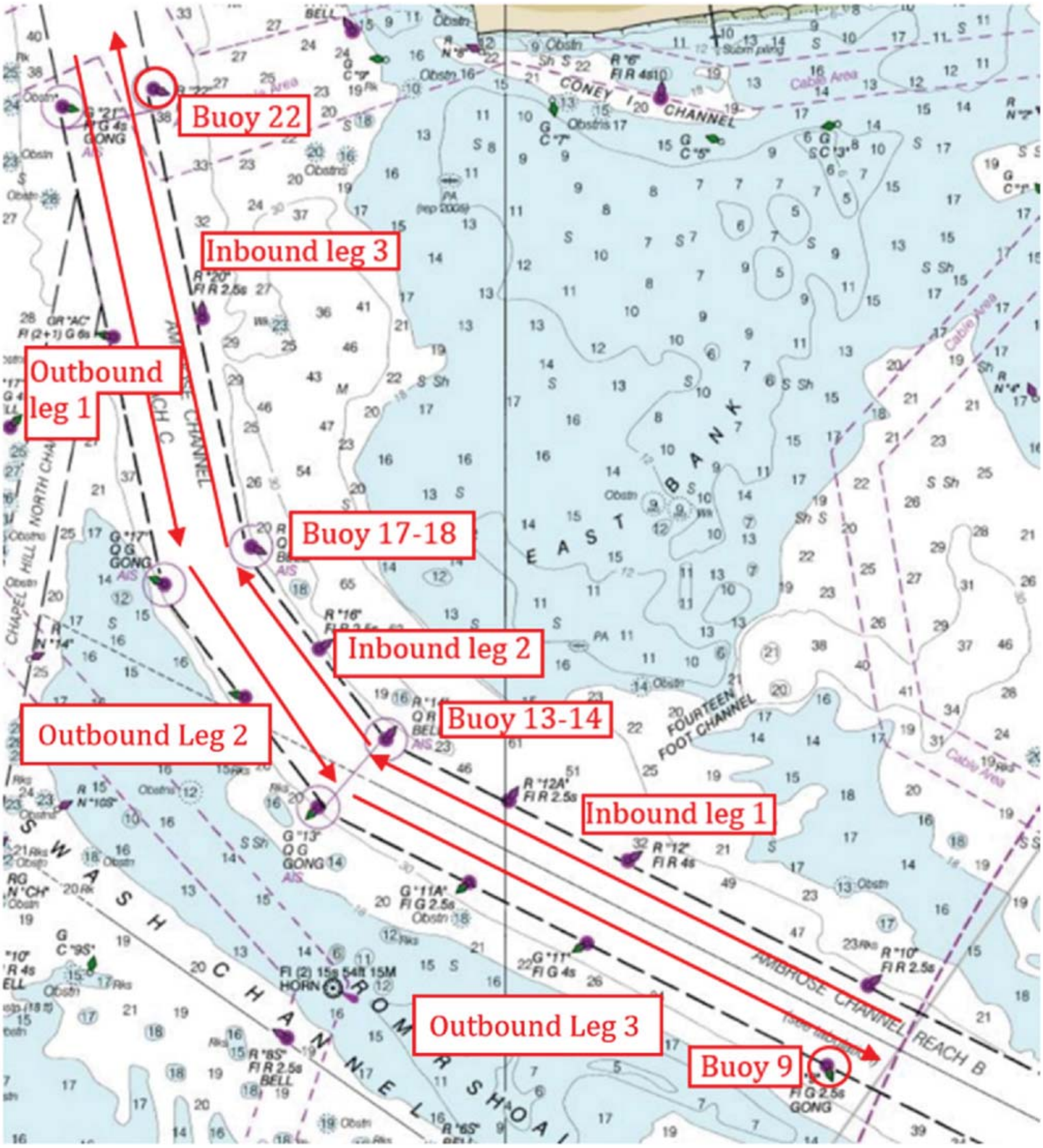

Fig. 3. Transit scenario.

Fig. 4. Google Glass (photo credit: Tim Reckman).

3.5.1. *Communication coding*

Speech act codes (Searle, 1969) or verbal protocols are often used to categorize utterances by the action each is intended to produce (Nonose et al., 2015), providing a profile of the content of communication (Svensson and Andersson, 2006). Speech acts may be analyzed to identify shortcomings in communication (Nonose et al., 2015) or give insight into cognitive processes and perceptions of task factors (Sexton and Helmreich, 2000). Communication content analysis may help explain performance and process differences between routine and non-routine tasks (Park and Kim, 2018) or with varied technology support (Parush et al., 2011).

The unit of coding was the utterance. An utterance from a

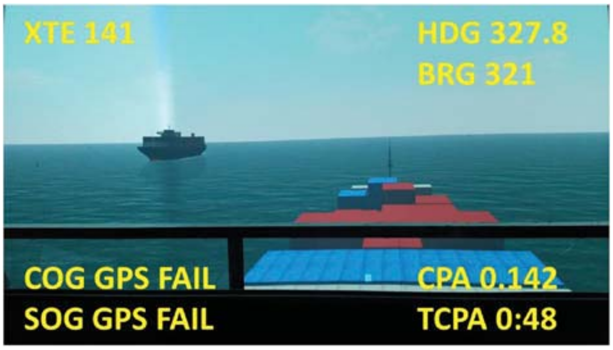

Fig. 5. GlassNav™ display superimposed on a view of the simulated transit.

communication source may specify the destination of the communication and the act is it intended to produce (Searle, 1969). Utterances were coded by a primary coder with experience as a ship's bridge officer for the U.S. Coast Guard, and two additional coders. All coders attended a one hour training program to become familiar with coding categories and to improve consistency. The training program included an overview of the work, the transit scenarios, and the technology; a detailed discussion of the code, including definition of an utterance; explanation and examples of the code categories; a discussion of ambiguous utterances; and a practice coding session. Coded data indicated that coders could perform the coding task with acceptable agreement (Krippendorff's $\alpha = 0.89$) A sample communication between the operator, acting as the Watch Officer, and the helmsman is shown in Table 3.

Communication was coded using a four-category, fifteen-subcategory scheme adapted from nuclear plant operations (Kim et al., 2010). Definitions of the code categories are shown in Table 4. Also coded were the time of each utterance, as well as their source and destination; communication sources and destinations could be either the subject, the helmsman, the Master, or an external party such as another vessel operator.

3.5.2. *Operator perceptions and characteristics*

Operator perceptions of self efficacy, trust, workload, and stress were assessed by validated instruments administered post-transit. Self efficacy was evaluated using the New General Self Efficacy survey (NGSE) (Chen et al., 2001). Trust was assessed using the Propensity to Trust Scale (PTS) (Merritt et al., 2013). Workload was measured with the NASA Task Load Index (TLX) (Hart and Staveland, 1988). Stress was assessed using the Short Stress State Questionnaire (SSSQ) (Helton and Näswall, 2015). Operator characteristics of subject type, age, gender, experience, and technology familiarity were collected in pre-transit background surveys.

Table 3
Coded communication sample between the operator, acting as the watch officer, and the helmsman.

Time	Source	Destination	Utterance	Coded Value
12:12.36	Watch Officer	Helmsman	Rudder right five	Command
12:12.38	Helmsman	Watch Officer	Right five, aye	C-Acknowledge
12:12.41	Watch Officer	Helmsman	Roger	Confirm
12:13.15	Helmsman	Watch Officer	Rudder is at right five	Assertion
12:13.18	Watch Officer	Helmsman	Roger	A-Acknowledge

3.5.3. *Operator performance and Situation Awareness*

Operator performance was assessed using three measures critical to maritime navigation: trackkeeping, threat avoidance, and the practice of good seamanship (Gould et al., 2009; Grabowski and Sanborn, 2003; International Maritime Organization, 1972). Trackkeeping is the maintenance of a vessel's intended track, assessed as the average cross track error (XTE) recorded at one-second intervals by the simulator. Threat avoidance measures the distance between own ship and another nearby vessel, recorded by the simulator as the closest point of approach (CPA) to another vessel when passing. The practice of good seamanship describes qualitative ship management skills, evaluated by observation during the transit using the NSAP. Four key tasks were also assessed using the NSAP: finding the ship's position at transit start; making passing arrangements with another vessel; noting GPS failure; and making radio contact with an overtaking vessel. SA was also assessed using the NSAP, using SA Level I (Perception) and SA Level II (Comprehension) queries from the Master, based on the Situation Awareness Global Assessment Technique (SAGAT) (Endsley, 1995).

3.6. *Analysis*

Data were collected for each transit, in each treatment condition. Hypothesis 1 explored data for 185 transits: 62 using conventional displays and 123 using WARDs. Communication timeliness was measured using a time series analysis of operator utterances in 150 10 second segments of the navigational transit, with the final 30 segments excluded from an Auto-Regressive Integrated Moving Average (ARIMA) model and cross-correlation function (CCF) due to inactivity. The underlying distributions and 95% confidence intervals were estimated by bootstrap. Mann-Whitney U-tests and Kolmogorov-Smirnov (KS)-tests were used to address data skewedness in exploring responsiveness, information sharing, and source diversity. Closed-loop communication was explored using t- and F-tests.

Table 2
Operator characteristics by subject type (N/B: non-binary).

Subject Type	Masters $n = 77$			Mates $n = 115$			Pilots $n = 19$			Total $n = 211$		
	$\bar{x}$		σ	$\bar{x}$		σ	$\bar{x}$		σ	$\bar{x}$		σ
Age in years	49.36		10.99	34.08		9.75	51.84		9.55	41.26		12.87
Experience (yrs)	20.48		11.59	7.19		6.19	23.22		9.55	13.56		11.22
	Female	*N/B*	*Male*	*Female*	*N/B*	*Male*	*Female*	*N/B*	*Male*	*Female*	*N/B*	*Male*
Gender	2	0	75	16	0	99	1	0	18	19	0	192
	Low	*Med*	*High*	*Low*	*Med*	*High*	*Low*	*Med*	*High*	*Low*	*Med*	*High*
Familiarity	9	37	31	4	62	49	1	13	5	14	112	85

Table 4
Communication Coding Scheme Categories and Definitions following (Kim et al., 2010).

Category	Subcategory	Definition
Call		Initiated by a communication source to gain the attention of the communication destination
	Call	Follows the format "Destination; Source"
	Response	Tells the source that the destination has received the call
Assertion		Statements of observed fact, judgments about their implications, or announcements to the system in general
	Observation	Statement which describes the status of equipment or the environment
	Judgement	Assessments of the implications of observed information
	Announcement	Made to the system in general to give information
	A-Acknowledge	Tells the source that the assertion was received
Request		An inquiry or statement of a question
	WARD	A request for information available from GlassNav™
	Bridge	A request for information available from the existing bridge equipment, but not GlassNav™
	External	A request for information that is not available on the simulated bridge equipment or GlassNav™
	Reply	Answers to requests
	R-Acknowledge	Tells the destination that the reply has been received
Command		A directive for a helm action to be taken
	Command	A directive to perform a helm action
	C-Acknowledge	Informs the source that the destination has received the command
	Confirm	Confirmation of an acknowledgment communication
Inaudible		A communication that cannot be heard or understood by the coder

Table 5
WARD impacts on communication (hypothesis 1 results).

Measure	Data Source	Method	Test Statistic	*p*-value	Finding
Timeliness	Time series of utterances over time	CCF, ARIMA	$z = 0.132$	$p = 0.897$	WARD use did not impact timeliness
Responsiveness	Time elapsed from request to reply	U-test	**$U = 2914$**	**$p = 0.008$**	WARD use significantly decreased responsiveness
		KS-test	$D = 0.193$	$p = 0.094$	
Closed-Loop Communication	Number of Confirmations & Acknowledgements	t-test	**$t = 4.029$**	**$p = 9.5 \times 10^{-5}$**	WARD use significantly increased closed-loop communication
		F-test	$F = 0.894$	$p = 0.635$	
Information Sharing	Count of information shared vs. Requested	U-test	$U = 3616$	$p = 0.569$	WARD use did not impact information sharing
		KS-test	$D = 0.085$	$p = 0.926$	
Source Diversity	Number of information Sources	U-test	$U = 4435$	$p = 0.069$	WARD use did not impact source diversity
		KS-test	$D = 0.194$	$p = 0.124$	

Table 6
WARD impacts on operator performance and SA (hypothesis 2 results).

Measure	Source	Method	Test Statistic	*p*-value	Finding
Trackkeeping	Simulator data	ANOVA	**$F = 6.615$**	**$p = 0.011$**	WARD use significantly improved trackkeeping
Threat Avoidance	Simulator Data	ANOVA	$F = 0.667$	$p = 0.415$	WARD use did not impact threat avoidance
Practice of Good Seamanship	NSAP items 5 & 7	ANOVA	**$F = 3.961$**	**$p = 0.049$**	WARD use significantly improved the practice of good seamanship
SA I: Perception	NSAP items 2 & 14	ANOVA	**$F = 9.099$**	**$p = 0.003$**	WARD use significantly improved SA Level I: Perception
SA II: Comprehension	NSAP items 3 & 15	ANOVA	**$F = 4.641$**	**$p = 0.033$**	WARD use significantly improved SA Level II: Comprehension

Table 7
WARD communication impacts on performance and SA (hypothesis 3 results).

Measure	Data Source	Method	Test Statistic	*p*-value	Finding
Responsiveness	Coded Audio Data	MANOVA	$F = 0.753$	$p = 0.607$	Responsiveness did not impact performance or SA
Closed-Loop	Coded Audio Data	MANOVA	$F = 1.045$	$p = 0.398$	Closed-loop communication did not impact performance or SA
Information Sharing	Coded Audio Data	ANOVA	**$F = 10.861$**	**$p = 0.001$**	Information sharing significantly improved threat avoidance
Source Diversity	Coded Audio Data	MANOVA	$F = 0.985$	$p = 0.437$	Source diversity did not impact performance or SA

Analyses for Hypotheses 2, 3, and 4 were examined using a Multivariate Analysis of Variance (MANOVA) with two-way interaction of 183 observations (43 conventional, 140 WARD, removing observations with missing data). Hypothesis 5 relied on a MANOVA with two-way interaction of 163 transit observations (53 conventional, 110 WARD, with observations reduced by missing data). Pillai's trace was selected for robustness with unbalanced samples. In both cases, logarithm transformations were applied to normalize skewed data. Data were analyzed in R 3.5.1 on Windows 10, using packages 'irr' and 'stats'.

4. Results and discussion

WARD use positively impacted operator performance but had mixed impacts on operator communication, increasing closed-loop communication but decreasing operator responsiveness (H1, Table 5). At the same time, WARDs improved almost all areas of operator performance (H2, Table 6), including trackkeeping, the practice of good seamanship, and operator SA. Information sharing and closed-loop communication improved operator threat avoidance when using WARDs (H3, H4; Tables 7 and 8), and some operator characteristics, such as age and technology familiarity, respectively, influenced the number of

Table 8
WARD impacts on operator performance and SA moderated by communication (hypothesis 4 results).

Interaction	Data Source	Method	Test Statistic	***p*-value**	Finding
WARD: Responsiveness	Coded Audio Data	MANOVA	$F = 0.419$	$p = 0.865$	WARD impacts on performance and SA were not moderated by responsiveness
WARD:Closed-Loop	Coded Audio Data	ANOVA	**$F = 9.178$**	**$p = 0.003$**	WARD impacts on threat avoidance were significantly increased by closed-loop communication
WARD:Information Sharing	Coded Audio Data	MANOVA	$F = 0.529$	$p = 0.786$	WARD impacts on performance and SA were not moderated by information sharing
WARD:Source Diversity	Coded Audio Data	MANOVA	$F = 0.746$	$p = 0.614$	WARD impacts on performance and SA were not moderated by source diversity

information sources consulted by operators and operator information sharing (H5, Table 9).

WARD use increased closed-loop communication ($t = 4.029$, $p = 9.5 \times 10^{-5}$; Table 5), but decreased operator responsiveness ($U = 2914$; $p = 0.008$; Table 5). Closed-loop communication is the standard in this and other safety-critical settings to reduce cognitive load and failures (Oliver et al., 2017). Increased access to situated information provided by the WARDs may have encouraged operators to confirm WARD information, increasing closed-loop communication, but introducing delays in responsiveness, as observed in earlier studies of novel displays (Klueber et al., 2019; Riggs et al., 2017). Increased closed-loop communication ($F = 9.178$, $p = 0.003$; Table 8) and information sharing ($F = 10.861$, $p = 0.001$; Table 7) both significantly improved threat avoidance, a desirable effect in safe navigation.

Information sharing increased with technology familiarity ($F = 6.626$, $p = 0.011$; Table 9), perhaps because familiarity with a wearable display reduced information access effort (He et al., 2018). Technology familiarity is a reasonable expectation in this safety-critical system and is required by federal licensing regulations for ship's navigation officers. WARD users mentioned that more familiarity with the WARD would have increased its use and the accompanying benefits, a sentiment supported by prior studies (Lawry et al., 2019).

Diversity of information sources is an important characteristic of highly reliable systems, supporting checks on information accuracy and encouraging consideration of wide perspectives (Weick, 1987). Although WARD use did not directly impact source diversity ($U = 4435$, $p = 0.069$; Table 5), significant differences in source diversity were observed in WARD users' trust ($F = 4.649$, $p = 0.033$; Table 9) and age ($F = 4.046$, $p = 0.046$; Table 9). Younger WARD users and those with lower technology trust utilized more diverse information sources, which is one means for operators in complex systems to develop or improve requisite variety (Jahn and Black, 2017), a desirable outcome. Operators were observed using conventional displays to confirm WARD information, perhaps suggesting low trust in the WARD. This could be expected of a novel technology, and previous studies suggest that more experience with WARDs could build trust (Rupp et al., 2018).

WARD users showed significantly more requests confirming WARD information from their human counterparts than did users of conventional equipment ($t = 2.823$, $p = 0.005$), perhaps because established trust in conventional displays obviated the need for confirmation. Although the WARD text presentation was less rich than voice communication (Daft and Lengel, 1986), WARD users' combined use of rich information through human consultation and the less rich text displays aligns with media richness and HRO theory, as highly-reliable operators often use both types of information and heuristics to select less rich but more relevant information (Prytz et al., 2018). This supports notions that visual and audible information together can improve performance and trust (Klueber et al., 2019).

WARD use reduced operator responsiveness ($U = 2914$, $p = 0.008$; Table 5), which is critical in high consequence settings (Kim et al., 2007). These results could be explained by confusion or distraction introduced by the WARDs (Aaltonen and Laarni, 2017), although subjects did not mention confusion or distraction during their interviews. The decrease in median responsiveness of approximately half a second (conventional display: $\tilde{x} = 5.804$; WARD: $\tilde{x} = 6.333$) while statistically significant, may not be meaningful in a maritime setting where ship's motion must be anticipated many minutes ahead of a decision and navigational transits in confined waters such as New York harbor occur over periods of 30 minutes to several hours.

Operator discomfort with WARDs did not present an issue: Some operators reported slight physical (18 WARD users, 12.857%) or visual (23 WARD users, 16.429%) discomfort but did not feel it affected performance. Statements were made by several operators during interviews, stating they "forgot [the WARD] was there, and went to the [conventional display]".

Table 9
WARD impacts on communication moderated by operator individual characteristics (hypothesis 5 results).

Measure or Interaction	Data Source	Method	Test Statistic	**p**-value	Finding
WARD		ANOVA	**$F = 6.339$**	**$p = 0.013$**	WARD use increased source diversity
		ANOVA	**$F = 12.827$**	**$p = 4.5 \times 10^{-4}$**	WARD use increased closed-loop communication
WARD:Self Efficacy	NGSE	MANOVA	$F = 1.029$	$p = 0.394$	Self efficacy did not moderate WARD impacts on communication
WARD:Trust	PTS	ANOVA	**$F = 4.649$**	**$p = 0.033$**	Low trust increased WARD impact on source diversity
WARD: Workload	TLX	MANOVA	$F = 1.126$	$p = 0.291$	Workload did not moderate WARD impacts on communication
WARD: Stress	NGSE	MANOVA	$F = 0.659$	$p = 0.621$	Stress did not moderate WARD impacts on communication
WARD: Subject Type	Background Survey	MANOVA	$F = 0.657$	$p = 0.623$	Subject type did not moderate WARD impacts on communication
WARD:Age	Background Survey	ANOVA	**$F = 4.046$**	**$p = 0.046$**	Higher age reduced WARD impact on source diversity
WARD: Gender	Background Survey	MANOVA	$F = 1.54$	$p = 0.193$	Gender did not moderate WARD impacts on communication
WARD: Experience	Background Survey	MANOVA	$F = 0.879$	$p = 0.478$	Experience did not moderate WARD impacts on communications
WARD: Familiarity	Background Survey	ANOVA	**$F = 6.626$**	**$p = 0.011$**	High familiarity increased WARD impacts on information sharing

5. Conclusions

In this study, WARD use improved operator performance, conformance with best practices, and SA, with mixed impacts on operator communication. These impacts are important in safety-critical settings, where effective operator performance, SA, and communication can prevent catastrophic loss of life, property, or damage to the environment. Results suggest that WARDs providing real-time situated information led to improvements in operator performance and SA. In addition, the situated displays increased closed-loop communication and source diversity, both of which can play a role in developing operator requisite variety, a desirable effect in safety-critical systems. Technology familiarity increased information sharing, and both closed-loop communication and technological familiarity improved threat avoidance, which is critical to safe and continued operations. However, work is needed to explore whether the reduced responsiveness seen with WARD use in this study is generalizable to the use of other mobile, situated displays in other safety-critical settings.

The results of this work raise several new and interesting questions that were not directly investigated here. This initial study considered WARDs as a single technology; future work could consider the impact of highlighted or consolidated information on conventional displays, mobility of situated displays, or overlaid augmented reality information on operator performance, SA, and communication. In addition, this work could be extended to investigate how trust in technology relates to closed-loop communication, as lower levels of trust, observed here to increase source diversity, may also impact closed-loop and other communication. Finally, this work did not explore how WARD use may have changed as operators gained familiarity with the novel technology, another topic for future investigation.

Declarations of interest

None.

Acknowledgments

The authors wish to thank CAPT Robert Becker, CAPT Glen Paine, CAPT Eric Friend, CAPT Scott Conway, LCDR Allen Birch (USCG, Ret.), CAPT Mike Cosenza (USCG, Ret.), CAPT Bob Kimball, Catie Gianelloni, Hao Cheong, Colleen Schaffer, and Rob Weiner of the Maritime Institute of Technology and Graduate Studies – Pacific Maritime Institute; Andrew St. Cerny and Gregg Ferrando of Transas; Professor Emeritus Thomas R. Willemain of Rensselaer Polytechnic Institute; and three anonymous coders for their help with this work. This work was partially supported by the Maritime Institute of Technology and Graduate Studies – Pacific Maritime Institute and the McDevitt Foundation at Le Moyne College. The Second Author was designated a Google Explorer in 2013.

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