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Systematic Literature Review on Cyber Situational Awareness Visualizations

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ABSTRACT The dynamics of cyber threats are increasingly complex, making it more challenging than ever for organizations to obtain in-depth insights into their cyber security status. Therefore, organizations rely on Cyber Situational Awareness (CSA) to support them in better understanding the threats and associated impacts of cyber events. Due to the heterogeneity and complexity of cyber security data, often with multidimensional attributes, sophisticated visualization techniques are often needed to achieve CSA. However, there have been no attempts to systematically review and analyze scientific literature on CSA visualizations until now. In this paper, we have systematically selected and reviewed 54 publications that discuss visualizations to support CSA. We extracted data from these papers to identify key stakeholders, information types, data sources, and visualization techniques. Furthermore, we analyze the level of CSA supported by the visualizations, maturity of the visualizations, challenges, and practices related to CSA visualizations to prepare a full analysis of the current state of CSA in the organizational context. Our results reveal certain gaps in CSA visualizations. For instance, the most focus is on operational-level staff and there is a clear lack of visualizations targeting other types of stakeholders such as managers, higher-level decision makers, and non-expert users. Most papers focus on threat information visualization and there is a lack of papers that visualize impact information, response plans, and information shared within teams. Interestingly, only a few studies proposed visualizations to facilitate up to *projection* level (*i.e.* the highest level of CSA) whereas most studies facilitated *perception* level (*i.e.* the lowest level of CSA). Most of the studies provide evidence of the proposed visualizations through toy examples and demonstrations, while only a few visualizations have been employed in industrial practice. Based on the results that highlight the important concerns in CSA visualizations, we recommend a list of future research directions.

INDEX TERMS Situational Awareness, Visualizations, Cyber Security, Systematic Literature Review

I. INTRODUCTION

"The only truly secure system is one that is powered off, cast in a block of concrete and sealed in a lead-lined room with armed guards". These words by Gene Spafford illustrate the persistent vulnerability that networks and systems have in terms of cyber attacks, with cyber attacks increasing in sophistication and regularity. The outbreak of the COVID-19 pandemic has impacted every industry, and particularly healthcare services, workers in remote areas, and the unemployed have all emerged to become new cyber attack targets [1]. A report published by IBM Security [2] shows that the

global average cost of a data breach in 2021 is estimated at US\$4.24 million, compared to US\$3.86 million in 2020 [3], with the latest statistics revealing that the average time for companies to identify a data breach in 2021 is 212 days, up from 207 days in 2020 [3]. Especially during the COVID-19 pandemic, a large number of companies reported that they experienced the identification and containment of a data breach to take longer. These statistics show that the number, depth and breadth of incidents related to cyber attacks around the world are increasing. Such incidents iterate the need for better and faster mechanisms, tools, policies, risk manage-

ment approaches, training and technologies that can help safeguard the cyber environment of an organization. This all comes down to effective and efficient cyber security.

Cyber related data is automatically generated at millisecond levels of resolution from diverse data sources and often very voluminous. Furthermore, cyber attackers are increasingly applying sophisticated techniques in their attacks. As a result, implementing effective cyber-security measures has become especially challenging. In this context, Situational Awareness (SA) has become paramount to facilitate correct and timely decision making to prevent or reduce the impact of cyber attacks. Situational (or situation) awareness is traditionally defined following the seminal work of Endsley [4] as “the perception of the element in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future”.

Cyber data visualization can provide efficient and meaningful insights to overwhelming amounts of data, allowing decision makers to both explore and monitor the cyber status at various abstractions levels [5]. Although various visualizations to support CSA have been proposed in the past, there is no clear understanding of the different stakeholders of those visualizations, different types of information visualized, data sources employed, visualization techniques used, levels of CSA that can be achieved and the maturity levels of the visualizations, challenges and practices for CSA visualizations.

Responding to this evident lack of investigation into an important topic, we aimed at systematically analyzing the literature on CSA visualizations. This systematic review would enable both researchers and CSA visualization designers to gain in-depth and holistic insights into the state-of-the-art CSA visualizations and support in transferring the research outcomes into industrial practice [6]. Furthermore, the results can be used to identify limitations of the existing literature related to CSA visualizations, and gaps that require further attention from the researchers. The key contributions of this systematic literature review are listed down below:

- A synthesized body of research knowledge on CSA visualizations providing guidance for researchers and CSA visualization designers who want to better understand the topic.
- A comprehensive understanding of the different stakeholders of CSA visualizations, different types of information types visualized, data sources employed, visualization techniques used.
- An analysis of the levels of CSA that can be achieved through the proposed visualizations and the maturity of the proposed visualizations.
- An analysis of the challenges identified in designing and developing CSA visualizations, and practices that have been reported to implement CSA visualizations successfully.
- Identification of the potential gaps for future research highlighting important and practical considerations for CSA visualizations that require further attention.

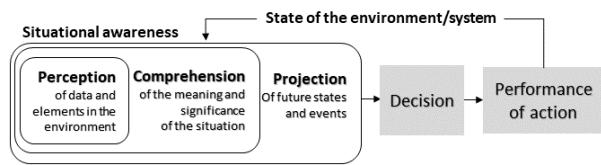


FIGURE 1. Three Levels of SA. Adapted from [4]

The rest of the paper is organized as follows: Section II gives an overview of CSA and visualizations employed for achieving CSA. Section III describes the methods that we used to conduct this SLR, including the review protocol. Section IV describes our results, including the demographic information and the quality assessment of the included studies, and addresses the research questions (RQs) through the analysis of selected studies. In Section V we discuss key future research and threats to the validity. Finally, Section VI concludes the review.

II. BACKGROUND AND RELATED WORK

This section provides a discussion and related work on SA, CSA and CSA visualizations.

A. SITUATIONAL AWARENESS

Situational Awareness refers to the human cognitive capacity to analyze its environment and act accordingly. SA has been recognized as critical for successful decision making across a broad range of situations in various domains, including military command and control operations, health care and air traffic control. SA is particularly important for the understanding and comprehension of the implications of a situation, drawing conclusions and making informed decisions about the future. It can be considered from two different aspects [5]. The **technical aspect** of SA is concerned with collecting, compiling, processing, and fusing data. Here, information and data fusion is the most important concept that considers aggregation and extraction of knowledge from various information sources to estimate current and/or predict future states. The **cognitive aspect** of SA is concerned with a person's mental awareness in a given situation specifically person's capacity to comprehend the technical implications and draw conclusions to make informed decisions.

Endley's model [4] defines three SA levels (see Figure 1) that can be used to measure the extent to which a human decision maker is aware of the situation and whether they have reached a certain level of SA:

- Perception (Level 1): The lowest level of SA is associated with the user's perception of the status, attributes and dynamics of the relevant elements of the environment.
- Comprehension (Level 2): Comprehending or forming of a synthesis of the situation based on the different elements in the perception level. This allows the user to go beyond being just aware of the elements in the en-

vironment to comprehend the situation and understand the significance of those elements.

- Projection (Level 3): The highest level of SA is associated with the ability to predict future state or events of the elements of the environment. The accuracy of the prediction is highly dependent upon the accuracy of SA Level 1 and Level 2.

It is important to note that the proposed levels of SA represent ascending levels of awareness and not linear stages [7]. By following this process the user can rationalise the situation at hand, enabling decision making and action. The person who comprehends and understands the meaning of the current situation will possess greater situational awareness than a person who simply reads the data without understanding its meaning. Similarly, someone who can predict probable future events and states will have a better understanding of the situation than someone who is unable to do so.

B. CYBER SITUATIONAL AWARENESS

Given the progressive and usefulness of SA research, it is increasingly applied to cyberspace [5]. Hence, CSA can be considered an extension or a subset of traditional SA to cyberspace.

A systematic literature review on CSA conducted by Franke et al. [5], describe and discuss peer-reviewed literature on this topic from the perspective of both national cyber strategies and science. Within the cyber security domain, SA requires adequate knowledge about the current and past cyber activities of the organization in order to effectively detect, identify and respond to various threats and attacks. CSA provides both holistic and specific information related to cyber threats and vulnerabilities, allowing organizations the ability to identify, process and comprehend information swiftly. Such suspicious and interesting activities can be diverse and might range from low-level network sniffing to activities obtained by external data sources such as social media. This, in turn, CSA helps organizations understand both their current and future risk situation and position in terms of their protection mechanisms.

In line with the three levels of SA, CSA is concerned with the ability to recognize the current state of assets and the cyber threat situations (*perception*), ability to comprehend the meaning of the cyber threat situation and/or assess the impact of the threats (*comprehension*), and the ability to project the future state of threats or actions (*projection*).

Current CSA research mainly focus on three aspects: data collection [8]–[10]; data processing and analysis [11]–[13]; and data visualization [14], [15]. Newer models and frameworks have been proposed to achieve CSA, such as cyber specific Common Operating Pictures (COPs) [16]. COP has historically been a military term used to describe a command and control solution that aggregates important operational information in a single picture, a “*a single identical display of relevant information shared by more than one command that facilitates collaborative planning and assists all levels of decision makers to achieve situational awareness*”. Conti et

al. [16] clearly articulated the roles of humans and machines in a Cyber Common Operating Picture (CCOP) for achieving CSA. Broadly speaking, they argued that CCOPs should be designed to consider the tasks that are better suited to human cognitive capabilities and the ones that can be automated and processed at high speed by machines.

Advanced sophisticated data analytic techniques are often used to process and analyze complex cyber information both in real-time and offline to provide CSA. However, due to the volume and complexity of cyber data and attacks, powerful machine learning techniques alone is not adequate to achieve CSA [16], [17]. To achieve complete CSA, it is important to effectively link technical aspects with cognitive aspects in cyber security. To this end, effective data visualization is imperative; visualizations allow users to explore and analyze large amounts of data and easily identify trends and unexpected events enabling swift decision making and action [5], [17], [18].

C. CYBER SITUATIONAL AWARENESS VISUALIZATIONS

Although we observed an increasing number of literature around the topic of CSA visualizations, we did not find any existing systematic literature review or systematic mapping study focused on the visualizations aimed at CSA. However, there have been several existing reviews on visualizations for specific areas of security. In this section, we compare these existing reviews and discuss their gaps, and novelty of this SLR.

A number of studies look at visualizations related to network [19]–[21] and malware analysis [22]. For instance, Shirave et al. [19] present an SLR on network security visualizations. The authors identified five classes of network security visualizations which included host server monitoring, internal/external monitoring, port activity, attack patterns and routing behaviour. In another study, Guimaraes et al. [21] present an SLR of information visualization for network and service management. They identified several well-explored topics on network and service management regarding the use of information visualization which includes IP networks, monitoring and measurement etc. They also analyzed the visualization techniques and tasks/interactions in information visualizations for network and service management. Their results revealed that standard 2D/3D displays are the most commonly used visualization technique in network and service management visualizations. They also point out a number of future research directions for information visualizations for network and service management, specifically *IoT*; *Big data*; *Cloud computing*; *SDN*; and *Human-centered evaluation*.

Wagner et al. [22] provide a survey of visualization systems for malware analysis. They categorized the literature based on a general approach to data processing and visualization using a malware visualization taxonomy. They also categorized the literature by their input files and formats, the visualization techniques utilized, the representation space and the mapping to time, certain temporal aspects, their

interactive capabilities, and the different types of available user actions.

Staheli et al. [23] provide a survey of visualization evaluations for cyber security. The authors identify the most common evaluation types for complex security applications and reveal trends and future directions. Franke et al. [5] conducted an SLR that specifically focused on CSA. Their survey is broad and includes publications that are not related to visualization. They focus on various topics, including introductory literature on CSA, and SA in industrial control systems, emergency management and SA architectures, algorithms and visualizations. In terms of visualizations, Franke et al. [5] specifically highlight the need for going beyond technical aspects of the visualizations to obtain a more comprehensive understanding of the relationship between CSA levels (*i.e.* mental state) and the CSA visualizations.

In summary, there are several shortcomings of existing literature reviews. Most of the aforementioned reviews have not been carried out considering CSA, and/or only consider specific areas related to cyber security visualizations (e.g. network analysis, malware analysis). Therefore, existing literature reviews do not provide an overall view of CSA visualizations. Furthermore, existing literature does not consider or describe important aspects such as the level of SA that could be reached (*i.e.* mental state) using the visualization, diversity of stakeholders, types of information visualized, and challenges and practices for CSA visualizations. Therefore, in this research we conduct an SLR to obtain a complete view of literature on visualizations targeting CSA while considering above mentioned aspects important to the CSA domain; thereby narrowing the existing knowledge gap in this field.

III. METHODOLOGY

The research methods in a SLR provides a well-defined process for identifying, analyzing, and interpreting literature relevant to particular set of research questions (RQs). We followed the three-phased guidelines published by Kitchenham and Charters [24]: defining a review protocol, conducting the review, and reporting the review. We describe the main steps of this SLR, detailing the process illustrated in Figure 2, in the following subsections.

A. RESEARCH QUESTIONS

This SLR focuses on providing an extensive overview and analysis of existing literature on CSA. We formulated five RQs to guide this SLR. Table 1 presents the RQs, along with their motivation.

Answering these RQs will provide an in-depth understanding of the stakeholder of the CSA visualization (RQ1), the types of information visualized, data sources used, and how the cyber information is visualized (RQ2), the level of CSA is facilitated by the visualization (RQ3), CSA visualization maturity (RQ4), challenges for CSA visualizations (RQ5), and practices for supporting effective CSA visualization (RQ6). The findings will enable researchers to obtain an in-

TABLE 1. Research Questions

Number	Question	Motivation
RQ1	Who are the stakeholders that use and benefit from CSA visualizations?	To understand types of people that are intended to benefit from the proposed CSA visualizations.
RQ2	What are the types of information visualized, data sources used and how the cyber information is visualized?	To understand the different types of information presented in CSA visualizations, data sources used, and visualization techniques and task interactions employed to visualize CSA data.
RQ3	What level of CSA is facilitated by visualizations?	To understand the level (<i>i.e., perception, comprehension and projection</i>) supported by visualizations.
RQ4	What is the maturity of the proposed visualizations that facilitate CSA?	To help researchers assess the maturity of the CSA visualizations.
RQ5	What are the reported challenges in employing visualizations to facilitate CSA?	To identify the challenges for designing and developing CSA visualizations reported in the literature.
RQ6	What practices have been reported to implement CSA visualizations successfully?	To understand the good practices, guidelines lesson learnt, shared experiences to implement CSA visualizations.

depth overview of this topic, identify limitation and gaps, and potential future directions.

B. SEARCH STRATEGY

In this subsection, we discuss the search terms and data sources used in this SLR. We used the guide presented by [25] to iteratively develop the search string of this study. The base keywords used as search terms were constructed by considering the three aspects related to the SLR topic: cyber, situational awareness, and visualizations. Then, we systematically modified the search string by adding a set of alternative search terms. These alternative search terms were obtained by considering researchers' own knowledge and experience, synonyms, key terms used in the existing related research papers.

- **Cyber** – cyber*
- **Visualizations** – visual* OR dashboard OR dash board OR dash-board OR picture OR diagram OR graphic OR video OR image OR audio OR multimedia OR multi media OR multi-media
- **Situational awareness** – situational aware* OR situational-aware* OR situation aware* OR common operating picture OR common operational picture OR CCOP

The identified search terms were merged using Boolean AND and OR to construct the final search strings. We conducted several pilot searches to identify the best search string. We also verified the inclusion of well-known primary studies when finalizing the search terms. The final search

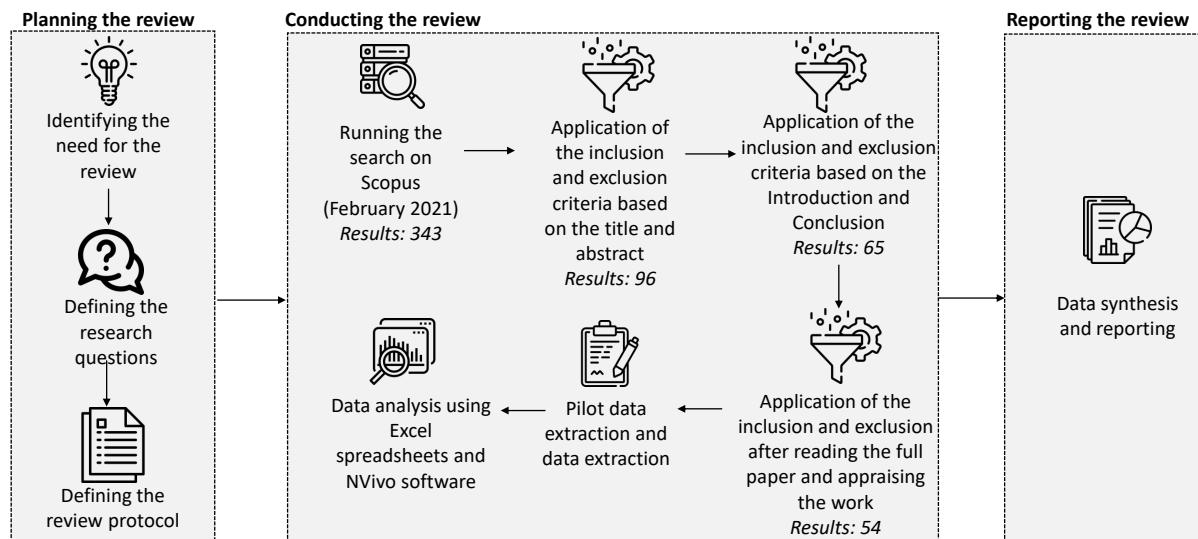


FIGURE 2. Methodology

string combines each base keyword category with an AND operation:

cyber AND (visual* OR dashboard OR dash board OR dash-board OR picture OR diagram OR graphic OR video OR image OR audio OR multimedia OR multi media OR multi-media) AND (situational aware* OR situational-aware* OR situation aware* OR common operating picture OR common operational picture OR CCOP).*

Previous researchers [25], [26] have shown that Scopus indexes a large number of journals and conference papers indexed by other search engines, including ACM Digital Library, IEEE Xplore, Science Direct, Wiley Online Library and SpringerLink. Furthermore, digital libraries such as SpringerLink and Wiley Online Library place several restrictions on the meta-data of the published studies in large-scale searches. The search string also needs to be modified for each digital library, resulting in errors being introduced. As such, we made use of the Scopus search engine to find potentially relevant papers. Using Scopus enabled us to use one search string while retrieving most of the relevant studies. The search terms were matched with the title, abstract, and keywords of papers in Scopus. The search was conducted in February 2021 resulted in 343 papers that matched the search string.

C. STUDY SELECTION

Three authors applied the inclusion and exclusion criteria detailed in Table 2 to systematically select the final set of papers included in this SLR. The criteria were discussed with all the authors and agreed upon before the study selection phase. We refined the inclusion and exclusion criteria in several iterations to ensure we accurately classify the papers. One of the key selection criteria is that the paper should introduce a visualization for CSA with a design or implementation (I1).

TABLE 2. Inclusion (I) and exclusion (E) criteria

Inclusion or Exclusion	Criteria
I1	The paper should introduce a CSA visualization with design and/or implementation.
I1	The paper should be peer-reviewed.
I2	The paper should be published in the English language.
E1	Any editorials, position papers, keynotes, reviews, tutorial summaries, and panel discussions are excluded.
E2	If a conference paper and a journal paper duplicates the same work, the conference paper will be excluded and the journal paper will be retained.
E3	Short papers of less than five pages are excluded.
E4	Papers of which the full text are not available at the time of the study are excluded.

In the meantime, we decided not to include any short papers (E3) because they presented only concepts or ideas. They lack well-defined visualizations and most importantly they did not provide sufficient and relevant evidence to answer the defined RQs.

By applying the inclusion and exclusion criteria to the papers' titles and abstracts, the number of papers was reduced to 96. The inclusion and exclusion criteria were then applied to the introduction and conclusion of the remaining papers, resulting in a further exclusion of 31 papers. The majority of the papers excluded at this point was as a result of the papers not specifically addressing visualizations for CSA. For example, we excluded papers that mainly address physical infrastructure in the smart-grid industry. In the last stage, we read the full text of the remaining 65 papers and included only 54 of those in the final set. For example, we excluded the papers that claim visualizations for CSA in the abstract and introduction but do not have proper visualization design

TABLE 3. Data extraction form

Item	Question	Related RQ	Description
D1	Authors	Demographics	–
D2	Year	Demographics	–
D3	Publication type	Demographics	–
D4	Publication venue	Demographics	–
D5	Stakeholders	RQ1	Types of people intended to benefit from the proposed CSA visualization
D6	Information visualized	RQ2	Types of information that are visualized
D7	Data sources	RQ2	Data sources used for visualization
D8	Visualization techniques	RQ2	Visualization techniques employed
D9	Tasks or interactions	RQ2	The ways in which a user can interact with the visualizations
D10	Level of CSA	RQ2	Level of CSA facilitated through the visualizations
D11	Maturity of visualizations	RQ3	Assessment of the reported evidence
D12	Challenges reported	RQ4	Challenges and barriers that have been reported to design, implement and adopt CSA visualizations
D13	Practices	RQ5	Lessons learnt, good practices, and authors' experiences in successfully implementing CSA visualizations

or implementation. Any disagreements that the three authors had during the study selection were discussed with the other authors in detail and resolved before moving on to the data extraction.

D. DATA EXTRACTION

Data extraction was performed by three authors, in accordance with the guidelines set out by Kitchenham et al. [24], where multiple researchers review different primary studies due to time or resource constraints. This process recommends a method of checking to ensure that researchers extract data in a consistent manner. We extracted data from the selected primary studies using a pre-defined data extraction form (see Table 3). When extracting data we consider a single visualization to be a region in a user interface with a clear visual boundary where information is displayed as a group. Before the data extraction, we conducted a pilot data extraction and compared the results on a selected random sample of primary studies to make sure the data extraction form can capture all the required information in the best possible summarised version. Any disagreements were discussed in detail and resolved before moving into the data extraction from all the papers.

E. DATA ANALYSIS AND SYNTHESIS

The demographic and contextual set of data items (D1 to D4 in Table 3) were analyzed using descriptive statistics.

Other extracted data (D5 - D13) to answer the RQs were analyzed using either thematic analysis or using existing taxonomies. Thematic analysis was used where taxonomies were not available to analyze the collected data. We describe in detail how the data was analyzed below.

1) Thematic analysis for qualitative data analysis

The data extracted for D5, D6, D7, D12 and D13 were analyzed using thematic data analysis technique, Thematic data analysis is a widely used qualitative data analysis method. We used the steps proposed by Braun and Clarke's to thematically analyze the qualitative data collected [27]. First, we familiarized with the extracted data by carefully reading each of them. After familiarizing with the data, the data were saved the NVivo data analysis tool for further analysis. Based on the principals of thematic analysis, we then performed open coding. This involved breaking the data into smaller components to generate the initial codes. The key points of the data were summarized using codes (i.e., a phrase) of three-five words. Next, codes were grouped together and assigned to potential themes. This was an iterative process as it was important to revise and merge codes based on their similarities.

2) Use of existing taxonomies for analyzing the extracted data

To analyze the data extracted for D8, D9, D10 and D11, we utilized existing taxonomies. We observed a range of taxonomies proposed in the information visualization field to analyze data collected for visualization techniques (D8). However, some of these are too specific or not related to our purpose. For example, researchers in [28] propose a taxonomy specifically for static (i.e., non interactive) visualizations, whilst other specific taxonomies have been proposed for dynamic graph visualizations [29], [30] and treemap visualizations [31].

The taxonomy proposed by Guimarães et al. [21] is closely related to our work. Guimarães et al. merged two taxonomies to achieve the framework needed for an adequate general classification of *visualization techniques* and *tasks or interactions* for end-users. For the first criterion (i.e. visualization techniques), the researchers in [21] used the “Information Visualization and Data Mining” taxonomy proposed in [32]. These taxonomies are widely accepted and referenced by the visualization community. Based on the visualization technique taxonomy proposed by Guimarães et al. [21], it is possible to divide the techniques used in the visualizations into five generalized categories: i) *standard 2D 3D displays*, ii) *geometrically transformed displays* iii) *iconic displays*, iv) *dense pixel displays*, v) *stacked pixel displays*. In addition to these categories we added four more categories – *geographical displays*, *immersive environment*, *single value displays* and *tables/text summaries* – to capture visualization techniques we observed in our papers. Detailed descriptions on these categories are given in Section IV-D3a.

To analyze the tasks/interactions (D9), Guimarães et al. [21] merged the taxonomies proposed by Keim [32] and Schneiderman [33] and added a new task and interaction technique called *move/rotate*. The resulting taxonomy had nine categories: i) *overview*; ii) *zooming*; iii) *filtering*; iv) *details on demand*; v) *history*; vi) *relate*; vii) *extract/share*; viii) *move/rotate*; and ix) *linking and brushing*. We added a new task/interaction called *customization* to capture information on user interactions related to customization of visualizations. It is important to note that the *overview* category is concerned with the ability to gain an overview of the entire data collection using other *tasks/interactions*, such as *zooming* and *filtering*. Hence to remove the duplication of information we did not use the *tasks/interactions* called *overview* in this study. Detailed descriptions on the *tasks or interactions* used in this study are given in Section IV-D3b.

Using data collected in D10 we explain how the visualizations support SA. Here we mapped each visualization to the three levels of SA defined by Endsley [4]. Data collected for D11 is used to explain the maturity of the proposed visualizations that facilitate CSA, we have used a six-level hierarchy proposed in [34] for describing the visualization maturity. The details of this hierarchy proposed in [34] is given in Section IV-F.

F. QUALITY ASSESSMENT

The 54 primary studies were evaluated by same three authors who performed the data extraction. The quality assessment was performed against the set of quality assessment questions listed in Table 4 (adopted from [35], [36]). Each question was answered according to a ratio scale – ‘Yes’, ‘No’, or ‘Partially’ – during the data extraction process. The answers for each study show the quality of a selected study and the credibility of the study’s results. Previous studies highlight that the quality assessment result of the included studies can reveal the potential limitations of the current research and guide future research in the field [24], [36]. Similar to [35], the quality assessment was not used for study selection but was employed for validating the results of the selected studies.

IV. RESULTS

This section reports the synthesis and analysis results of the data extracted from the 54 primary studies to answer the research questions.

A. DEMOGRAPHICS

Our dataset comprises papers published between 2003 and 2020. Only eight papers in our dataset were published before 2010, with the remaining 46 papers (85.2%) published in or after 2010. Of those papers, about 44.4% (24 papers) were published in or after 2017. This shows that CSA has only started to gain popularity in the last decade. The distribution is shown in Figure 3. Most of the selected studies are published in conferences (44 studies, 81.5%). Only five studies (9.3%) are published in workshops. The remaining

TABLE 4. Study quality assessment results

Study quality assessment question	Yes	Partially	No
Is there a rationale for why the study was undertaken?	54 (100.0%)	0 (0.0%)	0 (0.0%)
Is there an adequate description of the context?	48 (88.9%)	6 (11.1%)	0 (0.0%)
Is there a justification and description of the research design?	37 (68.5%)	15 (27.8%)	2 (3.7%)
Has the study an adequate description of the technique for visualization?	38 (70.4%)	15 (27.8%)	1 (1.9%)
Is there a clear statement of the findings?	33 (61.1%)	16 (29.6%)	5 (9.3%)
Do the researchers critically examine their potential bias and influence to the study?	5 (9.3%)	17 (31.5%)	32 (59.3%)
Are limitations of the study discussed explicitly?	6 (11.1%)	9 (16.7%)	39 (72.2%)

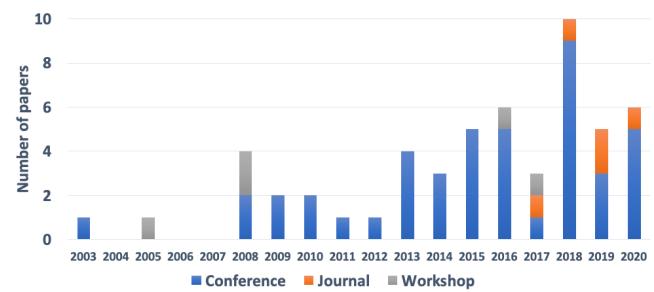


FIGURE 3. Distribution of papers in years and venue types

five studies (9.3%) are published in journals. We found that the *International Symposium on Visualization for Cyber Security (VizSec)* is a popular venue for publishing work on CSA visualizations as they have published 13.0% (7 studies) of the selected studies. The *International Conference on Cyber Situational Awareness, Data Analytics and Assessment (CyberSA)* has three publications (5.6%), and the *International Conference on Big Data* has two publications (3.7%). Most other venues only show one paper. The selected studies are generally published in venues targeted at security, visualization, big data and general software engineering. This finding demonstrates that this research topic has been broadly considered with different research interests.

B. QUALITY ASSESSMENT RESULTS

Table 4 illustrates the quality assessment results of the 54 publications selected. As shown in Table 4, all studies state the rationale for the conducted study (Q1). Q2 was answered positively by most studies (88.9%), which means the reviewed studies have an adequate description of the context in which the research was carried out. Concerning Q3, 37 out of 54 studies (68.5%) provided adequate descriptions of the research design (Q3). The answers to Q4 and Q5 reflect the accuracy of the data extraction results. 38 out of 54 studies (70.4%) described their proposed visualization

techniques adequately and 15 studies (27.8%) addressed these techniques to some extent. 61.1% of studies have a clear statement of their findings. Q6's majority (59.3%) "No" responses show that the researchers did not critically examine their bias and influence on the outcomes of the study. The majority of the studies (72.2%) did not discuss any limitations or drawbacks.

C. RQ1: WHO ARE THE STAKEHOLDERS THAT USE AND BENEFIT FROM CSA VISUALIZATIONS?

- CSA visualizations found in the primary studies mainly target three types of stakeholders: i) operational level staff; ii) managers and senior level decision makers; and iii) non expert users.
- Most visualizations focus on operation level staff, however, only a limited number of studies focus on managers and senior level decision makers and non expert users.

This section presents the findings for RQ1 and describes the various stakeholders of CSA visualizations. The data extracted for this section corresponds to item D5 in Table 3. In our selected set of primary studies, we found three main categories of stakeholders, noting that several papers targeted multiple stakeholders. These three categories of stakeholders are described below.

Operational level staff: We found that the majority of selected primary studies targeted the *operational level staff* and focus on facilitating their day-to-day business (64.8%). Among these papers, some visualizations were targeting network analysts. For example, researchers in [P38] propose a scalable platform to process and visualize data in real-time for large-scale networks. Furthermore, researchers in [P47] propose an ensemble visualization approach to improve network security analysis. Another set of papers focus on CSA visualizations target risk analysts and security analysts. For example, researchers in [P54] propose multiple views that allow security analysts to analyze the event history, asset relationships, plausible future events to identify the best course of action.

Managers and higher level decision makers: With cyber attacks becoming more frequent, sophisticated, targeted and widespread, cyber security decision makers need to make quicker critical decisions to contain and mitigate cyber attacks. Several studies have focused on CSA visualizations to assist *managers and higher level decision makers* (35.2%) to assess risks, allocate resources, and alter the state of operations of the organization in response to the real and potential security risks. For example, researchers in [P5], have proposed a Cyber COP that facilitates commanders decision making process by facilitating them to recognize the current state of assets and the cyber threat situation, impact of cyber attacks on the mission which is related to assets and future threat scenarios. In [P49], researchers demonstrate how composite visual data structures and their synthesis can

TABLE 5. Stakeholders

Stakeholder	Papers	Count
Operational level staff	[P3, P4, P6, P7, P9, P11, P12, P13, P14, P16, P19, P20, P22, P24, P26, P27, P28, P30, P32, P33, P34, P35, P37, P38, P39, P40, P41, P42, P45, P47, P48, P50, P51, P52, P54]	35
Managers and higher level decision makers	[P2, P5, P10, P12, P13, P16, P21, P22, P23, P24, P29, P31, P32, P36, P37, P43, P46, P49, P53]	19
Non-expert users	[P1, P44]	2

reduce or illuminate the direction of cyber security policies.

Non expert users: Two primary studies (3.7%) focus on CSA visualizations tailored to *non expert users*. In particular, these two papers [P1, P44] propose CSA visualizations to enable *non expert users* to actively monitor and observe their activity for greater online awareness. While [P44] focus on 2D visual analytics interfaces, [P1] focus on engaging 3-dimensional visualizations for home networking monitoring.

D. RQ2: WHAT ARE THE TYPES OF INFORMATION VISUALIZED, DATA SOURCES USED AND HOW THE CYBER INFORMATION IS VISUALIZED?

- Various types of information are represented through CSA visualizations. *Threat information* is the most common type of such information. However, only few studies consider *impact information*, *response plans* and *shared information*.
- Often multiple data sources are utilized together in CSA visualizations. Most frequent data sources are *asset identification systems* and *logs*. The *external data sources* and *human input and organizational information* are the comparatively less common data sources for CSA visualizations.
- *Iconic displays* and *geometrically transformed displays* are the prominent types of visualization techniques employed in CSA visualizations. On the other hand, *immersive environments* are very rarely used in the CSA visualizations.
- Only few interactions techniques are used in CSA visualizations frequently. These are *zooming*, *filtering* and *details on demand*. Other interactions techniques such as *relate*, *extract/share*, *move/rotate*, *linking and brushing* and *customization* are very rarely employed in CSA visualizations.

This section presents the findings for RQ2. In particular we discuss different types of information visualized in the CSA visualizations (see Section IV-D1), data sources used (see Section IV-D2) and how the cyber information is visualized (see Section IV-D3).

TABLE 6. Information types

Information types	Papers	Count
Assets	[P1, P5, P8, P13, P20, P22, P30, P31, P33, P34, P37, P39, P40, P41, P43, P45, P46, P51, P53, P54]	20
History and trends	[P2, P4, P7, P16, P21, P24, P25, P27, P30, P34, P37, P38, P44, P47, P48, P49, P50, P53, P54]	19
Impact information	[P2, P8, P9, P13, P21, P24, P33, P43, P54]	9
Response plans	[P2, P8, P16, P21, P28, P31, P33, P36, P39, P51]	10
Shared information	[P3, P10, P12, P31, P37, P51]	6
Network information	[P1, P5, P11, P12, P13, P14, P15, P24, P29, P34, P35, P36, P38, P40, P42, P44, P47, P49, P50, P51, P52]	21
Risk information	[P2, P4, P6, P9, P10, P12, P13, P14, P16, P17, P19, P21, P23, P25, P31, P32, P33, P36, P37]	19
Threat information	[P2, P3, P5, P7, P8, P10, P13, P16, P18, P19, P20, P21, P22, P23, P25, P26, P28, P30, P31, P32, P33, P34, P35, P37, P39, P41, P45, P46, P47, P48]	30

1) What information is visualized

This section presents the types of information visualized in our primary studies. The data extracted for this section corresponds to item D6 in Table 3. Our thematic analysis resulted in the identification of eight types of information as shown in Table 6. A single paper may visualize multiple types of information hence may have repeated entries in the table.

Assets: An asset in the context of cyber security could be any data, device or other components of an organization's systems that are valuable, mainly because it contains sensitive data or can be used to access such information. A clear understanding of the assets related information is vital to CSA. In our SLR we found 20 papers (37.0%) that visualized asset information. Among our primary papers, it was common to employ map views to visualize organizational cyber assets, geographic locations to which the target assets belong and the relationship between those assets [P5, P8, P31]. Apart from this cyber capabilities critical to the mission, network state in terms of assets, assets and relationship with cyber incidents were visualized in our primary studies.

History and trends: Analyzing the history and trend information allows users to easily contextualize the current cyber security status. Furthermore, understanding the trends and patterns allows users to make predictions about the future with some certainty. In our selected set of papers, we found 19 papers (35.2%) that visualized history and trend information. This involves historical data related to attacking behaviour, temporal information related to cyber security incidents, and trends in overall organizational performance. For example, we observed several papers provide the temporal context of cyber events to the users by displaying relevant data that happened before an event occurred [P4, P25]. Researchers in [P21] propose novel circle-based cyber security

metric display visualizations that are capable of displaying history information along with the current metric values. Only a few studies visualized history or trends with respect to overall organizational performance. For example, researchers in [P13] provide views for high-level management to analyze history and trends related to the impact of compromised network nodes and the cost of corrective actions.

Impact information: Understanding the impact or consequences of successful or potential cyber security events is a crucial step in identifying how to respond to those incidents or possible attacks. A limited number of papers provide various types of visualizations to support this (16.7%). For example, in [P13] the visualization uses the concept of area corruption to visually convey the impact of a compromised device on its supported process. Each compromised device will produce a hole in the area proportional to the value of its operational impact score. In [P2] researchers propose a proactive environment that shows the maximum level of impact or risk of the business devices.

Response plans: Papers (18.5%) that provide visualizations to assist users to determine the response plans for cyber incidents are grouped under this category. For a given situation, there can be multiple response methods. The visualizations in the selected set of papers assist users in either identifying these response methods and/or selecting the most suitable response plans by analyzing their costs and benefits. For example, researchers in [P5] propose visualizations that allow doing "what if" projections to explain to commanders the cyber side of the different "courses of action" (CoAs) that are proposed to him by his staff. In another example, response plans are presented to users in various dimensions such as risk mitigation, return on responsible investment and impact [P2].

Shared information: Achieving complete situation awareness requires members of different teams and different organizational positions, working across different work shifts to collaborate and share information with each other. In our primary set of papers, we observed a limited number of studies (11.1%) that include visualizations to support communication and collaboration among different team members. These visualizations consist of information related to observations and hypotheses performed or insights gained by the analysts. They also include analyst movements for the coordinators, email communication with the team, and communication workflows. For example, researchers in [P3] focus on a mind mapping system for supporting collaborative cyber security analysis and researchers in [P37] propose visualizations to show shared incident reports and as well as to facilitate the coordination of incident responses and defenses among the multiple stakeholders.

Network information: Several papers in our data set visualize various network related information (38.9%). The visualized information in this category includes information related to network data, network topology, network reports and network communication. For example, in [P38] both streaming and archived network flow data is visualized in

TABLE 7. Data sources types

Data sources types	Papers	Count
Security tools	[P2, P5, P6, P7, P8, P12, P13, P16, P18, P19, P21, P26, P28, P31, P32, P39, P41, P52, P53]	19
Asset identification and management systems	[P1, P5, P7, P20, P21, P22, P23, P24, P28, P29, P30, P31, P33, P34, P36, P37, P38, P39, P40, P42, P43, P45, P46, P54]	24
External data source	[P1, P6, P8, P9, P11, P16, P19, P20, P21, P23, P28, P30, P31, P41]	14
Human input and organizational information	[P2, P3, P7, P8, P10, P12, P13, P17, P18, P20, P21, P22, P28, P31, P33, P36, P37, P51]	18
Logs	[P4, P10, P14, P16, P20, P21, P23, P25, P31, P33, P34, P35, P36, P37, P38, P40, P42, P44, P45, P47, P48, P49, P53]	23
Network traces	[P1, P4, P14, P15, P16, P18, P19, P20, P21, P22, P23, P24, P27, P29, P30, P31, P33, P50, P53]	19

real-time to support the monitoring of network activity, identifying network attacks and compromised hosts and anomaly detection. In another example, visualizations were proposed for the analysis of firewall log events [P50].

Risk evaluation: We observed several primary papers (35.2%) in this SLR that look at visualizing information that allows the user to assess the risks related to possible attacks and threats. Risk evaluation information can take on various forms, for example, known vulnerabilities on critical assets can be related to security alerts for risk evaluation [P33], changes in risk levels [P6, P13], possible attack paths [P28], suspicious or known-malicious IP addresses [P4], classification and distribution of cyber security events [P19, P21, P23, P25] and attacker capacities [P16].

Threat information: Threat information is the most sought out piece of information in our primary studies (55.6%). Analyzing and understanding information with respect to incidents with potential harm to the organization is a crucial aspect of an organization's ability to correctly focus its cyber security strategy and budget. We observed various views in our primary studies to analyze the cyber threat situations. These views help analysts and decision makers to identify diverse aspects of the threats including relationships of threats with assets [P4, P5], the status and progression of a threat [P2], the evolution of threats [P7]. For example, researchers in [P5] provide views to the users to analyze the attack scenario in the form of an attack chain generated through attack scenario analysis of high-level threat alerts. These views allow the user to analyze how an attack is taking place in terms of the attack chain, identify any anomalies and also predict the next attack phase.

2) What data sources are used

This section presents the different data sources used for CSA visualizations in our selected set of primary papers. The data extracted for this section corresponds to item D7 in Table

3. Our thematic analysis resulted in the identification of six types of data sources as shown in Table 7. We observed that often multiple data sources are used in the selected set of primary papers to generate CSA Visualizations. As a result, one paper can appear under two data sources in Table 7.

Security tools: We found 35.2% of the primary papers in our SLR utilized information obtained from security tools. This include Security Information and Event Management (SIEM) [P2, P5, P8], risk analysis tools [P8] and output from various analysis tools [P16, P26]. For example, in [P5], researchers use high-level alerts generated by the correlation rule set defined in SIEM to represent nodes in the visualized attack scenarios. Researchers in [P8] uses outputs of various risk analysis tools and incident response trackers for the proposed Cyber Common Operating Picture.

Asset identification and management systems: One of the key aspects of cyber security is to systematically discover and select all relevant information assets that the organization holds; then potential security risks or gaps that affect them can be identified. There are 44.4% primary papers that utilized data from asset identification and management systems. For example, the Cyber COP system architecture proposed in [P5] includes an asset database created using information gathered through *asset identification and management systems*. In their architecture various mechanisms such as Simple Network Management Protocol (SNMP) and local agents are used to gather asset information.

External data sources: With the ever-increasing and complex cyber security incidents, organizations now need to move beyond data internal to the organization to make swift and effective cyber security decisions. Therefore, integration of external knowledge and data components is becoming an essential component for CSA. However, only 25.9% of the primary papers use external data sources in their visualizations. These data sources include common attack pattern enumeration, external domain sinkholing, GIS (Geographic Information System) maps, Malware sharing platforms, National vulnerability database, and passive DNS systems. For example, in [P16], domain sinkholing strategies and a well-defined list of command and control server domains are adopted as the external data sources to identify networks with machines participating in botnet activities.

Human input and organizational information: Cyber security depends on various human inputs and organizational information. We observed 33.3% papers use different forms of human input and organizational information in their proposed CSA visualizations. The human input consists of user-reported security incidents, expert knowledge and security related configuration parameters such as patching compliance rating. Furthermore, organizational information include mission dependencies and businesses processes. Researchers in [P17] uses expert knowledge about risk profiles stored in text file format as input to their expert system for facilitating an institutional risk profile definition for CSA.

Logs: A log is a record of previous activities of a system and organisation can use them take corrective as well as

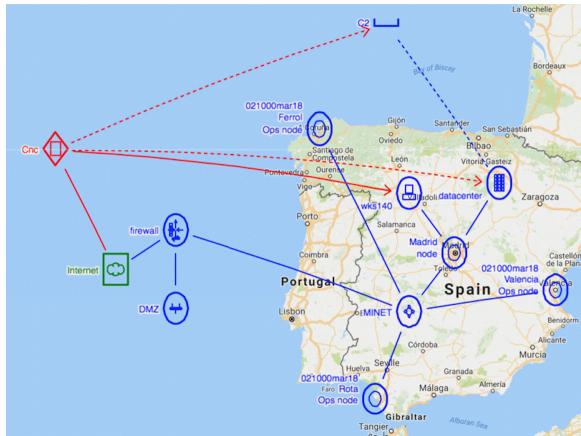


FIGURE 4. Visualization for Improved Situational Awareness (VISA) demonstrator employed in [P8] provides a common operational picture to the military staff. The visualization employs traditional military symbols.

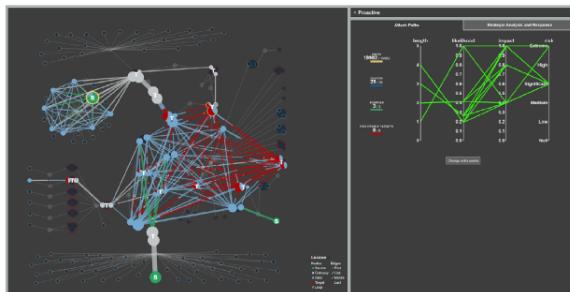


FIGURE 5. Visualization proposed in [P2] provides two views for the proactive environment (i.e. two visualizations): i) view on the left shows the network topology; and ii) view on the right summary of information related to attack graph and parallel coordinates visualization to support its analysis.

preventive measures. In case of a cyber incident, logs can be used to identify what assets have been compromised and their severity. It is observed that 42.6% papers use logs as a data source for CSA visualizations. This include database logs, firewall logs, IDS logs, network logs, and web and web proxy logs.

Network traces: We found 19 (35.2%) papers using network traces. This category consists of raw data and also network data collected from tools such as Wireshark and Splunk [P1]. Furthermore, Network traffic [P19, P20, P21, P22, P23, P24, P29, P30, P31], TCP/IP packet traces [P27] fall under this category. For example, in [P4, P16], the authors analyze data from network flow in addition to, firewall logs, and web proxy logs. In this context, a network flow represents an aggregation of a set of packets exchanged by a pair of systems.

3) How is the cyber information visualized

CSA visualizations employ various visualization techniques. Furthermore, diverse tasks/interactions are linked with CSA visualizations to improve user experience. In this section, we report how the CSA information described before is visualized considering the visualization techniques and related

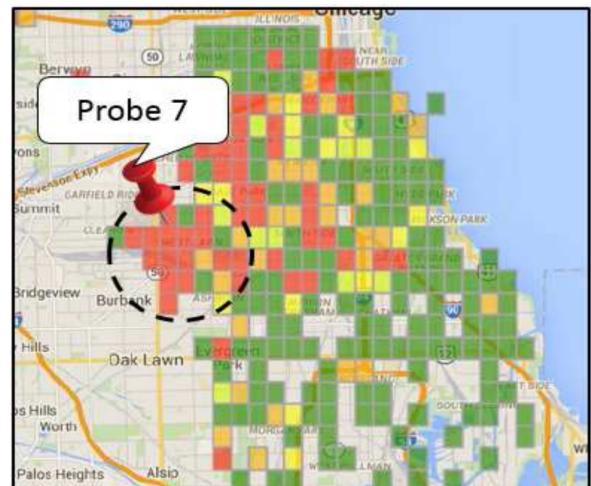


FIGURE 6. Visualization proposed in [P19] uses heatmaps used to determine the general location of Field Area Network (FAN) where the anomalous traffic is emanating. Here dashed circle indicates possible problematic areas.



FIGURE 7. Visualization proposed in [P21] is a treemap.

tasks/interaction techniques (*i.e.*, the data extracted for this section corresponds to items D8 and D9 in Table 3).

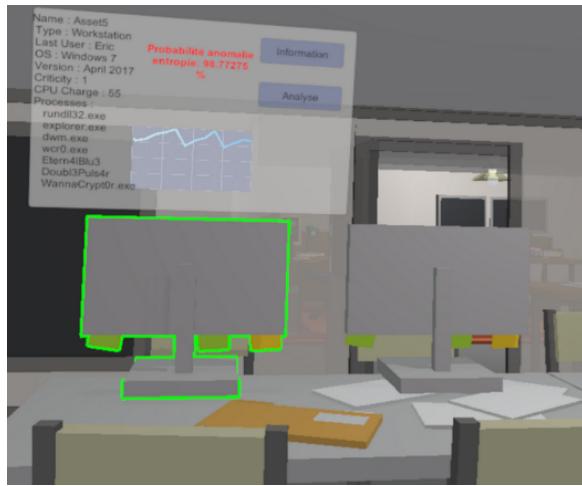
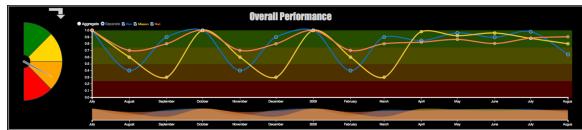
a: Visualization techniques

Table 8 presents how the *visualization techniques* are distributed over the selected studies. We describe these categories below.

Iconic displays: *Iconic displays* are the most common class of visualization techniques reported in the studies considered in this SLR (85.2%). In *iconic displays*, the attributes of multidimensional data items are mapped onto the features of an icon for the representation. Some of the common *iconic displays* reported in our primary studies include color icons [P2, P4, P13, P14, P16, P18] and shape icons [P8, P12, P21]. Often color icons are used to highlight the importance/significance of the reported values [P13, P20, P22, P25, P26]. Furthermore, some of the primary studies associate

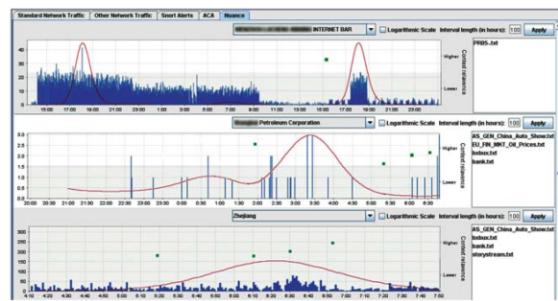
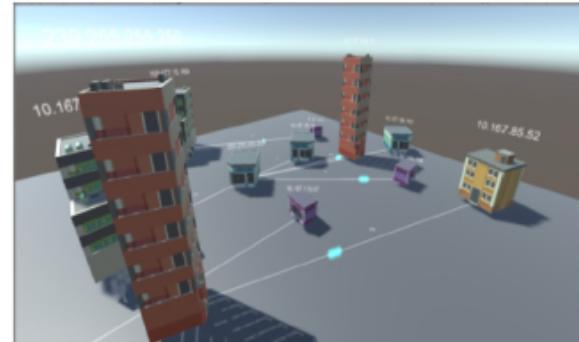
TABLE 8. Visualization techniques

Visualization Techniques	References	Count
Iconic displays	[P1, P2, P3, P4, P5, P6, P7, P8, P10, P11, P12, P13, P14, P16, P17, P18, P19, P20, P21, P22, P23, P24, P25, P26, P27, P29, P30, P31, P32, P33, P34, P36, P37, P39, P40, P41, P44, P45, P46, P47, P49, P50, P51, P52, P53, P54]	46
Geometrically transformed displays	[P1, P2, P3, P4, P5, P7, P8, P9, P10, P11, P12, P13, P14, P15, P18, P19, P21, P22, P23, P24, P25, P28, P30, P31, P32, P33, P38, P39, P40, P43, P45, P46, P47, P49, P50, P51, P53, P54]	38
Standard 2D 3D displays	[P2, P4, P9, P13, P14, P16, P17, P19, P21, P23, P25, P26, P29, P30, P34, P36, P37, P38, P40, P41, P42, P44, P47, P48, P49, P50, P53]	27
Tables/text summaries	[P2, P4, P5, P10, P12, P13, P16, P22, P26, P28, P30, P31, P32, P34, P35, P36, P37, P38, P39, P42, P45, P48, P49, P51, P54]	25
Geographical displays	[P1, P4, P5, P8, P12, P13, P16, P19, P23, P26, P30, P31, P34, P38, P39, P41, P42, P52, P54]	19
Stacked displays	[P6, P18, P20, P21, P28, P32, P33, P36, P40, P43, P44, P49, P50]	13
Single value displays	[P8, P13, P34, P37, P38, P39, P40, P41, P42, P43, P48, P51, P54]	13
Dense displays	[P4, P8, P13, P19, P20, P27, P44, P47, P49, P50]	10
Immersive environments	[P8, P11, P12, P39, P40]	5

**FIGURE 8.** Visualization proposed in [P39] is in an *immersive environment*.**FIGURE 9.** Visualization proposed in [P13] proposes a tachometer view to facilitating financial security managers get an overall view of the system performance. Furthermore, the view also provides trends and patterns of various indicators.

icon size with numerical attributes. For example, in [P5] the size of the node is used to represent its importance to the respective mission. Several studies use special icons that are familiar to the user in their visualizations. For example, the work reported in [P1] uses shape icons that are familiar to the user such as laptops, cables, buildings, and roads in to visualize the cyber status (see Figure 11).

Geometrically transformed displays: Often cyber security data consists of more than three attributes and, therefore, they do not allow a simple visualization as 2D or 3D plots described previously. This category includes visualizations that use interesting transformations of multidimensional data

**FIGURE 10.** Visualization proposed in [P30] uses standard 2D bar charts and line charts.**FIGURE 11.** Metaphoric visualization proposed in [P1] uses the buildings and cars as metaphors to show the network activity to non-expert users. Uses the relative positioning to show the IP addresses.

sets. We found 70.4% of the primary studies in our SLR use *geometrically transformed displays* in their visualizations. Common examples are the node-link diagrams [P2, P3, P5, P12, P31] and parallel coordinate plots [P2]. Parallel coordinates plot each multidimensional data item as a polygonal line that intersects the horizontal dimension axes at the position corresponding to the data value for the corresponding dimension (see Figure 5). Apart from this we also observed other visualizations with interesting transformations of multidimensional data. For example, in an area corruption chart proposed in [P13], each compromised device produces a hole

in the area representing the supported sub-process. The hole is proportional to the value of its operational impact score. Furthermore, the Mission-Attacker-Controls triangle (MAC) proposed in [P8] is a 3D triangular plot that is used to show the relative forces of the mission, the attacker's interest in the asset, and the security controls.

Standard 2D 3D displays: A large number of the primary studies selected for this SLR use *standard 2D 3D displays* (50.0%). This includes visualization techniques like x-y plots (e.g., scatter plots [P14, P21, P25], bar charts [P4, P26, P29, P30], pie charts [P29]) and line charts [P9, P17, P30]). For example, the work reported in [P26, P30] uses bar charts to illustrate the distribution of the standardized incidence rate and the per-minute observed traffic levels respectively. In [P25] scatter plots are used to show similar alerts grouped together where an alert is represented as one dot in the visual space.

Tables/text summaries: We identified tables and text summaries as a popular form of presenting cyber information in the selected papers (46.3%).

Geographical displays: In our selected set of primary studies, 35.2% of the studies use *geographical displays* to visualization of geographical information. Maps are often employed to present the geographical distribution of information related to assets [P5, P8, P31], risks [P16, P19, P23], and threats [P5, P8]. For example, researchers in [P13] use maps to illustrate how the network nodes are geographically distributed. The work reported in [P16] employs maps to illustrate how the attacker capacity is distributed worldwide and to provide the user with a closer look at the organizations infected by malware. In [P20] maps are used to display cities with extremely high or low malicious activities.

Stacked displays: *Stacked displays* are representations of hierarchical data and hierarchical layouts for multidimensional data. Only a limited number of studies (24.1%) use this display in their visualizations. Treemaps are an example of a hierarchical data representation found in paper [P20, P21], displaying hierarchical data as a set of nested rectangles. For example, in the treemap visualization proposed in [P21] (see Figure 7), the business value of the host defies the rectangle size, and the calculated host security level defines the color. Another example of *stacked displays* can be found in the work reported in [P6] where the risk levels are visualized using a risk tree visualization. In [P28] a tree view is used to represent the entire attack graph in the form of a directory hierarchy. In the work reported in [P33], a hierarchy of layers presents how types of operational missions, mission-critical tasks, and types of assets are connected together.

Single value displays: *Single value displays* show an interesting representation of a single/instantaneous value that is meaningful on its own. We observed this visualization in 24.1% of the selected set of papers. Gauge representation are a common form of *single value displays* [P8, P13]. Researchers in [P13] (see Figure 9), use gauge representations to provide a glance view of several performance indicators to the financial security manager.

Dense pixel displays: Each data point in *dense pixel displays* is mapped to a colored pixel so that they can be grouped into adjacent areas that represent individual data dimensions. Only a few studies (18.5%) use this type of display. Heatmap is an example of dense pixel displays employed in studies reported in this SLR [P4, P8, P13, P19, P20, P27]. A heat map is a two-dimensional representation of data in which values (i.e. magnitude of phenomena) are represented by different colors (see Figure 6).

Immersive environment: *Immersive environments* allow users to immerse themselves in the artificially-created virtual environments through a collection of computer hardware and software so that users could perceive themselves to be included in and interact in real-time with the environment and its contents. Only a limited set of studies (9.3%) employ *immersive environments* in their visualizations [P8, P11, P12, P39, P40]. In [P8, P11, P12], virtual reality head-mounted displays are used to create an illusion for the user of immersion in virtual cyberspace. In [P39], a Collaborative Virtual Environment is deployed for the 3D Cyber COP model to help cyber analysts to mediate analysis activities, the *immersive environment* is shown in Figure 8. These environments provide the users with the sensation that they are existing within an environment, opposed to being on the outside looking at it on a screen.

Multiple visualization techniques are often utilized together in a single visualization. We observed that apart from *standard 2D 3D displays* and *tables/text summaries*, other visualization techniques are combined with *iconic displays* in more than 50% of the visualization instances of our selected set of papers. *Iconic displays* place the information en-richer role in most of these visualizations. For example, color or shape icons are often used with *geometrically transformed displays*, *geographical displays* and *stacked displays* to emphasize the status or severity or impact of a particular phenomena [P1, P5, P16, P22, P23, P31, P33]. Apart from *iconic displays*, *geometrically transformed displays* are often combined with other visualization techniques. For example, the work reported in [P1, P11] combined node-link diagram—an example of a *geometrically transformed display*—with *immersive environments*. In these examples, the users can immerse in the environment through the virtual reality headsets to investigate the properties of the node-link diagrams. It is also interesting to note that *single value displays* instances are used in combination with *standard 2D 3D displays* more than 50% of the time. When source literature is referred to, it is clear that *standard 2D 3D displays* are used to provide the additional information to interpret the metrics visualized through the *single value displays*. For example, in Figure 9, a *standard 2D display* shows trends and patterns of the associated metrics while the tachometer shows the overall system performance.

We also compared the cyber security information types discussed in Section IV-D1 with the utilized visualization techniques. According to Figure 12, it is evident that all the information types often employ *iconic displays* as a visu-

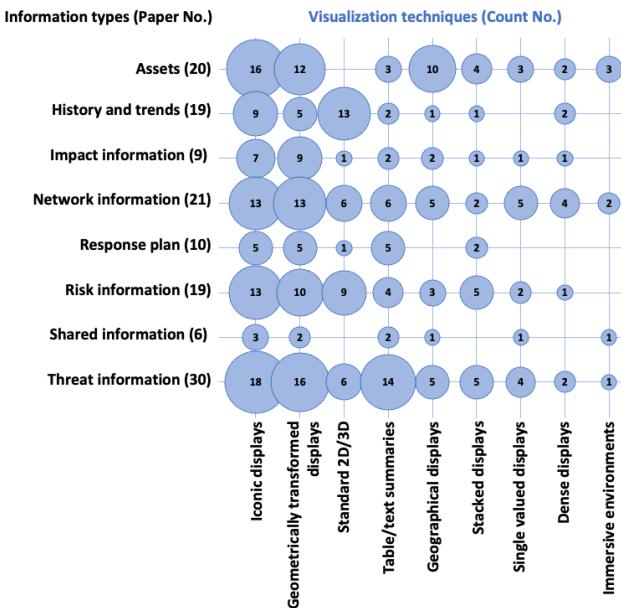


FIGURE 12. Visualization techniques vs information types

TABLE 9. Tasks/interactions techniques

Tasks/interactions	References	Count
Zooming	[P2, P7, P8, P13, P20, P22, P23, P28, P32, P40, P46, P47, P48, P53]	14
Filtering	[P2, P3, P4, P7, P13, P16, P25, P26, P28, P35, P38, P40, P41, P44, P45, P46, P47, P48, P49, P53]	20
Details on demand	[P2, P12, P13, P16, P19, P21, P25, P28, P30, P40, P41, P42, P43, P44, P45, P46, P47, P49, P50, P51, P53]	21
History	[P2, P7, P16, P44, P49, P50, P53, P54]	8
Relate	[P2, P4, P5, P7, P40, P53]	6
Extract/share	[P4, P16, P28, P31]	4
Move/rotate	[P8, P11, P12, P51]	4
Linking/brushing	[P50]	1
Customization	[P6, P8, P28, P37, P38]	5

alization technique. Furthermore, *geometrically transformed displays* are often employed in visualizations that present information related to network [P5, P11, P14, P15, P24], assets [P1, P5, P8, P13, P22], risks [P14, P18, P21, P23, P32], threats [P13, P19, P32] and impact [P8, P9, P13, P21, P24]. When presenting asset information *geographical displays* are often employed as a visualization technique [P5, P8, P13, P31]. *Standard 2D 3D displays* are often employed to visualize information related to history and trends [P25, P27] and risk evaluation [P16, P17]. *Tables/text summaries* are mainly used to convey information related to threats [P5, P22, P31, P32] and response plans [P2, P16, P28]. Furthermore, *immersive environments* commonly visualize network information [P11, P12].

b: Tasks/interactions

Interaction techniques allow users to directly interact with the visualizations and facilitate effective data exploration.

Table 9 illustrates the tasks/interactions type distribution over the selected set of papers. We also point out that there are 16 papers (29.6%) that we did not classify into tasks/interactions topics. A similar observation was made previously in [21]. Similar to [21], we are also unsure whether authors do not highlight these features or, in fact, the proposed visualization does not provide such features. The tasks/interactions classification used in this paper is described in detail below.

Zooming: *Zooming* helps to present data in a highly compressed form to provide an overview of the data, whilst at the same time, allowing a flexible display of the data at different resolutions based on the user needs. As evident from Table 9, *zooming* functionality is indicated in 25.9% of the publications. This functionality allows users to zoom in on items of their interest. For example, in [P8], an operational picture of the situation is initially presented at a higher level of abstraction and when the users zoom in, the abstract nodes are replaced by their detailed representations.

Filtering *Filtering* allow users to interactively partition the data set into segments and focus on interesting subsets. In our selected set of primary studies, 37.0% of the papers use the *filtering* functionality. For example, the parallel coordinates visualization proposed in [P2] allows users to filter a set of attack paths by brushing on one or more axes. The *filtering* allows a complex set of attack paths to be quickly reduced only to paths that respect certain conditions defined by the user. In [P25], allows the user to filter cyber events based on several criteria.

Details on demand *Details on demand* functionality allows users to select an item or group and get details when needed. This functionality is mentioned in 38.9% of the primary papers. *Details on demand* are often provided through the clicking/double-clicking options [P13, P16, P21, P28, P30] and through tool-tips [P2, P25].

History: *History* allows support users to keep and view the history step by step through different options such as undo and replay. As evident from Table 9, this functionality is only mentioned in eight publications (14.8%).

Relate: View relationships among items. Through the *relate* interaction users can click on one item and see its relationships to other items. Only six (11.1%) publications included this user interaction.

Extract/share: Allow users to share item(s) that they desire with others or extract item(s) that they desire for later use. After extracting, the users could save the data to a file in a format that would facilitate other uses such as sharing, printing, and graphing [P4, P16]. We found only four papers (7.4%) in this category.

Move/rotate Moving and rotating the visualization [P8, P11, P12]. Moving and rotating is related to 3D displays and immersive environments. We only observed four papers (7.4%) that discussed this user interaction.

Linking and brushing: *Linking and brushing* allows interactive changes made in one visualization to automatically be reflected in other visualizations. However, we only found one paper (1.9%) that mentioned this ability. In [P50] ana-

TABLE 10. Cyber Situational Awareness Level

Situational Awareness Level	References	Count
Perception	[P1, P2, P4, P5, P6, P8, P9, P10, P11, P12, P13, P14, P15, P16, P17, P18, P19, P20, P21, P22, P23, P24, P25, P26, P27, P28, P29, P30, P31, P33, P34, P35, P36, P37, P38, P39, P40, P41, P42, P43, P44, P45, P46, P47, P48, P49, P50, P51, P52, P53]	50
Comprehension	[P2, P3, P4, P5, P7, P8, P13, P16, P19, P20, P21, P22, P23, P24, P26, P28, P30, P31, P32, P34, P36, P37, P38, P39, P40, P43, P44, P46, P54]	29
Projection	[P2, P5, P8, P16, P21, P24, P28, P39, P43, P54]	10

lists are allowed to make good use of both heatmaps and line charts to overcome their weakness by implementing *linking and brushing* interactions.

Customization: Editing the visualization (edit mode). We observed this user interaction only in 5 (9.3%) publications. In both [P5] and [P28] users are allowed to customize the visualizations by changing the layout. In [P6] users are given a series of visualization techniques to choose from. Here the user is able to pick the visualization technique that best suits them to visualize the information at hand.

E. RQ3: WHAT LEVEL OF CSA IS FACILITATED BY THE VISUALIZATIONS?

- Most studies (92.6%) facilitate the *perception* level and many studies (53.7%) facilitate *comprehension* level.
- Only a limited number of studies (18.5%) provide visualizations to achieve *projection* level.

As described in Section II-A, Endsley [4] model provides three ascending levels of SA, namely *perception*, *comprehension* and *projection*, which may or may not be linear. In this section, we analyze what levels of CSA, described in Section II-A, can be achieved through the proposed visualizations. It is also important to highlight that some publications included in this SLR provide multiple visualizations that may facilitate achieving multiple SA levels. In the case where a single visualization can be used to achieve multiple levels of CSA, we assigned the corresponding highest level of CSA for that particular visualization. Table 10 illustrates the levels of CSA supported by the publications selected in this SLR and presents the distribution of papers across the three CSA levels. As one publication could provide multiple visualizations, in Table 10, a single publication can be reflected in multiple levels of SA.

a: Perception

Visualizations that provide users with an overview of the status, attributes, and dynamics of the cyber environment

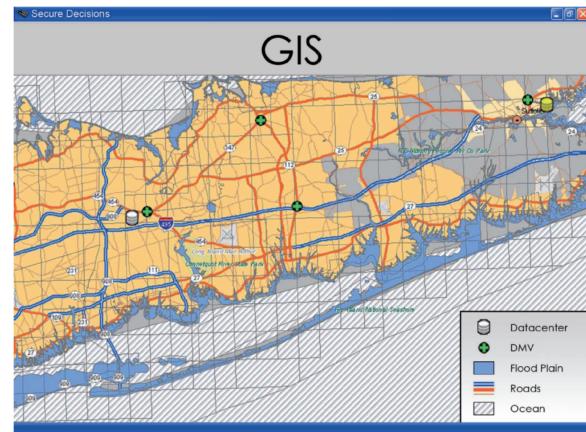


FIGURE 13. Visualization proposed in [P31] provides the user an overview of the geographical distribution of critical infrastructure.

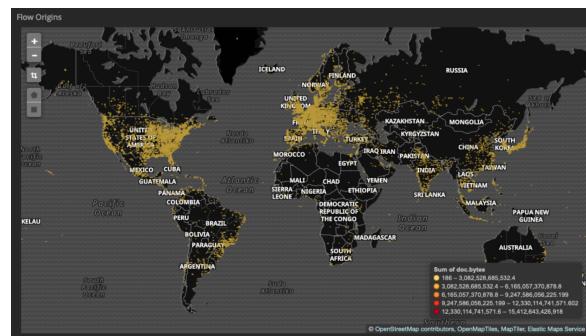


FIGURE 14. Visualization proposed in [P38] shows information about the location of source IP addresses.

have been linked to the *perception* level (see Figure 14). These visualizations allow the user to often answer the question "What is happening in the cyber environment?". Most studies in this category provide visualizations that present a high-level overview of the cyber assets [P5, P20, P31, P33], network topology [P2, P29], cyber threats [P4, P5, P25, P26], and cyber risks [P2, P14, P16, P28]. For example, Cho et al. [P5] propose a geographical perspective view that allows the user to identify the status of cyber assets and threats. Carvalho et al. [P16] provide an indication of the attacker's capacity by visualizing the distribution of bots over a world map. Kopylec et al. [P31] provide the user with an overview of the geographical distribution of critical infrastructure using maps. Angelini et al. [P2] provide a visualization to allow users to obtain an overview of the network topology and risk status of the system. For this, they have superimposed an attack graph over the network topology. Using the attack graph the user can get an overview of the risk posture of the organization (see Figure 5). Yu et al. [P26] use a world map to show cities with the highest Standardized Incidence Rate (SIR). SIR metric can be used to identify cities with higher levels of infection and is defined as "the number of malicious IP addresses for every 100,000 actual machines that could be infected in a city".

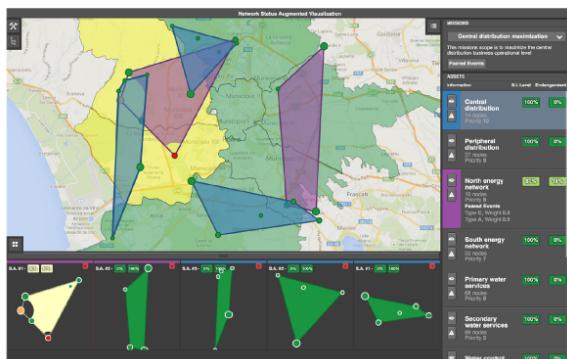


FIGURE 15. Visualization proposed in [P13] shows the impact of compromised nodes through the concept of area corruption.

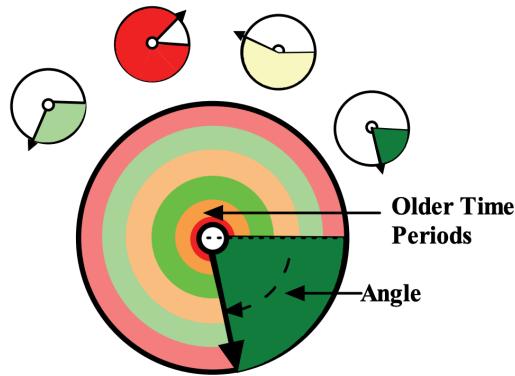


FIGURE 16. Visualization proposed in [P24] to allow decision makers to interpret the cyber situation. History information is included in the visualization. Small dials provide more information on the individual components of the system. The dial is reinforced to facilitate rapid interpretation.

b: Comprehension

Comprehension allows users to move from just being aware of the elements in the cyber environments to comprehending the situation. Therefore, visualizations that facilitate the users to understand the meaning of the elements in the cyber environment are linked to this category (see Figure 15 and Figure 16). These visualizations allow the user to answer questions like “Why it is happening?” and “What is the meaning?” with respect to elements in the cyber environment. A number of studies in this category provided visualizations that provide the context of the elements in the cyber environment [P2, P4, P5, P24, P32]. For example, the work reported in [P4] provides an ‘event detail page’ that provides the context of a selected cyber event. This includes horizon graphs of several flow fields and heatmaps of IP addresses that provide temporal context to the event. These visualizations prioritize showing trends and patterns since this is most important for context. Understanding the context of a specific event allows users to comprehend its meaning and this can be considered a higher mental state than being just aware that a cyber incident has occurred. Authors in [P24] propose a visualization by extending standard gauge visualizations



FIGURE 17. What-if analysis result proposed in [P43] provides a predictive analytics capability.

(see Figure 16). Their visualization includes a large dial and a set of smaller dials. The large dial provides the overall status of the system, network, or mission; while the prototype focuses on systems, the design can easily be generalized. The smaller dials show how individual components of the system are being impacted which provides context to understand the information shown on the large dial. Furthermore, to provide more context into what is shown on the larger dial, history information has been added by providing rings within the dial where the outer ring shows the current value. The work reported in [P5] allows us to see how a specific attack has been taking place in terms of five attack phases of a proposed attack chain model. This allows users to closely investigate the attack progression and take actions if needed.

Some visualizations in the *comprehension* category also specifically looked at providing information on the significance/consequence of cyber incidents to the user [P8, P13, P28]. Understanding the impact/significance/consequence of the cyber incidents allows users to comprehend the situation and is a higher mental state than being just aware of the cyber incidents that have occurred. For example, the work reported in [P28] visually displays the effects that occur when a specific node or protection domain is affected. This allows users to move from just being aware of the threat situation to understanding and comprehending the threats with respect to organizational goals. In [P13] the impact of a compromised device on its supported process is shown through the concept of area corruption. The idea is to have a hole in the area representing the supported sub-process for each compromised device. The hole is proportional to the value of its operational impact score. This allows users to understand the significance of the cyber incidents and their relationships to the supported process.

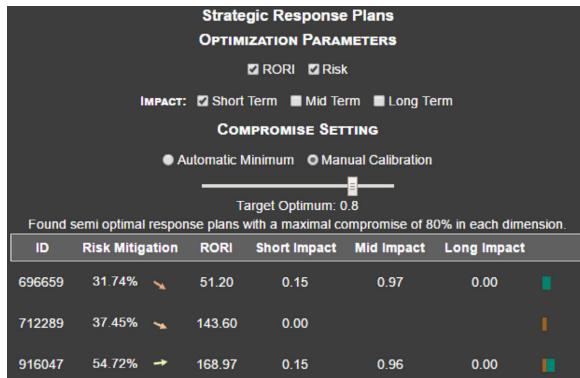


FIGURE 18. In [P2], response plans are shown in a table and classified by their characteristics.

c: Projection

The visualizations that facilitate the *projection* level allow users to predict the future cyber threat situation and/or possible future actions. These visualizations allow the user to answer questions like “What will happen next?” and “What can I do?” with respect to the cyber environment. A number of studies in this category have provided visualizations to illustrate the impact from possible future threats [P8, P21, P24] and possible plans to respond to the cyber security situation of the organization [P2, P21] (see Figure 17 and Figure 18). For example, the work reported in [P8, P28, P43] facilitates what-if analysis to assist the user to identify possible future actions. Through the what-if analysis proposed in [P28], the user can specify a starting point for the attack (the presumed threat source), as well as an attack goal (critical network asset to protect). The results of what-if analysis allow the user to model the effects of software patches or other mitigation solutions on the system. In [P8], what-if analysis will allow the decision maker to analyze different action plans based on the importance given to the mission, the attacker’s interest in the asset, and the security controls. Furthermore, the system also provides recommendations for optimal network defense. In [P2] response plans are shown to the user based on the current cyber situation. The proposed visualizations also allow users to understand how each response plan could reduce the risk on the network devices. Kotenko and Novikova [P21] visualize the *Return-on-Security-Investment* index for each countermeasure that characterizes possible damages due to the security incident and cost of security incidents.

We also analyzed the distribution of visualization techniques, (described in Section IV-D3a), with respect to the three levels of CSA (see Figure 19). According to Figure 19, *iconic displays* are the most commonly used visualization technique at *perception* and *comprehension* level. At the *projection* level the most popular visualization technique is *geometrically transformed displays*. Furthermore, it is interesting to note that popularity for *standard 2D 3D displays* and *geographical displays* gradually reduces over the CSA levels where there are no *standard 2D 3D displays* and *geographical displays* at the *projection* level.

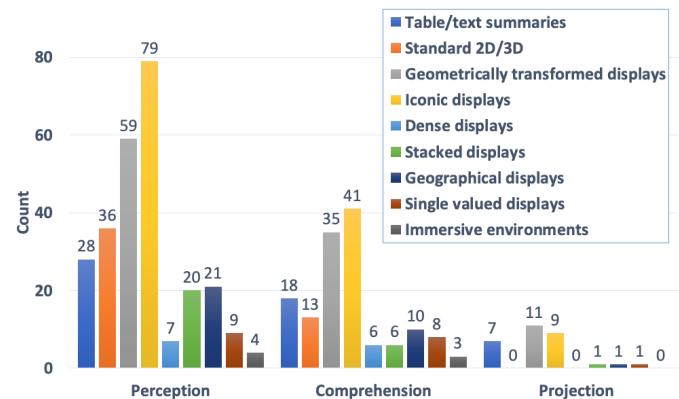


FIGURE 19. Visualization techniques for achieving different levels of SA

TABLE 11. The evidence is available in the selected studies to adopt the proposed visualization techniques.

Maturity level	References	Count
No evidence	[P5, P13, P18]	3
Demonstration or toy examples	[P6, P7, P8, P9, P11, P12, P14, P17, P19, P20, P21, P22, P23, P25, P26, P27, P28, P29, P31, P33, P35, P37, P41, P43, P44, P46, P47, P48, P49, P52, P53, P54]	32
Expert opinions or observations	[P1, P2, P30, P36, P40, P50]	6
Academic study	[P3, P39, P45, P51]	4
Industrial case study (casual case study)	[P10, P15, P24, P32, P34]	5
Industrial practice	[P4, P16, P38, P42]	4

F. RQ4: WHAT IS THE MATURITY OF THE PROPOSED VISUALIZATIONS THAT FACILITATE CYBER SITUATIONAL AWARENESS?

- Most studies use demonstrations or toy examples in their evaluations.
- Unfortunately, most proposed CSA visualizations lack rigorous and industry-suitable evaluation.

To answer RQ4, we analyzed the data collected for D11 in Table 3. The importance of rigorous evaluation to assess the appropriateness of the proposed solutions has been emphasized by the software engineering research community [37]. As mentioned in Section III-E2. We used a six-level hierarchy, proposed in [34], for assessing the reported evidence. The proposed six-level hierarchy is listed below: i) no evidence; ii) evidence obtained from demonstration or working out with toy examples; iii) evidence obtained from expert opinions or observations; iv) evidence obtained from academic studies (e.g., controlled lab experiments); v) industrial studies (e.g., causal case studies); and vi) evidence obtained from industrial practice. This hierarchy is used in previous studies to evaluate the maturity of visualizations in other domains [35]. In particular, ‘no evidence’ and ‘demonstration or toy examples’ are at the weak end of the hierarchy, while

'industrial practice' indicates that the method has already been approved and adopted by an organization which may indicate convincing proof that something works.

Table 11 presents the distribution of the studies according to the six levels of evidence. From Table 11, it is evident that 3 studies (5.6%) do not have any evidence of the proposed visualizations. Most of the primary studies (59.3%) selected in this SLR show their maturity through demonstrations or toy examples. Some of these studies used fictional scenarios and simulated data sets for their demonstrations [P7, P8, P9, P21, P23, P54]. For example, authors in [P23], using a set of test scenarios that simulate five attacks of varying complexity, demonstrate their implementation of smart grid trust visualization. Authors in [P7] show capabilities of the visualizations using simulated data sets (thus avoiding sensitivity issues). Authors in [P8] explained fictional scenarios using which derive and generate data conditions applicable to their visualizations. In other studies [P14, P17, P20, P26, P27, P49], publicly available data sets are used to demonstrate the capabilities of the visualizations.

Six of the selected studies (11.1%) use expert opinions to evaluate their visualizations [P1, P2, P30, P36, P40, P50]. For example, the work reported in [P30] proposed a set of visual interfaces to help analysts to identify and explain off-normal activities. Seven analysts provided feedback on the proposed visualizations by participating in workshops. In [P2], 104 experts, including 12 real users of the system, provided their opinions on the system through a close-ended questionnaire after being exposed to a 3-hour live demonstration of the visualization system.

Four of the selected papers (7.4%) use academic studies to provide evidence of the proposed CSA visualizations [P3, P39, P45, P51]. In [P3], a two-phase experiment was conducted in a controlled lab environment. The first phase was an observational study to see how the four senior undergraduate students completed a given task in the proposed system based on a given network monitoring data set. The second phase was conducted with further seven participants. Four of them are undergraduate students, two are graduate students, and one is a professional software engineer. In the second phase, participants reviewed the outputs of the first phase and completed a questionnaire about the system.

The maturity of the visualization of five studies (9.3%) is demonstrated through industrial case studies [P10, P15, P24, P32, P34]. For example, the work reported in [P32] proposed a visual paradigm for correlation of network alerts from disparate logs, and their prototype was deployed and tested at the Air Force Research Lab (AFRL) in Rome, New York, for one week. This allowed them to collect perspectives from analysts and other personnel about the usability of the tool and features that should be added.

Only four studies (7.4%) [P4, P16, P38, P42] provide evidence of industrial practice for the proposed visualizations. In [P4] presents a real-world example of how the visualizations are being used by analysts at a large (5000 users) Security Operations Center (SOC) on a daily basis. In the study,

TABLE 12. Reported challenges

Challenge	Key point	Count
Handling large amount of data	<ul style="list-style-type: none"> Information cluttering [P2, P3, P4, P6, P7, P12, P13, P15, P16, P18, P21, P25, P28, P30, P31, P44, P50] Streaming data challenges [P4, P53] 	18
Uncertain, missing or erroneous data	<ul style="list-style-type: none"> Missing or inadequate information [P2, P10, P49] Dealing with errors in data [P2, P6, P23, P26] 	6
Different data formats and standards	<ul style="list-style-type: none"> Diverse data sources [P10, P16, P19, P53] IP address space [P20, P26] 	6
Comprehensibility of information	<ul style="list-style-type: none"> Visualizations to suit the user and time [P8, P22, P29, P37, P43, P47] Simple Vs. precise visualizations [P6, P11, P12, P18, P21, P54] Facilitating the identification of patterns, trends and relationships [P2, P9, P13, P14, P16, P32, P44] Choosing appropriate aesthetics [P1, P11, P16, P32] 	20
Ease of use	<ul style="list-style-type: none"> Easy integration and consistency with existing tools [P11, P25, P28, P53] Easy to use visualizations [P14] 	5

the analysts are defined as experts with experience ranging from two to 10 years in network security. Observations on how analysts use the proposed visualizations were conducted over six months in multiple sessions (approximately one hour each). They also solicited analyst feedback over email over 12 months. Authors in [P16] explain that the proposed visualization system is used in the real world and they have obtained feedback from the customers. However, detailed feedback from the customers is not presented in the paper.

G. RQ5: WHAT ARE THE REPORTED CHALLENGES IN EMPLOYING VISUALIZATIONS TO FACILITATE CYBER SECURITY AWARENESS?

- We identified several challenges for CSA visualizations reported in literature. The most commonly reported challenges are *handling a large amount of data* and *comprehensibility of information*.
- Less commonly reported challenges are *uncertain, missing or erroneous data*, *different data formats and standards* and *ease of use*.

This section presents the thematic analysis findings for RQ5 and describes various challenges with respect to cyber security visualizations (see Table 12) that are reported in the selected papers. The data extracted for this section corresponds to item D12 in Table 3.

1) Handling large amount of data

In the era of big data and the Internet of Things, cyber security data collection volumes are ever-expanding. As a result, in terms of CSA visualizations, there is a huge degree of complexity involved in storing and viewing a large volume of both raw and analyzed data (33.3%) [P3, P12, P13, P15, P16, P25]. The streaming nature of data [P4, P53] can further introduce challenges for analysis due to the continued growth and dynamic nature of the data. Even when information is visualized using several layers, handling large amounts of data is still a huge concern. For example, when historical data is added the number of layers grows faster, making it difficult to analyze any unfolding trends or patterns. As the density of information increases, users get overloaded with information, and important data could be occluded [P16, P31]. Therefore, it is crucial for CSA visualizations to be flexible and scalable to cater to immense volumes of data that are generated by modern data sources.

2) Uncertain, missing or erroneous data

Several studies have discussed challenges with respect to uncertain, missing, or erroneous data for CSA visualizations (11.1%). Having uncertain, missing, and erroneous data in CSA visualizations mean that those visualizations could present misleading information to the user which can lead to flawed decision making. Therefore, CSA visualizations should consider techniques to compensate for data flaws and statistical variability [P26] to deal with false positives [P6] and missing, fragmented or inaccurate data [P2, P49].

3) Different data formats and standards

The number of devices connected, and the number and variety of applications or services that are employed in current CSA visualizations are very high. This means that creating these visualizations would require a high volume of heterogeneous formats of data to be stored and analyzed (11.1%) [P10, P16, P53]. For example, researchers in [P16] use data from different data sources in their platform for real-time detection and visualization of cyber threats. These data sources are divided into external data and internal data. External sinkholing, passive DNS, or social media data are examples of external sources used in their work. Network flow, logs, and analysis outputs captured inside the network are examples of internal data sources employed in their work. Having diverse sources and data would require systems and practices in place to store and analyze apparently uncorrelated data in order to build effective CSA visualization systems.

4) Facilitating comprehension of information

Ensuring that users can comprehend and synthesize the provided information is a huge challenge in CSA visualizations. In fact, 37.0% of primary studies mention this challenge. The CSA visualizations have to be simple enough to enable users to easily understand the visualization, and precise enough to enable them to make correct decisions swiftly [P12, P54]. Not all the available information has to be shown to users at once to enable them to make decisions. On the other hand, not providing adequate information could lead to flawed decision making. The information in CSA visualizations should be visualized in a way that users can quickly and easily identify any patterns, trends, and relationships [P44]. Choosing appropriate aesthetics also plays an important part in facilitating its comprehension of the information shown in CSA visualizations [P1]. Another key challenge is providing the right type of visualization at the right time [P22] and making sure the provided visualizations relate to users' knowledge and experience [P8, P22, P37].

5) Ease of use

Several studies (9.3%) explain that for CSA visualization to be effective and useful they need to be easy to use. If visualizations have adequate information for users to make decisions, but the users cannot easily identify or find that information then those visualizations will not be effective. Since each user will be different, the user requirements have to be taken into careful consideration to understand how to design visualizations that are easy to use. Another common challenge in CSA visualizations is that they are often standalone and do not integrate well with existing tools and data. Users often trust certain tools and data sources that they understand and heavily rely on. So if the CSA visualizations are not consistent with existing tools and systems or do not integrate well with them then they will be less effective and useful [P53]. When CSA visualizations do not integrate well with existing tools and practices then it limits the capacity for users to collaborate, effectively communicate, and share information with others.

H. RQ6: WHAT PRACTICES HAVE BEEN REPORTED TO IMPLEMENT CYBER SITUATIONAL AWARENESS VISUALIZATIONS SUCCESSFULLY?

- We identified several practices to implement CSA visualizations reported in the literature. The most commonly reported practices are *condensed presentations, providing context, and layouts and aesthetics to reduce visual complexity*.
- Less commonly reported practices are *flexibility handle differences in data and facility to share information*.

This section presents the thematic analysis findings for RQ6 and describes key practices with respect to cyber security visualizations (see Table 13) that are reported in the se-

lected papers. The data extracted for this section corresponds to item D13 in Table 3.

1) Condensed presentation

CSA information that needs to be visualized is often complex and multi-dimensional. Therefore, CSA visualization researchers have looked into condensed forms of information representation to provide more information using a single visualization. As detailed in Section IV-D3, our primary papers have used various forms of visualization techniques such as *geometrically transformed displays*, *iconic displays*, *dense displays*, *geographic displays*, *stacked displays*, to present diverse multi-dimensional data in compact ways. Furthermore, multiple visualization techniques are superimposed to provide additional information to the user in a single visualization. For example, color or shape icons are often used with *geometrically transformed displays*, *geographical displays*, and *stacked displays* to emphasize the status or severity, or impact of particular phenomena (refer to Section IV-D3). Furthermore, user interactions such as *details on demand*, *zooming* and *filtering* allows users obtain information only on demand which facilities showing information in a condensed way.

2) Providing context

As CSA visualizations often deal with a tremendous amount of data, the user performance in comprehending the provided information and projecting for the future could suffer tremendously without support to reason out the context. In fact, previous research has highlighted that providing context to interpret information is the key to developing CSA [P30]. We observed several ways visualizations available in our primary papers facilitate users to comprehend information by providing context. For example, researchers in [P4] identify the temporal context of an event as an important design practice for CSA. They used horizon graphs of several flow fields and heatmaps of IP addresses to provide context to a cyber event. Furthermore, researchers in [P13] adopt the practice of showing trends and patterns of how the network compromises could affect the organization's performance. Researchers in [P30] attach relevant contextual information to the charts so that users can easily understand why certain activity changes might be taking place. On the other hand, limited studies have looked at context-adaptive CSA visualizations. For example, researchers in [P18] propose a real-time adaptive system for recommending the appropriate level of detail views tailored for hierarchical network information structures. This system reasons the contextual information associated with the network, user task, and user cognitive load to adapt the network visualization presentation to facilitate context-aware reasoning.

3) Layouts and aesthetics to reduce visual complexity

The visual complexity of visualizations influences the way a user will interact with those visualizations. Several papers have focused on better layouts and aesthetics to reduce visual

TABLE 13. Reported practices

Practice	Key point	Count
Condensed presentation	<ul style="list-style-type: none"> Condensed forms of visualizations [P2, P4, P8, P13, P21, P24, P26, P38, P40, P43, P50, P54] Superimposing different visualizations techniques [P5, P8, P34, P37, P38, P42] User interactions to support users obtain information only on demand [P2, P13, P16, P22, P30, P38, P39, P40, P41, P43, P44, P46, P53, P54] 	24
Providing context	<ul style="list-style-type: none"> Context-aware adaptive visualizations [P18, P41, P49] Providing trends and patterns [P4, P13, P16, P21, P24, P30, P34, P38, P41, P44, P47, P49, P51, P53] Details to provide context for threats or risks [P2, P4, P5, P8, P9, P13, P34, P35, P37, P43, P44, P54] 	23
Layouts and aesthetics to reduce visual complexity	<ul style="list-style-type: none"> Reducing complexity of data using layout options [P28, P37, P38, P41, P53]. Providing multiple views for information visualization [P2, P4, P5, P12, P13, P16, P20, P25, P33, P37, P38, P39, P41, P50] Importance for visual attributes to reduce visual complexity [P1, P2, P3, P5, P8, P11, P13, P16, P22, P37, P43, P46, P50, P53] 	23
Facility to share information	<ul style="list-style-type: none"> Providing the ability to share visualized information [P3, P4, P10, P12, P16, P37, P38]. 	7
Flexibility to handle differences in data	<ul style="list-style-type: none"> Extra views to handle accurate and missing information [P2, P34, P50]. Flexibility to have different data models [P7]. 	4
User-driven requirements	<ul style="list-style-type: none"> Consultation industrial partners or real users or observations to gather requirements [P2, P4, P11, P12, P24, P37, P38, P41, P42, P45]. 	10
Real world evaluations	<ul style="list-style-type: none"> Evaluation with real users [P2, P4, P16, P24, P32, P39, P50] Real-world deployment and short term use [P10, P15, P24, P32, P34] Real-world deployment and long term use [P4, P16, P38, P42] 	12

complexity. In terms of having better layouts, the authors of [P28] propose a top-level layout approach to perform incremental layout algorithms. This approach allows them to import and display large attack graphs in seconds which previously could take several hours to load. In [P14], they use the client-server layout in Gephi for reducing the complexity of bipartite graphs. In [P25] aggregated alert events are presented using multiple coordinated views with timeline, cluster, and swarm model analysis displays. The framework aims to improve situational awareness and to enable an analyst to quickly navigate and analyze thousands of detected events, and also be able to combine sophisticated data analysis techniques with interactive visualization for ease of maneuvering through complex information. Researchers in [P4] propose several views to present different types of information. These views include overviews that allow users to scan information within seconds and other views to conduct detailed analysis if needed. Several primary papers discuss the importance of focusing on aesthetics to reduce visual complexity. Researchers in [P8] discuss selecting icons/symbols in the visualizations that relate more to the users' day-to-day business. They claim that will allow users to easily understand and interpret information that is visualized. Another paper [P11] discusses using dark background so that users can visualize things unobtrusively in a 3D environment.

4) Facility to share information

Complete CSA is implausible to achieve by only considering interactions between an individual analyst/decision maker and their technology [16], [38]. Achieving complete SA requires diverse stakeholders to collaborate and share information with each other. Often each stakeholder will have different and sometimes overlapping perspectives on the situation. It is likely that two or more such perspectives will need to be combined to obtain complete SA. Unfortunately, there is a lack of technologies conducive to humans collaborating, effectively communicating, and sharing information and knowledge with each other in the context of CSA. A limited number of our primary papers have reported practices that enable visualization data to be shared with others. For example, researchers in [P4] have introduced watchlists in their visualizations for managing suspicious IP addresses lists that can be shared with analysts. In [P3], the researchers propose a mind mapping tool that allows analysts to directly interact with each other and review past analysis, share their findings and divide tasks in a timely manner.

5) Flexibility to handle differences and issues in data

As explained in Section IV-G, key challenges with respect to CSA visualizations include handling differences in data formats and standards, and dealing with uncertain and erroneous data. A limited number of primary papers in this SLR report practices to handle these differences and issues in data. For example, researchers in [P7] explain that previous graph-based tools that focus on specific analytic use cases against fixed data models and proposes schema-free data model so

that the model is decoupled from the storage implementation. The proposed approach applies data transformations that map elements of the source data to nodes, edges, and their properties rather than relying on a fixed schema for the data sources. Researchers in [P2] propose a method to deal with possible missing or inaccurate information in alert messages. Their algorithms consider two different matches: i) approximate matches and ii) exact matches. The exact match allows taking into account possible inaccurate or wrong information which includes but is not limited to a missing source IP address in the alert and a mismatch in the CVE due to different classifications used by the underline IDS.

6) User driven requirements

A clear understanding of user needs is an essential part of software design and could be considered one of the deciding factors of the success of systems [39]. However, we only observed 18.5% of the primary papers have consulted industrial partners or real users when designing CSA visualizations. For example, researchers in [P24], conduct a series of brainstorming and interviews with analysts, network managers, security researchers, and visualization researchers before coming up with visualization mock-ups to facilitate immediate high-level SA. Furthermore, researchers in [P12] visit and observe four Security Operations Centers (SOC) of their industrial partners understand cyber security collaborative practices before designing a collaborative 3D Cyber Common Operating picture Platform.

7) Real world evaluations

The software engineering research community had emphasized the criticality of rigorous evaluation to assess the appropriateness of the proposed solutions [37]. However, as detailed in Section IV-F, among the selected studies, there is a lack of rigorous evaluation that utilizes more mature methods such as real world deployments and case studies with real users. Our findings clearly demonstrate that most primary papers do not involve real users in their evaluations. Only a few papers looked into conducting case studies or deploying the proposed visualization systems in the real world to understand how the users perceive those systems in practice.

V. DISCUSSION

There is an increasing realization that cyber security visualizations can enable significant progress towards achieving the goal of CSA. Throughout this review, we have identified, categorized, and discussed the knowledge related to CSA visualizations in various dimensions. Such a body of knowledge can help understand their nature and potential areas of application, and identify the areas of future research direction. In this section, we first discuss the key findings from this SLR and the potential future research and development opportunities in the CSA visualization domain based on the identified key limitations and gaps. Next we also discuss threats to validity for this SLR.

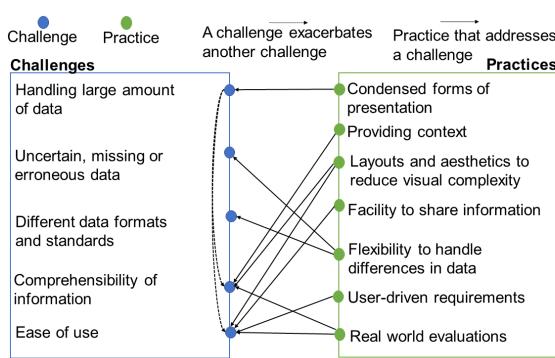


FIGURE 20. Mapping of challenges to practices.

A. MAPPING OF CHALLENGES TO PRACTICES

Figure 20 presents a mapping of the identified challenges in Section IV-G onto the practices reported in Section IV-H. The mapping provided in Figure 20 is intended to provide readers with a quick way to determine which challenges are related to which practices. For example, driving CSA visualization designs based on user needs and preferences, focusing on better layouts and aesthetics to reduce visual complexity, and providing the ability for users to share visualized information easily allows users could allow CSA visualization to be easy to use. Furthermore, conducting real-world evaluations will ultimately provide evidence of whether the designed and developed CSA visualizations are easy to use in practice. Figure 20 also indicates that there might be dependencies among the challenges. For example, large amounts of cyber security data could create difficulties for users to use the CSA visualizations and comprehend information presented through CSA visualizations.

B. NEED TO LOOK BEYOND OPERATIONAL LEVEL STAFF

As identified in Section IV-C, visualizations focusing on CSA are mainly designed to facilitate operational level decision makers. From an organizational perspective, there is a clear lack of scientific research that presents information for managers and higher-level decision makers. Usually, managers and higher-level decision makers are tasked with overseeing the operations and activities of an organization and making strategic decisions that can influence the future of the organization. However, they may not have the cyber expertise and hence may have to rely on domain experts to interpret the cyber security status of the organizations, causing delays in the decision making process. To be best placed to make cyber security decisions effectively and efficiently, executives should have access to information on the entire organization's potential risks, opportunities, and challenges in a format that is easy to digest and translate to the business dimensions. Hence future research could be conducted to specifically target the design of CSA visualizations for managers and higher-level decision makers. A better understanding of their information needs and visualization preferences

will facilitate the development of effective visualizations for this cohort.

Additionally, future studies can invest effort in developing fully customizable Common Operating Pictures to facilitate cyber security decision making [16]. Such platforms can provide all levels of staff a common view of cyberspace to facilitate collective decision making. Among our set of selected primary papers, we found only a few papers [P5, P8, P12, P20] that explicitly claim to focus on Common Operating Pictures. These studies are still in their infancy and not able to provide the true power of Cyber Common Operating Pictures. These systems further lack fully customizable dashboards that would allow organizations to adapt the information that they want to visualize and tailor to a particular audience.

Outside the organizational context, there are opportunities to design visualizations for CSA focusing on non-expert users. The internet now plays a significant role in many aspects of both our work lives and our personal lives and even revolutionized how society interacts today. With the ever-increasing security threats online and lack of cyber security awareness of non-expert users that act in cyberspace, there is a serious need for researchers to design more visualizations to promote personal cyber situation awareness thereby allowing them to be proactive about their own personal safety when acting online.

C. FACILITATING USERS TO UNDERSTAND THE CONTEXT

As discussed in Section II-A and Section IV-E, understanding what is happening in the cyber environment is only the first level of CSA (i.e. *perception*). Ability to comprehend/interpret the current cyber situation is crucial to move beyond *perception* level and reach *comprehension* level. Our results clearly show that most studies provide visualizations to facilitate *perception* level (92.6%) compared to *comprehension* level (53.7%). Challenges in comprehending the information visualized are also reported by several studies in the SLR (see Section IV-G). Not having the ability to understand the data and its relationships could lead to poor interpretation of the displayed information, and hence could reduce the power of visualizations. Understanding the context allows users to move from just being aware of the situation to comprehending its meaning. Section IV-F provided several examples of how studies in this SLR facilitate the comprehension of the cyber situation by providing additional information about its context. Therefore, we assert that future research should consider ways of providing the context of what is being visualized and why it is happening as a crucial aspect of CSA visualizations.

D. NEED TO FACILITATE PROJECTION

As discussed in Section II-A and Section IV-E, CSA is not only about being aware of the current situation, comprehending its meaning and implications, but also about the ability in identifying the future state of threats and/or possible future

actions; that is the *projection* level according to Endsley's SA model. However, our results presented in Section IV-E revealed that only 10 studies (18.5%) actually provide visualizations to support *projection* level. These studies either focus on future threat states or response plans. On the other hand, most of the studies discussed in this SLR, provide information about the current cyber situation allowing the user to reach *perception* or *comprehension* level, but omit the process of identifying future threat landscape or response plans to users. We emphasize the need for a gradual but inevitable transition of visualization approaches towards facilitating *projection* level to achieve comprehensive CSA. Providing adequate information for users to understand the future cyber state and possible actions requires complex data analysis approaches, which may stem from AI and ML techniques.

E. CONTEXT-AWARE AND ADAPTIVE CSA VISUALIZATIONS

The ultimate goal of CSA visualizations should be to get the right information to the right person, at the right time, in the right way to facilitate swift decision making. The sheer volume of cyber security data could lead to over-crowding of displays decreasing the power of visualizations and thereby decreasing the capacity for a human to identify key information, trends, and patterns of data. As explained before, condensed/summarised forms of information visualizations and powerful user interactions could allow a user to find and navigate to the appropriate level of detail. However, this approach places control on the user to identify and navigate to where they need to focus on making decisions. Manual navigation to the required information could be seen as a laborious, error-prone process that could create a cognitive overload on users. Therefore, we argue that future research should focus more on visualizations that are capable of automatically adapting the information and visualization technique based on the context, user needs, and task at hand. Only a few papers [P18, P41, P49] in this SLR discussed this concept; hence we believe there is a clear gap in this area and argue that this research area (i.e., adaptive and context-aware visualization) should be investigated further in the future.

F. USER-CENTERED DESIGNS

Although CSA visualization has attracted the attention of researchers over the years, its adoption to real-world applications has been challenged due to system complexity, which requires a substantial amount of testing and evaluation before real-world deployment. Our results revealed that only five studies (9.3%) provided evidence for visualization methods to be adopted in the real world (see Section IV-F), and only four studies (7.4%) claimed that their solution had been used in production use (see Section IV-H). Many of the papers (59.3%) demonstrate the capabilities of their CSA visualizations through demonstrations with the toy or simulated data sets. To prove the capability and effectiveness of visualization systems to assist users to achieve CSA, it must undergo a

thorough evaluation process before real-world deployment. However, when closely analyzing our results, we can see that only 15 studies (27.8%) provide some forms of evidence for human evaluation of the proposed visualizations after the design is completed.

We assert that user-centered design should be an intrinsic part of the design philosophy of CSA visualizations. Traditional practices of user-centered design incorporate a clear understanding of users' needs, wants, and limitations throughout the design process, which helps in evaluating the effectiveness of the proposed systems or tools. Therefore, we emphasize that first understanding users' CSA needs, and then iteratively improving the visualizations based on their feedback is crucial to implement visualization that is usable and effective. However, only 10 studies (18.5%) in this SLR have attempted to understand the requirements from users for CSA visualizations. Only one study [P30] discusses iterative user involvement throughout the process including brainstorming, design, and evaluation. We believe the availability and cost of experts could also create challenges for user-centered design approaches in the CSA visualization domain. Therefore, we assert that adopting user-centered design approaches within the cyber security visualization domain requires methods that are not only effective but also efficient.

G. FACILITATING COLLABORATION AND INFORMATION SHARING

Achieving complete SA requires members of different teams and different organizational positions, working across different work shifts to collaborate and share information with each other [38], [40], [41]. Lack of ability to collaborate and share information within the organization could limit the ability of organizations to take full advantage of their staff's expertise and the relationships for the management of vulnerabilities, threats, and incidents, as well as other cyber security activities.

We only found a limited number of papers in this SLR that provided some form of support for collaboration and information sharing. In terms of collaboration, researchers in [P3] propose a direct approach where analysts can request other analysts to join their investigation into potential attacks. They aim to have an effective real-time response to a potential cyber threat, by allowing cyber security analysts to work in teams, quickly exchanging their findings and dividing tasks among each other. The work reported in [P12] encourages collaboration through transparency, where other users of the system can view the task others are performing. We observed that four studies (7.4%) in this SLR provide means to share information with others using the *extract/share* user interaction (see Section IV-D3b). Using this user interaction, users are able to share information with both internal and external partners. Furthermore, only six studies facilitate visualizations of shared information (see Section IV-D1). In essence, although collaboration and information sharing could significantly improve CSA [38], [40], it has been often

overlooked as indicated by the related low number of studies in our SLR. Therefore, to improve CSA, visualization designers should consider collaboration and information aspects further. It is important to note collaboration and information sharing should be considered not only within the organization but also across organizations.

H. DATA SOURCE AGNOSTIC VISUALIZATIONS

Section IV-D2, revealed that various data sources are employed in CSA visualizations. Based on the results, *Asset identification and management systems* as a data source are predominantly used in the selected set of papers (44.4%). More importantly, our results demonstrate that multiple data sources are fused together in CSA visualizations. For example, data obtained from *Asset identification and management systems* are often used with other data sources together to identify the network status or threats to the assets. In Section IV-G, several papers have reported that dealing with diverse data sources is a challenge in CSA visualizations. These findings suggest that future CSA visualizations should give careful consideration to heterogeneous data types which need to be conveniently stored and prepared for analysis [10]. In this context, we emphasize that it is important to follow the principles and best practices of scalable big-data systems to store and analyze such heterogeneous data for building effective CSA visualizations.

I. THREATS TO VALIDITY

We strictly followed the guidelines provided by [24], however, we had similarities to other SLRs in terms of validity threats, which we will discuss below.

Missing primary studies: Most of the SLRs face the limitation of missing primary studies. This is mainly due to limitations in the search method and non-comprehensive venues. To minimize the effects of this issue we used a number of strategies. We used Scopus as our search engine. Scopus is the largest indexing system leading to the most comprehensive search results among other digital libraries [42], allowing us to expand the coverage of relevant studies. Furthermore, our search string was carefully identified. When constructing the search terms we consulted the search strings used in the existing SLRs [5]. We iteratively improved the search string based on the pilot searches by making sure all known papers can be captured through the search string. All authors carefully checked the search string before executing the search. Furthermore, although we did not impose any restrictions on the publication date of the papers, we acknowledge that the studies added to the database after the search date (*i.e.*, February 2021) are not considered in the review which is an inevitable limitation in SLR studies [43].

Bias in study selection: Studies can be selected based on the subjective judgments of researchers regarding whether or not they meet the selection criteria. To address this issue, we strictly followed the predefined review protocol, recording the exclusion reasons for all excluded papers. A pilot set of selected studies was shared with all the authors to make sure

all authors agree with the inclusion and exclusion criteria. The first three authors largely conducted the study selection and had ongoing internal discussions about the papers that raised doubts about their inclusion or exclusion decisions; whenever a decision couldn't be made, the remaining authors were consulted.

Bias in data extraction and analysis: To reduce the bias in the data extraction, we first created a data extraction form (see Table 3) to consistently extract and analyze the data for answering the RQs of this SLR. Then, the first three authors conducted a data extraction pilot with a subset of papers. Any differences in the data extraction were discussed and resolved; where necessary, the remaining authors were consulted. After that, the set of papers were divided and the first three authors extracted data separately. To analyze the extracted data both quantitative and qualitative methods were applied. It should be noted that we did not have any interpretation unless the data items were explicitly provided by the study. It should be noted that occasionally it was difficult to interpret the extracted data because of a lack of sufficient information about the data items. Consequently, in certain cases, interpretation and analysis of the data were subjective, which might have influenced the results of the data extraction.

VI. CONCLUSION

With cyber-attacks becoming ever more sophisticated and creating potentially disruptive impacts, cyber security visualizations are more necessary than ever. We present in this paper the details of the design, the execution, and the results of a systematic review of CSA visualizations. We selected 54 papers published up to February 2021 for data extraction, analysis, and synthesis based on predefined inclusion and exclusion criteria. The systematic and detailed analysis of the extracted data from these papers has enabled us to reach the following conclusions:

- Based on the results presented in Table 4, we can clearly see that most papers fail to critically examine the researcher's own bias and influence on the study (59.3%), or discuss the limitations of the study explicitly (72.2%). Discussion on the researcher's own bias and influence on the study and limitations of the study could increase the credibility of the reported findings as well as provide insights for future research. Therefore, we encourage future researchers in this domain to pay more attention to these.
- We observed several stakeholders who use and benefit from CSA visualizations (see Section IV-C). However, our results clearly show that most papers (64.8%) provide visualizations for operational-level staff such as network analysts, risk analysts, and security analysts. There is a clear lack of research that looks at other types of stakeholders such as managers and higher-level decision makers and (general) non-expert users.
- Our results revealed diverse types of information visualized through the CSA visualizations. The most common

- types of information visualized are the *Threat information* (55.6%). However, we observed that there is a lack of attention given to visualizing impact information, response planned, and information shared within teams.
- There were only 15 studies (27.8%) that provide evidence for some form of user evaluations of the proposed visualization after the design is complete. As explained in Section IV-F, most studies either do not provide any evidence or only provide demonstrations/toy examples as evidence of the proposed visualizations. Lack of rigorous evaluation could be the main reason for the limited number of studies (7.4%) that provide evidence for industrial practice.
 - We categorized that the visualizations of the selected papers under nine visualization techniques. From the results, presented in Section IV-D3a, it is clear that there is increase in popularity for *iconic displays* and *geometrically transformed displays*. Other visualizations are less employed in the selected set of papers. *Iconic displays* is an interesting way to encode information while increasing the hedonic quality of the visualizations. *Geometrically transformed displays* allow users to understand complex, multi-dimensional cyber data through interesting transformations. It was also clear that many visualizations, combine multiple visualization techniques together, often by superimposing them, to provide more information in a condensed manner. However, more user evaluations are needed to comment on their effectiveness.
 - The power of visualization can be enhanced through user interactions. However, we noticed that a significant number of papers (16 papers, 29.6%) did not discuss user interactions. As explained in Section IV-D3a we are unsure whether this is because authors do not highlight these features or visualizations actually do not have user interactions. Furthermore, we noticed that while user interactions like *zooming*, *filtering* and *details on demand* have got much attention, other user interactions have got less attention. For example, *extract/share* and *move/rotate* were found only in four papers and *linking/brushing* was only found in one study. Therefore, we conclude that user interactions should be given more prominence in future CSA visualizations.
 - The findings from this review also enable us to conclude that the majority of the visualizations in the selected set of papers only facilitated up to *perception* level (92.6%). Less number of studies facilitated *comprehension* level (53.7%) and *projection* level (18.5%). Without the ability for *comprehension* and *projection*, holistic CSA cannot be achieved. Therefore, as explained in Section V, it is important that future researchers and practitioners in the CSA visualization community focus more on these two CSA levels.
 - Finally, the mapping of challenges with practices will be beneficial for researchers and CSA designers to easily understand what practices exist for facilitating each

challenge reported for CSA visualizations.

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APPENDIX A SELECTED PRIMARY STUDIES

ID	Title	Author(s)	Venue	Year
P1	What makes for effective visualization in cyber situational awareness for non-expert users?	Carroll F., Chakof A., Legg P.	International Conference on Cyber Situational Awareness	2019
P2	MAD: A visual analytics solution for Multi-step cyber Attacks Detection	Angelini M., Bonomi S., Lenti S., Santucci G., Taggi S.	Journal of Computer Languages	2019
P3	AOH-Map: A Mind Mapping System for Supporting Collaborative Cyber Security Analysis	Zhong C., Alnusair A., Sayger B., Troxell A., Yao J.	IEEE Conference on Cognitive and Computational Aspects of Situation Management	2019
P4	Situ: Identifying and explaining suspicious behavior in networks	Goodall J.R., Ragan E.D., Steed C.A., Reed J.W., Richardson G.D., Huffer K.M.T., Bridges R.A., Laska J.A.	IEEE Transactions on Visualization and Computer Graphics	2019
P5	Cyber kill chain based threat taxonomy and its application on cyber common operational picture	Clio S., Han I., Jeong H., Kim J., Koo S., Oh H., Park M.	International Conference on Cyber Situational Awareness	2018
P6	Combining real-time risk visualization and anomaly detection	Väistänen T., Noponen S., Latvala O.-M., Kuusijärvi J.	ACM International Conference Proceeding Series	2018
P7	Mission-focused cyber situational understanding via graph analytics	Noel S., Rowe P.D., Purdy S., Limiero M., Lu T., Mathews W.	International Conference on Cyber Conflict	2018
P8	A comparative analysis of visualization techniques to achieve cyber situational awareness in the military	Llopis S., Hingant J., Perez I., Esteve M., Carvajal F., Mees W., Debatty T.	International Conference on Military Communications and Information Systems	2018
P9	Comparative analysis and patch optimization using the cyber security analytics framework	Abraham S., Nair S.	Journal of Defense Modeling and Simulation	2018
P10	Blue Team Communication and Reporting for Enhancing Situational Awareness from White Team Perspective in Cyber Security Exercises	Kokkonen T., Puuska S.	Conference on Internet of Things and Smart Spaces	2018
P11	Enhancing cyber defense situational awareness using 3D visualizations	Kullman K., Cowley J., Ben-Asher N.	International Conference on Cyber Warfare and Security	2018
P12	From Cyber Security Activities to Collaborative Virtual Environments Practices Through the 3D CyberCOP Platform	Kabil A., Duval T., Cuppens N., Le Comte G., Halgand Y., Ponchel C.	International Conference on Information Systems Security	2018
P13	Cyber situational awareness: from geographical alerts to high-level management	Angelini M., Santucci G.	Journal of Visualization	2017
P14	Deriving cyber use cases from graph projections of cyber data represented as bipartite graphs	Eslami M., Zheng G., Eramian H., Levchuk G.	IEEE International Conference on Big Data	2017
P15	A Study into Detecting Anomalous Behaviours within Health-Care Infrastructures	Boddy A., Hurst W., Mackay M., El Rhalibi A.	International Conference on Developments in eSystems Engineering	2017
P16	OwlSight: Platform for real-time detection and visualization of cyber threats	Carvalho V.S., Polidoro M.J., Magalhaes J.P.	IEEE International Conference on Big Data Security on Cloud	2016
P17	An expert system for facilitating an institutional risk profile definition for cyber situational awareness	Graf R., Gordea S., Ryan H.M., Houzanne T.	ICISSP 2016 - International Conference on Information Systems Security and Privacy	2016
P18	Adaptive visualization of complex networks with focalpoint: A context aware level of details recommender system	Inibhunu C., Langevin S.	Proceedings of the Human Factors and Ergonomics Society	2016
P19	Web-Based Smart Grid Network Analytics Framework	Pietrowicz S., Falchuk B., Kolarov A., Naidu A.	IEEE International Conference on Information Reuse and Integration	2015
P20	Configurable IP-space maps for large-scale, multi-source network data visual analysis and correlation	Miserendino S., Maynard C., Freeman W.	Proceedings of SPIE - The International Society for Optical Engineering	2014
P21	Visualization of security metrics for cyber situation awareness	Kotenko I., Novikova E.	International Conference on Availability, Reliability and Security	2014
P22	CyberVis: Visualizing the potential impact of cyber attacks on the wider enterprise	Creese S., Goldsmith M., Moffat N., Happa J., Agrafiotis I.	IEEE International Conference on Technologies for Homeland Security	2013

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P23	CyberSAVe - Situational awareness visualization for cyber security of smart grid systems	Matuszak W.J., DiPippo L., Sun Y.L.	ACM International Conference Proceeding Series	2013
P24	Visualization design for immediate high-level situational assessment	Erbacher R.F.	ACM International Conference Proceeding Series	2012
P25	Visualization techniques for computer network defense	Beaver J.M., Steed C.A., Patton R.M., Cui X., Schultz M.	Proceedings of SPIE - The International Society for Optical Engineering	2011
P26	EMBER: A global perspective on extreme malicious behavior	Yu T., Lippmann R., Riordan J., Boyer S.	ACM International Conference Proceeding Series	2010
P27	Intrusion monitoring in process control systems	Valdes A., Cheung S.	Annual Hawaii International Conference on System Sciences	2009
P28	A graph-theoretic visualization approach to network risk analysis	O'Hare S., Noel S., Prole K.	International Workshop on Visualization for Computer Security	2008
P29	Cyberspace situation representation based on Niche Theory	Zhuo Y., Zhang Q., Gong Z.	IEEE International Conference on Information and Automation	2008
P30	Putting security in context: Visual correlation of network activity with real-world information	Pike W.A., Scherrer C., Zabriskie S.	Proceedings of the Workshop on Visualization for Computer Security	2008
P31	Visualizing cascading failures in critical cyber infrastructures	Kopylec J., D'Amico A., Goodall J.	IFIP Advances in Information and Communication Technology	2008
P32	A visualization paradigm for network intrusion detection	Livnat Y., Agutter J., Moon S., Erbacher R.F., Foresti S.	Annual IEEE System, Man and Cybernetics Information Assurance Workshop	2005
P33	Visualization as an aid for assessing the mission impact of information security breaches	D'Amico A., Salas S.	Information Survivability Conference and Exposition	2003
P34	ML-based data anomaly mitigation and cyber-power transmission resiliency analysis	Anshuman Z.N., Sajan K.S., Srivastava A.K.	IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids	2020
P35	A novel architecture for attack-resilient wide-area protection and control system in smart grid	Singh V.K., Govindarasu M.	Resilience Week	2020
P36	Understanding and Enabling Tactical Situational Awareness in a Security Operations Center	Mullins R., Nargi B., Fouse A.	Advances in Intelligent Systems and Computing	2020
P37	A Dynamic Visualization Platform for Operational Maritime Cybersecurity	Zhao H., Silverajan B.	International Conference on Cooperative Design, Visualization and Engineering	2020
P38	Insight2: A modular visual analysis platform for network situational awareness in large-scale networks	Kodituwakku H.A.D.E., Keller A., Gregor J.	Electronics (Switzerland)	2020
P39	Alert characterization by non-expert users in a cybersecurity virtual environment: A usability study	Kabil A., Duval T., Cuppens N.	International Conference on Augmented Reality, Virtual Reality and Computer Graphics	2020
P40	Operator impressions of 3d visualizations for cybersecurity analysts	Kullman K., Asher N.B., Sample C.	European Conference on Information Warfare and Security	2019
P41	A Tri-Modular Human-on-the-Loop Framework for Intelligent Smart Grid Cyber-Attack Visualization	Sundararajan A., Khan T., Abu-rub H., Sarwat A.I., Rahman S.	Conference Proceedings - IEEE SOUTHEASTCON	2018
P42	DiPot: A distributed industrial honeypot system	Cao J., Li W., Li J., Li B.	International Conference on Smart Computing and Communication	2018
P43	Dagger: Modeling and visualization for mission impact situation awareness	Peterson E.	IEEE Military Communications Conference	2016
P44	Enhancing cyber situation awareness for Non-Expert Users using visual analytics	Legg P.A.	International Conference on Cyber Situational Awareness, Data Analytics and Assessment	2016
P45	Results and lessons learned from a user study of display effectiveness with experienced cyber security network analysts	Garneau C.J., Erbacher R.F., Etoty R.E., Hutchinson S.E.	Learning from Authoritative Security Experiment Results	2016

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P46	Visual analytics for cyber red teaming	Yuen J., Turnbull B., Hernandez J.	IEEE Symposium on Visualization for Cyber Security	2015
P47	Ensemble visualization for cyber situation awareness of network security data	Hao L., Healey C.G., Hutchinson S.E.	IEEE Symposium on Visualization for Cyber Security	2015
P48	Towards an integrated defense system for cyber security situation awareness experiment	Zhang H., Wei S., Ge L., Shen D., Yu W., Blasch E.P., Pham K.D., Chen G.	The International Society for Optical Engineering	2015
P49	Visual structures for seeing cyber policy strategies	Stoll J., Bengez R.Z.	International Conference on Cyber Conflict	2015
P50	VAFLE: Visual analytics of firewall log events	Ghoniem M., Shurkhovetskyy G., Bahey A., Ojjacques B.	The International Society for Optical Engineering	2014
P51	Capturing human cognition in cyber-security simulations with NETS	Giacobe N.A., McNeese M.D., Mancuso V.F., Minotra D.	IEEE International Conference on Intelligence and Security Informatics: Big Data, Emergent Threats, and Decision-Making in Security Informatics	2013
P52	On detection and visualization techniques for cyber security situation awareness	Yu W., Wei S., Shen D., Blowers M., Blasch E.P., Pham K.D., Chen G., Zhang H., Lu C.	The International Society for Optical Engineering	2013
P53	Visualization for cyber security command and control	Langton J.T., Newey B., Havig P.R.	The International Society for Optical Engineering	2010
P54	ViSAw: Visualizing threat and impact assessment for enhanced situation awareness	Nusinov M., Yang S.J., Holsopple J.	IEEE Military Communications Conference	2009



LIUYUE JIANG received the M.S. degree in computer science from School of Computer Science, The University of Adelaide, Australia, in 2019, where he is currently pursuing the Ph.D. degree with Centre for Research on Engineering Software Technologies (CREST), and he is funded by the Cyber Security Cooperative Research Centre (CSCRC).



MARTHIE GROBLER is passionate about making cyber security more accessible. Her research focus is on human centric cyber security, enhancing usability of security solutions by considering human factors. She spearheaded the establishment of a new human centric security research team, which is focused on addressing the alignment and integration of human factors in the cyber domain to enhance security adoption and efficiency. Her expertise falls within a very niche area of cyber security, the intersection between cyber security, usable security and human computer interaction. Marthie has a strong focus on improving cyber security across user groups, considering traditional usability metrics, governance and policies, as well as cyber security maturity and resilience. Her main developments are in the domains of cyber risk and governance, and cyber education and digital upskilling. She obtained her PhD in Computer Science (specialising in Digital Forensic Governance) at the University Johannesburg, South Africa and served several years as Professor of Practice at the University Johannesburg's Faculty of Science. She is an ISACA Certified Information Security Manager (CISM). Marthie currently holds a position as Team Leader: Human Centric Security at CSIRO's Data61 in Melbourne, Australia.



ASANGI JAYATILAKA is a post-doctoral researcher at the Centre for Research on Software Technologies (CREST) at the University of Adelaide (UoA). She received her PhD from the School of Computer Science at UoA. She is passionate about research on human factors in computing. This includes studying the effects of different human factors on technology development, whether and/or to what extent these effects of human factors are accounted for and how we can

best use these to build better tools and technologies that are both usable and effective. She has extensive experience in both qualitative and quantitative research methods. Her work has led to design, implementation and evaluation of technologies and tools in various domains including including cyber security, digital health, and pervasive computing.



MEHWISH NASIM is a lecturer in Computing and Mathematical Sciences at the College of Science and Engineering at Flinders University. She is also an adjunct lecturer at the University of Adelaide, an associate investigator with ARC Centre of Excellence for Mathematical and Statistical Frontiers, and a visiting scientist at CSIRO, Australia. She is a member of the Australian Mathematics Society and Women in Maths Special Interest Group. She did her Ph.D. in Computer Science from University of Konstanz, Germany. Her research lies at the intersection of applied mathematics and social psychology. She is particularly interested in network science, understanding grey-zone tactics, combating online misinformation, serious games, and decision making in the context of cyber security. She is working on AI-enabled situational understanding models for combating misinformation, using graph-theoretic knowledge-based constructs, coupled with natural language processing techniques and social psychology. Her work has led to the design of agent-based network simulation models that can be deployed in modern wargames which can be used by defence and the government for training decision-makers to combat online misinformation during crisis.



MANSOOREH ZAHEDI is a lecturer in Software Engineering (SE) at the School of Computing and Information Systems, the University of Melbourne. She has received her PhD from School of Software and Systems at IT University of Copenhagen, Denmark. Her research is stimulated by the challenges involved in continuously evolving Software Engineering processes and practices to enable organisations developing high-quality software intensive systems. Her primary research goal is to apply empirical research methods and tools to investigate the role of people, processes, and technologies in different software development paradigms. Her key research interests are human aspects in software engineering, socio-technical aspects of cyber security and continuous software engineering. She has conducted extensive field studies with different companies internationally and published empirically grounded findings. Her work has been published in several high-ranking software engineering venues e.g., EMSE, FSE, JSS, IST, ESEM, EASE. She has served the research community extensively in different capacities, e.g., workshop chair of Evaluation and Assessment in Software Engineering (EASE 2021), Short-papers chair of (EASE 2020), workshop co-chair of international conference on Agile Software Development (XP 2020), poster co-chair of international conference on Model Driven Languages and Systems (MODELS 18, 19), judge at SRC competition (ICSE 2020) and Social activities co-chair of Requirements Engineering conference (RE 2022).



M. ALI BABAR is currently a Professor with School of Computer Science, The University of Adelaide. He is an Honorary Visiting Professor with the Software Institute, Nanjing University, China. He is also the Director of Cyber Security Adelaide (CSA), which incorporates a node of recently approved the Cyber Security Cooperative Research Centre (CSCRC), whose estimated budget is around AU\$140 Millions over seven years with AU\$50 Millions provided by the Australia Government. In the area of software engineering education, he led the University's effort to redevelop a Bachelor of Engineering (software) degree that has been accredited by the Australian Computer Society and the Engineers Australia (ACS/EA). Prior to joining The University of Adelaide, he spent almost seven years in Europe (Ireland, Denmark, and U.K.) as a Senior Researcher and an Academic. Before returning to Australia, he was a Reader of software engineering with Lancaster University. He has established an Interdisciplinary Research Centre, Centre for Research on Engineering Software Technologies (CREST), where he leads the research and research training of more than 30 (20 Ph.D. students) members. Apart from his work having industrial relevance as evidenced by several research and development projects and setting up a number of collaborations in Australia and Europe with industry and government agencies, his publications have been highly cited within the discipline of software engineering as evidenced by his H-index is 52 with 11045 citations as per Google Scholar on December 16, 2021. He leads the theme on Platform and Architecture for Cyber Security as a Service with the CSCRC. He has authored/coauthored more than 220 peer-reviewed publications through premier software technology journals and conferences.

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