Analytic Review of Using Augmented Reality for Situational Awareness

Julia Woodward and Jaime Ruiz

Abstract—Situational awareness is the perception and understanding of the surrounding environment. Maintaining situational awareness is vital for performance and error prevention in safety critical domains. Prior work has examined applying augmented reality (AR) to the context of improving situational awareness, but has mainly focused on the applicability of using AR rather than on information design. Hence, there is a need to investigate how to design the presentation of information, especially in AR headsets, to increase users' situational awareness. We conducted a Systematic Literature Review to research how information is currently presented in AR, especially in systems that are being utilized for situational awareness. Comparing current presentations of information to existing design recommendations aided in identifying future areas of design. In addition, this survey further discusses opportunities and challenges in applying AR to increasing users' situational awareness.

Index Terms—Augmented reality, human computer interaction, situational awareness, systematic literature review.

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1 INTRODUCTION

Situational awareness is "the detection of elements in the environment within a volume of space and time, the comprehension of their meaning, and the projection of their status in the near future" [1]. Maintaining situational awareness (SA) is crucial in safety critical domains [2], and poor SA has resulted in aircraft crashes [2], oil spills [3], and medical errors [4]. For example, a lack of SA has resulted in errors during anesthesia [5], as anesthesiologists must constantly be aware of the patient's vital signs as well as the surrounding environment.

Previous research studies have started exploring utilizing augmented reality (AR) to increase users' SA (e.g., [6], [7]). Azuma [8] defined AR as systems that have the following characteristics: (1) combines real and virtual elements, (2) interactive in real-time, and (3) registered in 3D. AR supplements the real world through combining virtual objects with the natural environment [9]. When examining the mixed reality spectrum, AR is more towards physical reality than virtual reality [10]–[12]. AR keeps users situated in reality while allowing interaction with virtual objects. Through utilizing AR, users can receive real-time information overlaid over their environment, allowing for a more complete understanding of their surroundings. Thus, AR enables users to maintain SA within their environment. However, these prior studies have mainly concentrated on examining the applicability of using AR and how AR compares to traditional methods instead of information design (e.g., [13], [14]). It is important to consider how to design the presentation of information, as it can affect users' SA [15]. For example, including unclear and extraneous information can distract the user from the main task and prohibit the user from understanding the situation. Therefore, there is a need to research how to present information in AR for users' SA, especially with AR headsets. AR headsets provide mobility and hands-free capabilities, which allow for more user freedom and immersion compared to other AR platforms (e.g., smartphone, computer). These immersive qualities are important in contexts that require high SA, such as military and surgery. For example, during surgery having another external device (e.g., tablet) could be cumbersome and detrimental. Through using an AR headset, a surgeon would not have to hold or maneuver another device, while still receiving information to maintain SA during surgery. Furthermore, AR headsets are beginning to enter the consumer market and industrial settings (e.g., oil industry [16]). As these headsets become more prevalent, it is even more important to consider the presentation of information for users' SA.

We conducted a Systematic Literature Review (SLR) to research how visual information is being presented in AR and how AR is currently being applied to improve users' SA. Considering the definition of AR, it can go beyond one display technology (e.g., hand-held, head-worn, etc.) and can apply to all the senses. Reality can be augmented through sight, hearing, taste, touch (e.g., haptics), and smell. For example, prior work has examined audio AR (i.e., 3D spatial audio that is registered to the users' surroundings) [17], [18]. For the scope of this literature review, we focused on AR through visual displays (sight). We decided to concentrate on visual elements due to being able to provide highly complex and detailed information that is necessary to provide SA. In addition, visual interfaces are commonly used in contexts that require high SA (e.g., monitoring a patient's vital signs). There-

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fore, throughout the paper when we refer to "AR" we are specifically referring to augmenting the environment using visual elements.

The SLR resulted in a total of 140 relevant studies. We were able to identify future areas of design through investigating how AR is being utilized to increase SA and comparing how information is presented to existing AR design recommendations. For example, we found that while previous studies have examined how to design elements in AR (e.g., text [19], notifications [21]), none of the reviewed studies specifically considered the users' SA. In addition, a majority (81%) of the user studies that motivated their work within AR improving SA did not utilize specific SA evaluation techniques (e.g., *Situation Awareness Global Assessment Technique*, SAGAT [22]).

The paper is organized into six major sections, starting with a review of prior SLRs that concentrated on AR in Section 2. Section 3 presents the method used to conduct this SLR, and Section 4 explores the concept of SA. Next, Section 5 and 6 focus on prior work that has applied AR for improving SA and existing AR design studies and guidelines. Based on the prior work from Sections 5 and 6, Section 7 identifies open research questions and future areas of design to increase users' SA in AR.

2 RELATED WORK: LITERATURE REVIEWS

Prior work has conducted Systematic Literature Reviews (SLRs) focusing on AR in many different contexts such as industrial assembly and robotics [23], [24], healthcare [25]–[27], tracking and registration [28], warfare [29], evaluation methods [30]–[32], older adults [33] and general overviews [8], [9], [11], [34], [35].

Azuma [8] conducted a survey in 1997 defining the research space and application areas of AR, such as maintenance and healthcare. Azuma [8] also identified challenges in AR (e.g., properly aligning real and virtual objects) and described future research directions, such as portability and perceptual studies. Billinghurst et al. [11] built upon Azuma's survey by examining the field of AR from 1960-2010. The authors described the history of AR, outlined different tracking and display methods (e.g., optical vs video see-through), and talked about current issues in future AR adoption (e.g., social acceptance, tracking inaccuracy). Billinghurst et al. [11] also described three components that should be designed in AR applications: the real physical objects, the virtual elements to be displayed, and the interaction metaphor that links the real with the virtual. While the two surveys above (i.e., [8], [11]) focused on the general field of AR, other literature reviews have surveyed AR in specific contexts (e.g., warfare).

You et al. [29] completed a survey on how AR is being utilized in urban warfare for soldiers' situational awareness. The authors examined current projects (i.e., up to 2016) on AR for warfare (e.g., *Battlefield Augmented Reality System*, BARS) and identified key challenges such as obtaining the user's accurate position in real-time, accessing real-time geo-registered tactical information, and information overload. You et al. [29] also mentioned that it is crucial to study how information should be presented in battlefield AR systems; however, the authors did not focus on this topic in the review. Zhu et al. [25] conducted a survey about AR in healthcare education (i.e., medical training) up to 2012. The reviewed papers in Zhu et al.'s survey [25] highlighted that AR can aid in learning retention and skill acquisition, especially for surgery, however most of the papers (56%) presented a prototype without any type of evaluation. Al-Issa et al. [26] surveyed papers up to 2010 focusing on utilizing AR for physical rehabilitation. The authors concentrated on clinical studies and found that all of the studies reported improvement.

Other work has surveyed AR evaluation methods [31] and industrial assembly [23]. Dey et al. [31] conducted a survey from 2005-2014 examining the different AR evaluation methods from prior work. The authors found that less than 10% of the reviewed studies conducted user studies, and out of those the majority performed within-subject laboratory studies. Wang et al. [23] surveyed AR-based assembly systems between 1990-2015. The authors found that AR has been implemented in different parts of the assembly process, such as planning, design, and operation guidance and training. The majority of existing AR SLRs have concentrated on an overview of the applicability of AR in different contexts. This SLR goes beyond previous work by focusing on AR for situational awareness with an emphasis on information design.

3 METHOD

We conducted this Systematic Literature Review (SLR) using the guidelines proposed by Kitchenham and Charters [36] for performing software engineering literature reviews. Kitchenham and Charters organized the steps of a SLR into three main stages: planning, conducting, and reporting. This method section will focus on the steps taken for planning and conducting the review.

3.1 Planning: Research Questions and Protocol

The two main processes in the planning stage include specifying research questions and developing a review protocol. For the scope of this SLR, we formed the research questions to focus on the goal of how information should be designed for AR to increase users' situational awareness (SA), especially for AR headsets. The research questions include:

- **R1**: Can AR aid in increasing users' SA?
- **R1.1**: How is information commonly presented in AR applications?
- **R2**: Do existing AR design recommendations consider the users' SA?
- **R3**: How can we design the information in AR headsets to improve the users' SA?

The purpose of **R1** is to first identify if utilizing AR is a useful option for improving users' SA. Surveying findings from work that has applied AR to the context of SA will establish if continuing to research this topic is worth-

TABLE 1

PAPER IDENTIFICATION METHODS

Identification Method	Amount of Papers Identified
Search Protocol	79
Snowball Effect	54
Collaborators/Reviewers	7
Total	140

while. **R1.1** focuses on reviewing the presentation of information in AR applications that aim to increase SA. Understanding the presentation of information in current AR applications is the first step to recognizing how to improve the design. The goal of **R2** is to review existing AR design recommendations and examine if they take into account the user's SA. **R1** through **R2** do not focus on a specific AR platform (e.g., mobile device, AR headset, etc.), rather the questions aim to establish an overview of the current research area. **R3** represents the overall goal of this SLR in identifying future areas of design to increase users' SA for AR headsets.

The research questions above (**R1-R3**) were used to identify keywords for use as search terms, which resulted in: *augmented reality situational awareness*; *augmented reality*; *situational awareness*; *augmented reality headset*; *augmented reality HoloLens*; *augmented reality information presentation*; and *augmented reality notifications*. The generated keywords were then used to conduct searches using Google Scholar. Google Scholar was chosen as the search engine since it returns results from a broad number of sources and paper repositories (ACM Digital Library, SPIE, IEEE Xplore). The first ten pages of results from Google Scholar for each keyword were reviewed for relevant papers (approximately 100 papers per keyword), and then the collected papers were used to generate searches through a "snowball" effect (i.e., search based on citation analysis) [37]. More specifically, the bibliography section from collected papers were used to identify additional papers.

3.2 Conducting: Study Selection and Extraction

In this stage, the review protocol from the planning stage is used to conduct the SLR. For this SLR, papers were excluded if they were not written in English, not peer-reviewed, or if they were not related to at least one research question (e.g., AR, SA). In addition, if there were multiple publications from the same data, only the most recent was included. Existing literature reviews on AR have extensively reviewed work up to 2010 (e.g., [11], [34]) therefore this SLR mainly focuses on papers pertaining to AR published after 2010. The review protocol resulted in 140 papers (Table 1). For data extraction, the papers were read and summarized in a form that included the title, authors, year, method of being found (e.g., keyword), and findings. In conducting this SLR there is a possibility that some prior work was missed even though a systematic and thorough search occurred. Although relevant studies might have been missed, the review protocol for this SLR resulted in a wide range of papers.

4 SITUATIONAL AWARENESS

Situational awareness (SA) has been defined as "the detection of elements in the environment within a volume of space and time, the comprehension of their meaning, and the projection of their status in the near future" [1]. SA is both temporal (i.e., built over time) and spatial [38].

There are three main theoretical approaches to classifying and understanding SA: activity, ecological, and information processing [2]. The *activity approach* presents SA as one component out of many in a model for interpreting information, in which each component depends on the nature of the task and the individual's goals. The *ecological approach* displays SA as a dynamic interaction between humans and the environment, in which the context of the interaction defines SA. The final approach, *information processing*, presents SA as a product of an ongoing process of interpreting information; this approach is best captured by Endsley's theoretical three-level model of SA [38]–[40]:

- **Level 1 SA**: Perception of the elements in the environment, no interpretation of the data performed at this level.
- **Level 2 SA**: Comprehension of the elements and situation, interpretation of the data occurs at this level and is essential for understanding the environment.
- **Level 3 SA**: Prediction of the future status of the elements in the environment, highly dependent on the accuracy of the other two levels.

Endsley's three-level model is ascending and dynamic rather than linear, and is commonly used in prior work to define and analyze users' SA (e.g., [5], [41]).

Maintaining SA is crucial in safety critical domains, such as the military [42], aviation [41], and healthcare [4], [43]. A lack of SA can result in poor performance and errors [38]. For example, failures in perception and comprehension in nursing can be detrimental in patient care decisions [4], and poor SA has been attributed as a factor in the Deepwater Horizon oil spill [3]. Jones and Endsley [41] analyzed 143 incident reports from the Aviation Safety Reporting System database and found 262 SA related errors, the majority (76%) being level 1 errors (e.g., failure to perceive information). Schulz et al. [5] reviewed 200 cases from the German Anesthesia Critical Incident Reporting System and identified SA errors in 82% of the cases, mainly level 1 and 2 errors (i.e., perception and comprehension). SA can be impaired by limited attention, working memory capacity, stress, high mental workload, system design, and complexity [38], [44]. Spatial reasoning and experience (e.g., flying experience) are also factors that can influence SA ability [45].

4.1 Assessing and Designing for SA

Increasing SA has been investigated in multiple fields, such as aviation [44], [46] and mining [47]. Endsley and Robertson [46] examined SA in the field of aircraft maintenance. The authors determined requirements for SA in aircraft maintenance teams through a goal-directed task analysis (GDTA) (i.e., knowledge elicitation from domain experts); for example, one requirement was being aware of part and tool availability and the location of the aircraft to service. Based on the identified requirements, Endsley and Robertson [46] then investigated maintenance teams at a major US airline and found that the largest issue for SA existed when there were communication gaps between the organization or individuals. To improve SA, the authors suggested technological solutions (e.g., digitizing manuals and increasing the usability of software systems), as well as training recommendations, for instance increasing communication and shared mental models. Onal et al. [47] examined SA in the context of mining, since mining operators are often faced with complex information delivered by complicated systems. The authors used a GDTA methodology to gather SA requirements for shovel operators, and then designed a user interface based on the requirements. Endsley [15] proposed multiple design principles for increasing SA, such as determining SA requirements, including a direct presentation of higher-level SA needs (comprehension and projection), supporting a complete overview of the situation, having the system be goal-oriented, incorporating salient critical cues, removing extraneous information, and evaluating the system through different techniques.

Common methods for evaluating SA include subjective post-trial ratings (e.g., *Situation Awareness Rating Technique*, SART), objective freeze probe recall techniques (e.g., *Situation Awareness Global Assessment Technique*, SAGAT), and objective task performance metrics (e.g., response time, cognitive workload) [22], [48]–[52]. SART is a post-trial questionnaire, in which participants rate ten different SA dimensions (e.g., complexity, mental capacity) on a seven-point scale (1 = low, 7 = high) [48], [50]. During SAGAT the task will be frozen intermittingly and the participant will answer questions that pertain to the three levels of SA [22]. Salmon et al. [48] examined both SAGAT and SART during a military planning task and found that the SAGAT approach was more accurate in measuring participants' SA. However, Vidulich et al. [49] recommended using multiple methods for assessing SA (e.g., SAGAT and SART). Prior studies have also used task performance metrics (e.g., response time, errors) to evaluate SA and have found a correlation between SA and performance [52]. However, Endsley [52] cautioned that both task performance and SA are multi-dimensional and that using performance to measure SA is assuming what behavior will occur in a particular state of SA. Understanding how to evaluate systems that aim to increase SA is critical for assessing if the system and information is designed as efficiently as possible.

5 AR FOR SITUATIONAL AWARENESS

This section addresses **R1** in investigating if AR can aid in increasing users' SA; it is broken into two sub-sections: prior work that has (1) examined the benefits of AR and (2) specifically applied AR to the context of improving SA.

5.1 Benefits of Using AR

Utilizing AR can result in less errors [53]–[55], lower perceived cognitive workload [54], [56]–[58], faster completion times [59]–[62], and higher accuracy and efficiency [63]–[66]. Hou and Wang [56] compared AR using a computer display to a paper manual for providing instructions during a Lego assembly task. The instructions provided information on the components to mount and step-by-step assembly instructions. The authors found that the participants had less cognitive workload and were able to learn the assembly routine faster while using AR. In addition, there was no difference in gender in the AR condition, while there was in the paper manual condition (i.e., males were more effective). The authors discussed that the visualization elements of AR aided in sparing the users' mental resources and facilitated working memory for longer. Henderson and Feiner used an AR headset to aid in the psychomotor phase (i.e., physical manipulations) of procedural tasks [61] and help military mechanics in maintenance tasks [62]. Both systems provided dynamic overlaid instructions in the headset (e.g., animated step-by-step sequences). Using the AR systems allowed for faster completion times, greater accuracy, and less head movements. Providing overlaid instructions through an AR headset allowed the users to focus on the task instead of having to shift attention. Prior work has also shown that AR can aid in communication, such as Zarraonandia et al. [67] who applied AR to supporting communication in presentations. The presenter received continuous feedback of the audiences' current level of understanding in an AR headset; the audience members selected their understanding level on a separate application. The authors conducted a case study with lecturers and students at a university and found that the system helped the presenter better pace explanations and improve presentation flow. Providing visual feedback in an AR headset allowed the presenter to receive non-distributive feedback from the audience, which could be used to tailor the presentation.

While previous studies have shown benefits in using AR, some studies have also shown that AR can result in slower completion times [53]–[55], [68], higher discomfort and eyestrain [54], [68], and higher cognitive workload [69]. Velamkayala et al. [54] conducted a study to evaluate AR for collaboration during a navigation task. In the study, a passive user using a tablet could draw directions for an active user, which would appear in the active user's AR headset or smartphone. Using the headset resulted in significantly less errors and lower cognitive workload but had slower completion times. Also, some participants mentioned that the headset was uncomfortable and increased eyestrain; however, other studies have found that using an AR headset did not cause visual fatigue [64].

Although none of these studies specifically examined using AR for SA, they illustrate overall that AR as a technological tool may be useful (e.g., higher accuracy), which could aid SA. However, only applying AR may not result in improvement of users' performance due to conflicting findings (e.g., lower vs higher cognitive workload).

5.2 Utilizing AR for SA

AR has been applied to improving SA in multiple contexts, such as healthcare and military. Examining the findings from existing work will show if continuing to research AR for increasing users' SA is still a promising option. This section (*Section 5.2*) is broken down into different contexts that have applied AR for SA. We determined the contexts through grouping the papers by specified keywords and abstract themes. For example, the "Military and Security" context includes papers with the themes "military", "security", "warfare", and "emergency".

5.2.1 Driving

Driving requires a high level of SA, as the driver must perceive and comprehend the surrounding environment (e.g., be aware of other vehicles, pedestrians). AR has been applied to driving SA for multiple situations, such as detecting other vehicles and pedestrians [70]–[72], navigating [73], [74], and identifying road signs [73], [75].

Park et al. [70] developed an AR system to be overlaid on a vehicle windshield to increase SA. The system recognizes a dangerous situation and provides warning information. For example, it detects other vehicles and adds color depending on danger level (e.g., how close the other vehicle is). Phan et al. [71] designed a new pedestrian collision warning system using AR. The system includes two cues, a yellow bounding box around pedestrians and a warning label in the bottom left corner of the windshield. A study using a driving simulator found that the AR cues enhanced awareness of pedestrians. Prior work as also investigated using AR to increase awareness in the transition phase during automated driving (i.e., taking over the vehicle) [76], [77]. Lorenz et al. [76] examined using AR to aid in transition through highlighting areas to avoid in red and areas that are safe in green on the car windshield. The authors analyzed the AR system using a driving simulator and found that it did not affect take over times but aided in braking (i.e., participants were more cautious).

Other studies have focused on AR notifications for driving [74], [78]–[82]. Tran et al. [78] created a left-turn aid that projects the paths of oncoming vehicles on the windshield. The authors designed the aid through an iterative process with user feedback; they looked at a solid color path, a chevron arrow path, and a wireframe path and found that users preferred a solid red path. Kim and Wohn [74] compared a traditional 2D map paradigm (e.g., Google Maps) to an AR paradigm in supporting driving navigation. For AR, a red arrow would appear on the road in the participant's field-of-view to show which direction to follow. In a user study with a driving simulator, navigation with AR was faster and resulted in better route decision at complex points (i.e., change of direction), but resulted in higher cognitive workload. Merenda et al. [81] examined the difference between static and animated visual graphics. For example, a static blue arrow pointing in the direction of a parking spot compared to an animated blue arrow that would orient itself in accordance with the car. With static graphics, participants overestimated distances and made less accurate judgments, but had faster reaction times than with the animations.

Some of the work in this sub-section did not conduct an evaluation [70], [73], [82], [83], and out of the ones that did conduct an evaluation (n = 11) the majority (81.8%) used a driving simulator (e.g., [74], [79]); only two papers included an evaluation with an actual vehicle [81], [84]. Overall, current research is commonly applying AR to the context of driving. Negative consequences for using AR in driving have been found, but also great benefits such as pedestrian awareness [71].

5.2.2 Military and Security

Maintaining SA is critical in military and security contexts [42], as understanding the situation and environment is crucial in making complex decisions. AR has been examined in a wide range of military contexts [7], [85], such as flying Unmanned Aerial Vehicles (UAVs) [13], [86]. Ruano et al. [13] created an AR system for the flight of UAVs by overlaying flight mission data (e.g., route orientation, target identification) onto a live video stream on a computer screen, instead of having two separate screens as in previous UAV systems. The authors tested the system in an Airbus Ground Control Station demonstrator and found that it improved the SA of the UAV operators. Gans et al. [7] presented an AR headset system (ARC4) that delivers SA to dismounted soldiers. The AR interface overlays tactical information onto the user's real-world view, such as navigation waypoints, longitude and latitude, and environment features (Fig. 1). The authors evaluated their vision-based techniques for determining orientation but did not evaluate their interface design.

Other work has analyzed different AR presentation methods for multiple scenarios, such as ways to represent friendly or hostile forces [87], [88], navigation [87], [89], and occluded entities [90]. Livingston et al. [90] examined different methods for filtering information and representing occluded entities in mobile military AR applications. A tunnel metaphor for showing occluded entities in an AR headset led to the least amount of error (i.e., the num-

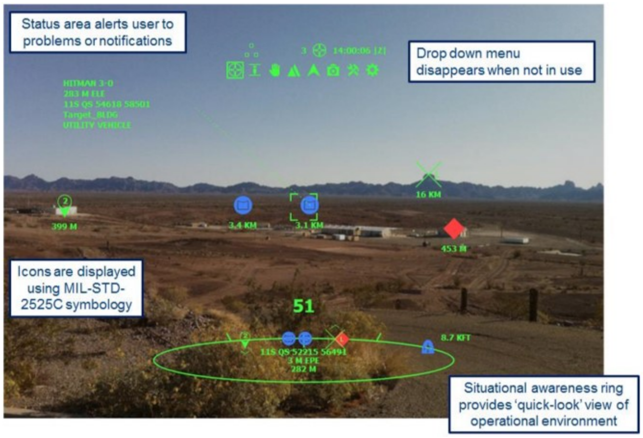


Fig. 1. ARC4 (*Augmented Reality Command, Control, Communicate, Coordinate*) interface, which provides situational awareness to dismounted soldiers through the use of an AR headset [7].

ber of virtual squares around an object represented the number of occluding layers). The authors also designed a 2D birds-eye view map, which would appear when the user looked down in the headset; they did not evaluate the design. In addition, Livingston et al. [90] conducted interviews with subject matter experts from the military community and found that they most wanted to know the location of friendly forces in the area, building and street labels, route data, and have a simple interface design due to high stress environments. Neuhöfer et al. [87] developed a prototype for a vehicle-mountable AR system for urban warfare scenarios. The system handles tracking through a Differential-GPS approach, while the type of display could differ depending on the situation (e.g., computer screen, headset). The system visualizes the status of surrounding forces (e.g., friendly, hostile) through different colors. For example, a hostile tower would appear red and detailed textual information would be in the upper left-hand corner (e.g., latitude and longitude). The authors also investigated using a mini-map or in-view directions for navigation and found that in-view directions resulted in faster reaction and completion times.

Other than military applications, AR has been used in the security domain (e.g., law enforcement, security guard) [91] and for crisis management [92]. Lukosch et al. [91] examined using AR to provide distributed team awareness in the security domain. In the study, one member had an AR headset while the other member was remote watching a live video stream from the view of the headset on a computer screen. The remote collaborator was able to manipulate the content in the AR headset, such as adding text. The authors tested the system in a training environment with different scenarios (e.g., collecting evidence) and found that the user wearing the AR headset had higher cognitive workload and lower alertness. However, the remote collaborator had higher SA, which was determined through SART. Sebillo et al. [92] designed an AR mobile interface to aid in training first responders in crisis management. The interface had two visualization methods: *MapMode* (classic 2D map) and *LiveMode* (i.e., added virtual content). For example, in LiveMode a damaged building would have a red overlay with building information in text.

While half of the papers mentioned in this sub-section (n = 5) did conduct some form of evaluation [13], [86], [87], [90], [91], only one [91] used SA evaluation techniques (i.e., SART). Brandão and Pinho [89] stated that they would use SAGAT to evaluate their AR design for dismounted operators in military and law enforcement in future work, but did not conduct a formal evaluation. In addition, the papers mainly focused on applying AR to different military situations instead of investigating different designs of representing information.

5.2.3 *Industrial*

Other studies have investigated AR in industrial contexts, such as monitoring the production process [93] and providing maintenance [94]–[97]. Aschenbrenner et al. [94] developed a mobile AR architecture to aid in remote analysis and maintenance of industrial manipulators. The system allows a remote user to view a virtual rendering of the plant within their current physical environment using a tablet PC to have a better understanding of the situation. The authors conducted a study in which participants' completed usability tests, a NASA TLX survey [98], and SART. Using AR resulted in higher usability and lower cognitive workload, but lower SA. Zhu et al. [97] created *AR-Mentor* (Fig. 2), a wearable AR mentoring system to assist in maintenance for complex machinery. AR-Mentor provides guidance through voice instruction and conversation with a virtual personal assistant and visual elements in an AR headset (e.g., 3D graphic animations, text, and live-action videos). The authors conducted preliminary training tests with novice users and found that it demonstrated promising effectiveness; however, the authors did not elaborate on how they evaluated the system or how they determined the results. Novak-Marcincin et al. [93] presented a conceptual design for monitoring a production process using AR. In the design, the user would look through a window into the industrial environment and augmented icons would appear on the glass over specific machines to represent different factors (e.g., working time left, completion state). The studies in this sub-section focused on architecture and applicability, rather than the presentation of the information.

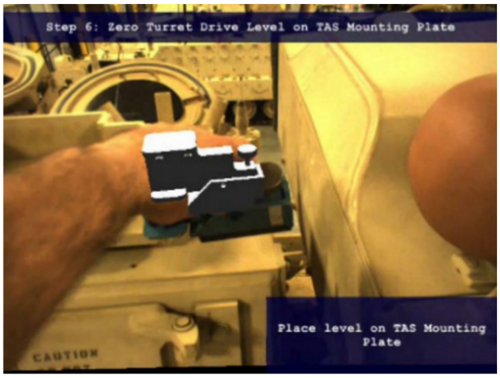


Fig. 2. *AR-Mentor* interface providing instructions for a maintenance procedure for a training vehicle [97].

5.2.4 *Medical*

Retaining SA is important in the medical and healthcare fields as reduced SA can result in poor patient care and errors [4], [5], [43]. Although maintaining SA is important in the medical field, training for SA is lacking in medical education curricula [43]. Previous studies have investigated using AR to aid in monitoring patient information [6], [14]. Pascale et al. [14] examined if AR can aid in the awareness of patient alarms. The authors found that using an AR headset to show patient vital signs resulted in faster reaction times to clinically important alarms, less error in missing alarms, and higher SA. The authors used SAGAT to evaluate the participants' SA. Liu et al. [6] investigated if an AR headset could aid anesthesiologists in monitoring patient information (Fig. 3). Six anesthesiolo-

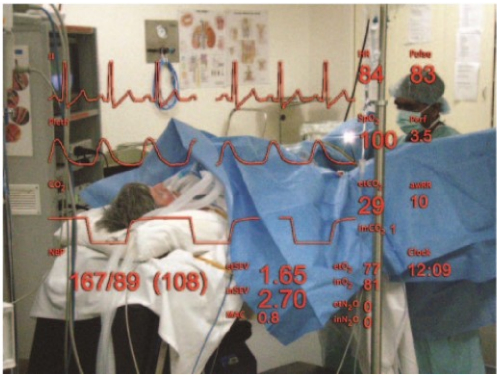


Fig. 3. Anesthesiologist’s view in an AR headset when monitoring patient information [6].

gists provided anesthesia to patients undergoing rigid cystoscopy using either standard techniques or the AR headset. When using AR, the anesthesiologists spent less time looking at the anesthesia workstation and more time monitoring the patient and surgical field. Both of the studies above found that using an AR headset helped in monitoring patient information; however, they did not study the presentation of the information in the headset.

5.2.5 Construction

Prior work has also examined utilizing AR in construction [99], [100]. Irizarry et al. [99] created a mobile AR system called InfoSPOT (i.e., *Information Surveyed Point for Observation and Tracking*). Through using InfoSPOT, AEC facility managers (i.e., Architecture, Engineering, and Construction) can access information about the facilities they maintain to increase SA. Users can view augmented information (e.g., icons, text) over real-world objects. The authors conducted a study in which participants completed location finding and data extraction tasks using a tablet PC in three different conditions: AR elements over real-world objects, AR elements over virtually outlined real-world objects, and a complete virtual model (i.e., not AR). While there was no difference between the AR conditions, the virtual model was the least preferred and took the most time. Wallmyr et al. [100] investigated if AR could benefit the SA of excavator operators in a simulated excavator environment. Augmented icons would appear on the simulated windshield, such as a yellow warning triangle or red stop sign. Using AR led to lower cognitive workload and faster detection of information.

5.2.6 Navigation

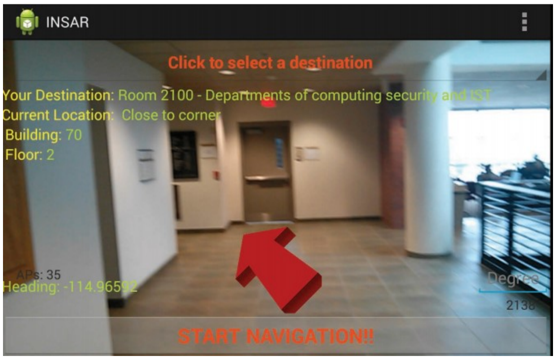
As mentioned above, AR has been applied to driving navigation; however, previous studies have also investigated using AR in other navigation contexts, such as maritime navigation [101], [102]. Grabowski [101] suggested applying Wearable Immersive AR (WIAR) to maritime navigation for helping officers receive real-time information such as the weather and vessel speed. Grabowski [101] also identified open research questions, such as researching the impact on decision-making. Hong et al. [102] created the *Maritime Augmented Reality System* (MARS) interface to aid in maritime navigation for remote operators. The system collects and displays the locations of other vessels in the area onto a live video feed on a computer screen (other vessels are represented as blue squares). The authors evaluated the system using SAGAT and found that the AR interface resulted in higher SA.

Along with maritime navigation, prior work has explored navigation for specific populations [103] and indoor locations [104]. Hervas et al. [103] designed a mobile smartphone AR application to help support cognitively impaired people in spatial orientation and navigation. The user’s familiar points of interest influence the navigation routes. Augmented graphical icons show different points of interest (i.e., gold stars) and text instructions appear at the top of the application. The authors conducted a study comparing the AR application to commercial GPS-based applications with cognitively impaired participants. The AR application resulted in a higher usability score than the commercial application. Alnabhan and Tomaszewski [104] developed INSAR (*Indoor Navigation System Using Augmented Reality*), which aids users in navigating indoor locations on a mobile device (Fig. 4). The application provides text descriptions and arrows pointing in the direction to go; however, the authors did not evaluate the presentation of the information.

5.2.7 Miscellaneous

Other contexts that have focused on increasing SA through AR include environmental site understanding [105] and remote collaboration [106]. Veas et al. [105] examined different environmental data visualization methods for outdoor mobile AR applications to improve site understanding. The authors created an application with two different views: a multi-view and a variable perspective view. The multi-view allows the user to access views from different perspectives and the variable perspective view provides both first person and third person views of the environment to allow for higher SA. The authors conducted usability studies and found that the views were usable; however, the authors did not examine the views in terms of how it influences SA.

For remote collaboration, Kim et al. [106] conducted two studies examining how to support and increase team SA. During the task, one user had an AR headset, while a



Your Destination: Room 2100 - Departments of computing security and IST
Current Location: Close to corner
Building: 70
Floor: 2
APs: 35
Heading: -114.96592
Degree
2138

Fig. 4. Screenshot of INSAR interface (*Indoor Navigation System Using Augmented Reality*) from mobile device [104].

remote user could watch a live video stream and draw annotations that would appear in the other user's headset. The first study investigated how to aid the remote user in drawing annotations. The authors investigated three methods: auto-freeze (i.e., video stream would freeze when drawing), manual freeze, and non-freeze. The participants preferred the auto-freeze method. In the second study, the authors examined three methods to notify the headset user that the remote user was drawing: a red outline around the display, freezing both users' views, and no notification. The participants preferred the red outline; the freeze method resulted in too much interruption.

5.3 Summary

Reviewing prior findings showed that using AR can result in benefits, such as lower cognitive workload and higher accuracy. Although, some studies did find conflicting negative effects, for instance slower reaction times and higher cognitive workload. In answering **R1**, (*"Can AR aid in increasing users' SA?"*) AR has been applied towards improving SA in many contexts (e.g., military, construction). Reviewing the results from previous studies affirmed that AR could aid in increasing SA and strengthens the argument for continuing to research how to utilize AR for SA. However, a majority of the user studies reviewed in *Section 5.2. Utilizing AR for SA* did not use specific SA evaluation techniques (81%) or focus on information design (78%). Only five of the studies [14], [72], [91], [94], [102], utilized specific SA evaluation techniques.

For **R1.1**, (*"How is information commonly presented in AR?"*) there was a wide range of designs, which were dependent upon the specific context of the applications; however, a majority included some form of textual information, color as a distinguishing factor, and presented the information in the user's central vision (e.g., Fig. 1-4).

6 PRESENTATION OF INFORMATION IN AR

This section addresses **R2** in reviewing if existing AR design studies and recommendations consider users' SA.

6.1 AR Design of Elements

Prior work has analyzed how to design specific elements in AR; this section is broken down into different elements: 1) text, 2) the location of elements, 3) notifications, instructions, and labels, and 4) the amount of elements. Similar to *Section 5.2. Utilizing AR for SA*, we determined the elements through paper keywords and themes.

6.1.1 Textual Elements

In researching how to design text for AR headsets, previous studies have examined different backgrounds, colors, and styles [19], [107], [108]. Albarelli et al. [19] investigated the difference between transparent and opaque text backgrounds (i.e., billboards) in an AR headset (Fig. 5). During the user study, participants had to stock items in a test grocery store while product information appeared in the headset. The product information was essential for the study task, therefore the participants had to constantly be aware of the information. Having a central display of information with a transparent background resulted in faster completion times, and participants preferred this display method due to the ease of reading the information.

Fig. 5. View from AR headset for (left) central transparent (right) and central opaque backgrounds [19].

Debernardis et al. [107] examined how the design of text affected readability in both optical and video see-through AR headsets. In optical see-through headsets the user views the real-world environment, while in video see-through headsets the user observes a real-time video feed of the environment. The authors investigated two solid color backgrounds (light and dark), five colors (white, black, red, green, blue), and two text styles (plain and billboard). Participants were faster in readability with the optical see-through headset. The authors recommended using white text with a blue billboard, as it performed well for every condition. However, other work has found different results. Fiorentino et al. [108] conducted a study looking at text styles for optical see-through AR headsets with three industrial image backgrounds (testbed frame, workbench, engine), four colors (white, black, red, green) and four text styles (simple text, outline, billboard, outline with billboard). The billboard text style resulted in faster completion times and higher text readability, but with black text and a white billboard. The authors recommended having maximum contrast between the text and background to increase readability.

While Fiorentino et al. [108] recommended having black text with a white billboard, Debernardis et al. [107] suggested not having a white billboard as large areas of white could lead to visual fatigue. Debernardis et al. [107] also found that white text with a blue billboard resulted in higher readability. The contrasting findings could be due to the studies examining the text against different background styles (i.e., solid colors vs industrial images), as well as Fiorentino et al. [108] not examining the color blue for text. However, it is not clear what exact factors led the studies to have divergent results. Also, both studies [107], [108] recommended using opaque billboards, but Albarelli et al. [19] found that transparent text backgrounds resulted in faster completion times.

6.1.2 Location of Elements

Previous studies have examined where to place specific elements based on reaction time and comprehension [20], [109]. Chua et al. [109] investigated reaction times for different locations in a monocular AR headset (i.e., Google Glass [110]). The authors used colors, application icons, and text as notification types. Participants had a faster reaction time for color, and although the center and bottom locations resulted in faster reaction times, participants preferred the top and periphery locations. The authors recommended the middle-right location as a balance between preference and performance. Rzayev et al. [20] examined how to display text for reading in an AR headset while the user is walking or sitting. The text appeared in three different positions (top-right, center, and bottom-center) and in two presentation types, line-by-line scrolling and Rapid Serial Visual Presentation (RSVP); RSVP presents text word-by-word in a fixed location. The authors found that the top-right location increased cognitive workload and reduced text comprehension, while the center and bottom-center increased comprehension and decreased cognitive workload. RSVP had higher comprehension during sitting, while line-by-line scrolling had higher comprehension during walking. Based on the results from these two studies [20], [109], elements should be placed in the center and bottom locations to reduce reaction time and cognitive workload.

While the studies mentioned above focused on screen-fixed placement, Gabbard et al. [111] discusses world-fixed placement (i.e., at the location of a particular object in the real-world) in AR systems for driving. Also, methods for dynamic placement of elements have been investigated [112]–[114]. Orlosky et al. [112] created *Halo Content*, a method to manage the location of elements (e.g., texts) in an AR headset. Halo Content moves the elements, so they do not occlude faces or gestures in dynamic unknown situations. In a user study, Halo Content resulted in a 55% reduction in element interference compared to a fixed layout. Chen et al. [113] proposed an adaptive display method, in which connected empty regions on a grid (i.e., empty places in the environment) are determined to be non-interest regions to place elements in an AR headset. During an assembly task, participants were faster and found the display method helpful.

6.1.3 Notifications, Instructions, and Labels

In addition to considering how to design textual information and where to place elements, prior work has explored different designs for notifications [21], [115]. Lucero and Vetek [21] created *NotifEye*, an application for receiving social network notifications for AR smartglasses. Notifications appear in the center of the user's field of vision (i.e., foveal vision) and consist of different color butterfly icons. The colors represent different social network sites (e.g., blue for twitter). The butterfly would fly from one part of the screen to another and then fade away if the user did not open the message. The authors conducted a navigation task and found that the participants were able to keep track of their surroundings when interacting with the notifications. Cidota et al. [115] explored how automatic audio and visual notifications about a remote user's activities affected a local user's workspace awareness during a puzzle task. The local user was wearing an AR headset, while the remote user was interacting with a laptop to provide instructions to the local user. The local users preferred the visual notifications, which consisted of an icon that would blink in the bottom right corner of the headset (e.g., green arrow), due to the visual notifications being less distracting.

As mentioned in *Section 5.2. Utilizing AR for SA*, augmented instructions have been used in navigation, assembly, and other contexts. Previous studies have looked at how to design and visualize these instructions [116], [117]. For example, Khuong et al. [116] compared two visualization methods for providing instructions in an AR headset during a Lego assembly task. A virtual model of the next assembly step was either overlaid directly over or adjacent to the actual physical model. The authors found that having the virtual model adjacent resulted in faster completion times and less errors. Directly overlaying the virtual model over the physical model was sensitive to misalignment, latency, and conflicting depth cues.

Other authors have investigated the design of labels [118], [119]. Kruijff et al. [119] examined how visual characteristics of labels (e.g., size, color) in AR affected search performance and noticeability in outdoor environments. The authors found that limiting the field-of-view resulted in lower noticeability of the labels but did not affect perceived cognitive workload. The color blue resulted in higher noticeability and participants preferred blue to other colors. Participants also preferred smaller sized labels in the central visual field and larger sized labels as the labels moved further into the periphery. Additional work has looked at the placement of labels. For example, Tatzgern et al. [118] proposed managing the placement of labels in AR headsets in 3D object space instead of 2D space to resolve clutter and overlapping labels. The authors suggested that each label consists of an annotation, a 3D pole, and an anchor point. The labels only move along the pole to avoid overlapping other labels. The authors applied their design in different contexts (e.g., labeling parts of a heart), but did not conduct a user study.

6.1.4 Amount and Detail of Elements

Along with contemplating the appearance of different elements, prior research has looked at the amount [120]. Ganapathy et al. [120] analyzed the appropriate amount and time-delay of textual information (e.g., building names) in an AR smartphone application for navigation. The authors found that participants preferred 7 elements, with 4 not being enough and 11 being too much; however, the participants wanted control of the amount of information. For time-delay, users were only willing to wait up to 3 seconds for information.

Different methods for controlling the amount and detail of information have also been analyzed, such as using eye-tracking techniques [121]–[123]. Ishiguro and Rekimoto [121] proposed using a mobile eye-tracker to determine the user's gaze location, which would control the position and level of detail of information in AR smartglasses (i.e., longer gaze resulted in detailed information). For example, if the user gazed at an email icon, the textual content of the email would appear. Toyama et al. [122] used a user's eye-gaze depth and cognitive state to determine if the user was focusing on the AR content in a headset or the real environment. If the user was focusing on the real environment, the AR information would dim in the headset. Prior work has also suggested using hierarchical clustering to control the amount of information [124] and examined different ways to handle output management [125]. Tatzgern et al. [124] developed an adaptive information density display for AR to aid in alleviating clutter (e.g., overlapping icons). The authors used hierarchical clustering to create a level-of-detail structure, in which nodes closer to the root encompass groups of items while leaf nodes contain single items. The method then selects items and groups from different levels depending on user defined preferences. When comparing the adaptive display to traditional AR browsers, users found that it allowed for easier comparisons and a better overview. Lebeck et al. [125] explored the idea of output management in terms of privacy and safety (e.g., preventing applications from interfering with one another). A windowing model, similar to traditional desktops, would result in high control but low flexibility, while allowing applications to free-draw anywhere in the user's field-of-view would result in high flexibility but low control. Therefore, the authors suggested having the operating system manage visual content at the granularity of AR objects rather than windows, which would allow for flexibility and control; the authors did not evaluate their design.

6.2 AR Design Recommendations

While the previous section included research studies that examined how to design specific elements (e.g., notifications), this section focuses on overall AR design recommendations. For instance, Ganapathy [126] suggested eight design guidelines for mobile AR applications:

- Clear textual information.
- Contrast for visibility.
- Organization of information should have meaning.
- Placement should not obscure item of interest.
- Draw attention to information that requires action.
- Ability to switch between interaction methods.
- Distinct icons that can be easily parsed.
- Filter information based on distance and visibility.

While Ganapathy [126] mainly focused on AR applications for mobile devices (e.g., smartphones) when proposing the eight design guidelines, the guidelines can translate to other AR form factors. For example, in AR headsets and smartphones the available screen space is limited, and they are both mobile and immersive. Other work has examined challenges [127], [128] and factors to consider [129], [130] when designing for AR. Muller [127] identified five representation challenges in AR: clarity, consistency, visibility, orientation, and information linking (i.e., recognize connections between virtual elements and the environment). Virtual elements must be immediately recognizable, visible, and consistent with the environment. If an AR display is too cluttered with virtual elements, the user may have trouble orientating themselves in the environment. Also, faulty tracking and latency can lead to inconsistency and lack of information linking. Kourouthanassis et al. [128] stated that mobile AR applications face unique design challenges, including real-time information retrieval, object recognition and tracking, and user interaction. The authors also presented five design principles: use context for providing content, include content relevant to the task, inform about content privacy, provide feedback, and support semantic memory (e.g., use common interface metaphors).

Regarding aspects to consider when designing, Dunston and Wang [129] presented four factors for AEC (i.e., Architecture, Engineering, and Construction) AR systems: mental effort, physical disposition (e.g., body position), surrounding environment, and if the user's hands are occupied. The authors also suggested avoiding large amounts of text, large images, and solid virtual objects. Tonnis et al. [130] presented a set of independent design dimensions to classify AR information: temporality (continuous or discrete), dimensionality (2D or 3D), frame of reference (egocentric or exocentric), mounting and registration (e.g., what is the content attached to), and type of reference (e.g., can represent items outside of the user's field-of-view). The authors applied the dimensions to a variety of AR applications and found that most applications had a continuous 3D egocentric presentation scheme. In general, information in an AR display should be clear, visible, and relevant to the task.

6.3 AR Information Visualization

Information visualization techniques have also been utilized for designing AR applications [131]–[134]. ElSayed et al. [132] used AR as an analytical tool and created *Situated Analytics*, a combination of real-time interaction and visualization techniques to allow users to analyze information about physical objects in their environment. In the paper, the authors situated their system within the context of grocery shopping and supported three types of queries: filtering (objects of interest highlighted in green), finding (object highlighted in green with green arrows pointing towards it), and ranking (numbers would appear on the objects), see Fig. 6. In their design process, the authors modified Shneiderman's mantra [135] (i.e., overview, zoom and filter, and details-on-demand) by first focusing on analysis, then highlight (show the important), zoom and filter, further analysis, and then details-on-demand. In a user study, participants completed grocery shopping analytics tasks and finished more quickly and accurately with Situated Analytics compared to a manual method. Zollmann et al. [133] examined different techniques in AR for overlaying (e.g., blending, X-ray) and filtering information (e.g., focus + context techniques, such as a 2D magic lens) in the context of monitoring con-

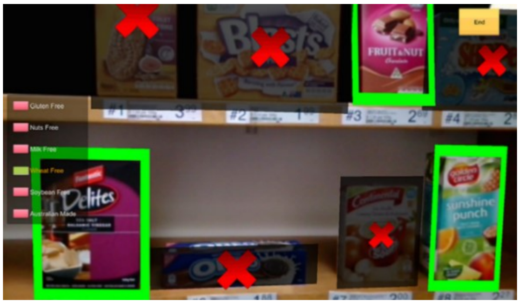


Fig. 6. *Situated Analytics* view during filtering task [132]. Objects highlighted with green rectangles match the filter specification.

struction progress. The authors proposed a 4D abstraction approach to address change blindness (i.e., not noticing a change) [136] and improve visual clutter. For instance, the 4D approach first shows the user an overview of the construction progress, and then the user can observe what the building looked like at specific time points using different color overlays (i.e., details-on-demand). The authors did not evaluate their design.

Other work has directly compared visualization techniques for specific elements, for instance examining how to represent X-ray views in AR [137] and out-of-view objects [138]. Gruenefeld et al. [138] designed *EyeSee360* to aid in visualizing out-of-view objects in AR headsets. The authors used circles to represent objects and the color of the circles depicted the distance (i.e., red closer, blue further away). EyeSee360 resulted in lower error when compared to existing techniques (i.e., arrow, wedge, and halo); there was no difference in cognitive workload.

6.4 Summary

Prior research has examined how to design specific elements in AR (e.g., text); however, some studies found conflicting results, for instance including or avoiding a white billboard for text. Design recommendations for AR suggest that information should be clear, meaningful, and not obscure the item of interest. Reviewing prior design recommendations provides a base for critiquing existing AR systems (expanded upon in the *Discussion* section). Regarding **R2** (*"Do existing AR design recommendations consider the users' SA?"*), none of the reviewed work in this section evaluated their designs in terms of SA or included a design recommendation based on SA.

7 DISCUSSION

R1 and **R2** did not focus on a particular AR platform (e.g., tablet, computer, headset); however, **R3** (*"How can we design the information in AR headsets to improve the users' SA?*) concentrates specifically on AR headsets. AR headsets provide mobility and hands-free capabilities that are crucial in contexts that require high SA (e.g., military, surgery). Furthermore, AR headsets are beginning to enter the consumer market and industrial settings (e.g., oil industry) [16]. Out of the reviewed studies, eleven specifically examined AR headsets for SA (see Table 2 below).

The findings from this literature review show that AR has been applied to aiding users' SA in a wide range of contexts (e.g., military, driving, healthcare, etc.). However, most of the user studies (81%) that motivated their work within improving SA only used performance metrics. In addition, previous studies have resulted in both higher [14] and lower SA [94] when utilizing AR. These contradictory findings show that only applying AR to a task may not increase SA; therefore, understanding how to design the presentation of information in AR is essential in maximizing positive effects, especially for AR headsets.

Using AR headsets can be affected by technological, physical, and perceptual challenges. Technical challenges include registration (i.e., accurately aligning real and virtual objects) [8], [11] and real-time tracking [8], [28], [88], as well as low resolution [62], [68], [81] and loss of visual acuity [139], [140], which can negatively affect text legibility, object recognition, and depth perception. Physical elements of the headset can also lead to challenges. The limited field-of-view can negatively affect performance [9], [11], [81] and increase cognitive load [58]. AR headsets can also negatively affect users' perception. The environment (e.g., lighting) and the partial transparency of graphics can affect users' color perception in AR headsets [139]–[141]. Users can also have difficulty noticing objects in their periphery [142] and overestimate object distances [143]. These challenges emphasize the need to focus on information design for AR headsets to maximize positive effects, since prior work has found that using AR headsets can lead to increased SA (e.g., [6], [14]).

This section (*Section 7. Discussion*) addresses **R3** through presenting future areas of design for AR headsets to increase users' SA. The discussion focuses on (1) analyzing the studies that applied AR specifically for SA, (2) examining the AR design recommendations, (3) critiquing AR for SA headset applications based on the existing AR design recommendations, and (4) identifying open research areas for applying AR to improve SA.

7.1 AR for SA Studies

The majority (78%) of reviewed user studies on utilizing AR for SA did not focus on researching the presentation of information (see Table 2). Instead, the studies mainly examined the applicability of using AR for different situations and compared AR to traditional methods. For instance, Ruano et al. [13] investigated using AR for flying UAVs by overlaying flight data onto one computer screen instead of having two separate screens (i.e., the traditional method). Phan et al. [71] developed an AR pedestrian collision warning system for driving, and Liu et al. [6] analyzed if using an AR headset could help anesthesiologists in monitoring patient vital signs. These studies did not focus on examining different information designs, or if their design had a positive or negative effect on SA. Therefore, there are **still open questions about how information should be designed for increasing users' SA, especially for AR headsets**.

Only a small number of studies that concentrated on

TABLE 2
OVERVIEW OF ALL IDENFITIFED PAPERS FOCUSING ON AR FOR SA APPLICATIONS

Context	Study	Display Type	Evaluated Design of Visual Elements	Used Specific SA Evaluation Techniques	Study Type
Driving (*Section 5.2.1*)	Lorenz et al. [76]	Head-Up	No	No	Experiment: user evaluation
	Ng-Thow-Hing et al. [82]	Head-Up	No	No	Interviews/System: no user evaluation
	Park et al. [70]	Head-Up	No	No	System: no user evaluation
	Tran et al. [78]	Head-Up	Yes ✓	No	Experiment: user evaluation
	Lin et al. [73]	Head-Up	No	No	System: no user evaluation
	Lee et al. [83]	Head-Up	No	No	System: no user evaluation
	Rane et al. [75]	Head-Up	No	No	Interviews/Experiment: usability evaluation with two usability experts
	Phan et al. [71]	Head-Up	No	No	Experiment: user evaluation
	Langlois and Soualmi [77]	Head-Up	No	No	Experiment: user evaluation
	Kim and Wohn [74]	Head-Up	No	No	Experiment: user evaluation
	Schwarz and Fastenmeier [79]	Head-Up	No	No	Experiment: user evaluation
	Kim et al. [80]	Head-Up	Yes ✓	No	Experiment: user evaluation
	Kim et al. [84]	Head-Up	No	No	Experiment: user evaluation
	Merenda et al. [81]	Head-Up	Yes ✓	No	Experiment: user evaluation
	Kim and Gabbard [72]	Head-Up	Yes ✓	Yes (SAGAT)	Experiment: user evaluation
Military and Security (*Section 5.2.2*)	Lukosch et al. [91]	Head-Worn	No	Yes (SART)	Interviews/Experiment: user evaluation
	Sebillo et al. [92]	Hand-Held	No	No	System: no user evaluation
	Mitaritonna and Abasolo [85]	Head-Worn	No	No	Survey: no user evaluation
	Brandão and Pinho [89]	Head-Worn	No	No	Opinion: no user evaluation
	Gans et al. [7]	Head-Worn	No	No	System: no user evaluation
	Livingston et al. [90]	Head-Worn	Yes ✓	No	Interviews/Experiment: user evaluation
	Neuhöfer et al. [87]	Can Differ	Yes ✓	No	System/Experiment: user evaluation
	Ruano et al. [13]	Computer Screen	No	No	System: user evaluation
	Roux [88]	Hand-Held	No	No	Survey/Opinion: no user evaluation
	Zollmann et al. [86]	Hand-Held	No	No	System: user evaluation
Industrial (*Section 5.2.3*)	Aschenbrenner et al. [94]	Hand-Held	No	Yes (SART)	System: user evaluation
	Alam et al. [95]	Head-Worn	No	No	System: no user evaluation
	Novak-Marcincin et al. [93]	Projector	No	No	Opinion: no user evaluation
	Sauer et al. [96]	Computer Screen	No	No	System: no user evaluation
	Zhu et al. [97]	Head-Worn	No	No	System: user evaluation
Medical (*Section 5.2.4*)	Pascale et al. [14]	Head-Worn	No	Yes (SAGAT)	Experiment: user evaluation
	Liu et al. [6]	Head-Worn	No	No	Experiment: user evaluation
Construction (*Section 5.2.5*)	Irizarry et al. [99]	Hand-Held	No	No	System: user evaluation
	Wallmyr et al. [100]	Head-Up	No	No	Experiment: user evaluation
Navigation (*Section 5.2.6*)	Grabowski [101]	Head-Worn	No	No	Survey/Opinion: no user evaluation
	Hong et al. [102]	Computer Screen	No	Yes (SAGAT)	System: user evaluation
	Hervas et al. [103]	Hand-Held	No	No	System: user evaluation
	Alnabhan and Tomaszewski [104]	Hand-Held	No	No	System: user evaluation
Miscellaneous (*Section 5.2.7*)	Veas et al. [105]	Hand-Held	No	No	System: user evaluation
	Kim et al. [106]	Head-Worn	No	No	Experiment: user evaluation

improving SA compared different designs for AR elements [72], [78], [80], [81], [87], [90] (Table 2). For example, Tran et al. [78] investigated different representations of incoming vehicles paths for an AR driving left-turn aid (e.g., solid color path, wireframe path). Out of these studies, only Livingston et al. [90] utilized AR headsets. The authors explored different representations of occluded entities in AR headsets for military applications. Although these prior research studies did analyze multiple designs, only Kim and Gabbard [72] evaluated the designs using an SA evaluation technique. It is **important to study how designs directly affect users' SA through specific SA evaluation metrics** (e.g., SAGAT or SART).

Out of the reviewed AR systems that motivated their work within improving SA, five studies applied specific SA evaluation methods [14], [72], [91], [94], [102], and only two examined AR headsets [14], [91] (Table 2). Most of the user studies (81%) only used performance metrics. Out of those, 50% made explicit claims that related the performance results to users' SA. This goes against Endsley [52], who advises that evaluating SA through performance metrics is assuming what behavior will occur in a particular state of SA and confusing the concepts of SA and task performance. Furthermore, the studies that used specific SA evaluation techniques only used one method (e.g., SAGAT or SART) which goes against Vidulich et al.'s [49] recommendation of using multiple methods.

7.2 AR Design Recommendations

Previous studies have examined how to design different AR elements (e.g., text, labels), but none of the reviewed studies specifically considered the users' SA. The studies investigated individual effects, such as readability, comprehension, and cognitive workload, but not overall SA. In addition, none of the overall AR design recommendations (e.g., Ganapathy's eight design guidelines [126]) included a recommendation based on SA. Several of the AR guidelines are similar to Endsley's [15] design principles for increasing SA. For example, Endsley's principle of incorporating salient critical cues [15] is similar to Ganapathy's recommendation of including distinct icons [126]. However, none of the AR guidelines directly considered the users' SA; for instance, none of the guidelines are similar to Endsley's principle [15] on including a direction presentation of higher-level SA needs. Thus, there is a **need to evaluate existing design guidelines using SA evaluation methods and propose AR recommendations that focus on improving users' SA**.

7.2.1 Location

Prior work recommends placing elements in the center and bottom locations in AR headsets to reduce reaction time and cognitive workload [20], [109]. However, the studies did not investigate the locations based on users' SA, so it is unclear if the center and bottom locations aid in improving SA. For instance, placing the information in the center could reduce reaction time but lower the user's awareness of the environment. The information in the center might also get in the way of the user's main task, which goes against Ganapathy's [126] AR design guideline of not obscuring the item of interest. In addition, while previous studies have presented methods for dynamically placing information based on the environment to increase readability [112]–[114], these methods have not been applied or examined in the reviewed studies that concentrated on using AR for SA. There are still open questions on how dynamically moving AR elements in a headset would affect users' SA, since the elements could distract the user from their surroundings. **Future work should examine how the location of elements specifically impacts users' SA, and if dynamic is beneficial.**

7.2.2 Text

In designing text for AR headsets, existing studies have found that including a billboard background for text aids in readability [107], [108]. Nonetheless, there are still open questions on how to design textual information in AR headsets. Debernardis et al. [107] recommended white text with a blue billboard background, while Fiorentino et al. [108] suggested white text with a black billboard. The divergent results may be due to the differing background styles and environments; however, the cause is not exactly clear. Also, these two studies examined opaque billboards, while Albarelli et al. [19] found that not having a background billboard resulted in faster completion times.

In addition, these prior studies focused on textual information that was essential to the main task (e.g., product information for restocking at a grocery store [19]) instead of secondary information. While secondary information might not be directly related to the main task, it is still necessary for maintaining SA. Therefore, **future work should study the design of textual secondary information for increasing users' SA**.

In conducting this SLR we found studies concentrating on the color and style of text (e.g., billboard vs. no billboard). There are still open research questions about other design attributes, such as the text size and font. While we might have missed relevant studies in our search based on our designated keywords, it still highlights an area for further exploration. Based on our literature review, it is not clear how to exactly design text for AR headsets to increase readability, as well as for improving SA. None of the studies evaluated the designs in terms of users' SA. **Future studies should clarify how to design text for improving users' SA, as well as further explore the effect of environment on text readability.**

7.2.3 Amount

The reviewed studies that focused on the amount and detail of elements did not examine SA. Ganapathy et al. [120] analyzed the specific amount of AR elements to include, but only through collecting participants' subjective preference. In addition, the study was for a smartphone application and not an AR headset, so it is unclear if the findings would translate to a different platform. Ishiguro and Rekimoto [121] proposed using eye-tracking techniques to control the level of detail for information, but did not examine how the level of detail or method affected users' SA. Having to gaze longer at an element to gain more detailed information could distract the user from their main task and reduce awareness. **Future studies should investigate the appropriate amount of infor-**

mation in AR headsets to support users' SA.

7.3 AR for SA Applications vs Recommendations

Section 6. Presentation of Information in AR summarizes AR design studies and recommendations. While none of the reviewed work considered the users' SA, it is still important to examine if current AR headset applications follow the existing design guidelines. This section (*Section 7.3.*) investigates the design of three AR headset applications that aim to increase SA: *ARC4* [7], Liu et al.'s application [6], and *AR-Mentor* [97] (Table 3).

7.3.1 ARC4 for Dismounted Soldiers

As mentioned earlier, Gans et al. [7] developed *ARC4*, an AR headset system that delivers SA to dismounted soldiers (Fig. 1). The information is in the center and bottom of the headset field-of-view, but also along the top and periphery. Including information in the top and periphery can reduce comprehension and increase response times [20], [109], and providing information in the center can obscure items of interest. The textual information is in the color green, which results in high contrast and is consistent with Ganapathy's [126] guideline of having high contrast for visibility. The interface also has different icons, which supports both Ganapathy's [126] and Endsley's [15] recommendation of having distinct icons and salient critical cues. The icon designs also support Kourouthanassis et al.'s [128] guideline of using use common interface metaphors, since it includes military symbology.

7.3.2 Aiding Anesthesiologists

Liu et al. [6] investigated if AR headsets could aid anesthesiologists in monitoring patient information (Fig. 3). The text in the application is red without a background billboard and located mainly in the center of the headset. The red text results in low contrast which goes against Ganapathy's recommendations for including high contrast for visibility and clear textual information [126]. Furthermore, in AR headsets the color red can become desaturated against a white background [141], which can affect contrast and readability. Even though the information is in the center of the field-of-view, it is slightly obscuring the patient (i.e., the object of interest) which goes against Ganapathy's guideline [126]. The content is related to the main task which is consist with Kourouthanassis et al.'s suggestion [128] and Endsley's [15] guideline for removing extraneous information; however, Liu et al. [6] does not consider the SA requirements of the anesthesiologists and does not focus on presenting the information in a way to support higher-level SA needs.

7.3.3 AR-Mentor for Maintenance

As mentioned above, Zhu et al. [97] created *AR-Mentor*, a wearable AR mentoring system to assist in machine maintenance (Fig. 2). The system includes both textual step-by-step instructions and 3D models. The text instructions are in white with a dark blue billboard background, which is consistent with Debernardis et al.'s [107] recommendation; however, the text is located on the top of the

TABLE 3

AR for SA Headset Applications vs Design Recommendations

Type	Design Recommendations	Gans et al. *ARC4* [7]	Liu et al.'s application [6]	Zhu et al. *AR-Mentor* [97]
AR	Clear textual information [126]	Yes ✓	No	Yes ✓
	Contrast for visibility [126]	Yes ✓	No	Yes ✓
	Organization of information should have meaning [126]	Yes ✓	No	No
	Placement should not obscure item of interest [126]	No	No	No
	Draw attention to information that requires action [126]	Yes ✓	No	No
	Ability to switch between interaction methods [126]	Yes ✓	No	No
	Distinct icons that can be easily parsed [126]	Yes ✓	No	No
	Filter information based on distance and visibility [126]	Yes ✓	No	No
	Use context for providing content [128]	Yes ✓	Yes ✓	Yes ✓
	Include content relevant to the task [128]	Yes ✓	Yes ✓	No
	Provide feedback [128]	Yes ✓	Yes ✓	No
	Support semantic memory [128]	Yes ✓	Yes ✓	No
	Avoid large amounts of text [129]	Yes ✓	No	No
	Avoid large images [129]	Yes ✓	No	No
	Avoid solid virtual objects [129]	No	Yes ✓	No
SA	Determine SA requirements [15]	No	No	No
	Direct presentation of higher-level SA needs [15]	No	No	No
	Support a complete overview of the situation [15]	Yes ✓	Yes ✓	No
	System should be goal-oriented [15]	Yes ✓	Yes ✓	Yes ✓
	Salient critical cues [15]	Yes ✓	No	No
	Remove extraneous information [15]	Yes ✓	Yes ✓	No
	Use different SA evaluation techniques [15]	No	No	No

field-of-view and includes extraneous information (e.g., the specific step title). In addition, the 3D model directly blocks the item of interest, which goes against Ganapathy [126]. The system is goal-oriented in supporting maintenance, which follows Endsley's [15] guideline, but does not support a complete overview of the situation.

7.4 Future Areas to Apply AR for SA

AR is being applied in a wide range of contexts, such as surgery [144]–[147], education and training [148], [149], and human-robot interaction [150], [151]; however, there is a lack of research in those areas in terms of how AR affects SA. For instance, AR headsets have been investigated for neurosurgery [152] and anatomic pathology [153], but only two of the reviewed studies analyzed AR for SA in the medical field (see Table 2). In addition, those two studies [6], [14] concentrated on displaying patient information not overlaying specific elements onto a patient's body (e.g., tumor localization [152]), and did not study the presentation of information. Other areas that had limited prior work on using AR for SA included construction, industrial contexts (e.g., production process), and the oil industry. While some of the reviewed previous studies focused on construction and industry, none of the studies examined AR for SA in the oil industry. AR headsets are being employed in the oil industry [16], so it is crucial that future work should research this area, especially on how to design the presentation of information.

Since AR is being used for SA (e.g., [6], [7]), not designing the presentation of information correctly, such as the information being too distracting or failing to provide a complete overview of the environment, could lead to poor SA and major consequences (e.g., aircraft crashes [2], medical errors [4]). This SLR illustrates that using AR for SA is a growing research area in a wide range of contexts, however the presentation of information is not fully being considered. Prior studies have mainly focused on applicability, which is important, but information design should not be ignored. The design of elements can have a major impact on the usability of a system, as well as the SA of the user. Therefore, this SLR points to a need for future research to consider and focus on the presentation of information in AR to increase users' SA, especially for AR headsets as they become more prevalent.

8 CONCLUSION

This Systematic Literature Review (SLR) provided an overview of how information is currently being presented in augmented reality (AR) and how AR is being applied to improve users' situational awareness (SA). Maintaining SA is important for error prevention, and previous studies have shown that AR can aid in increasing users' SA. Through conducting this SLR, we identified a total of 140 relevant studies. We found that AR has been applied to improving SA in a wide range of contexts (e.g., driving, military, construction), but a majority of the studies did not focus on information design. In addition, only several of the studies utilized SA evaluation techniques (e.g., SAGAT or SART). While prior work has focused on how to design elements in AR, the studies did not consider users' SA. There are still open research questions on how to design AR elements to support users' SA in terms of the location, design, and quantity of information. Future work should examine different information designs for improving users' SA in AR headsets, as well as evaluate those designs with common SA evaluation techniques.

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