Digitalisation-based Situation Awareness for Construction Safety Management – A Critical Review

Zhe Zhang[a], Brian H.W. Guo[a], Alice Chang-Richards[b], Ruoyu Jin[c], Yu Han[d]

[a]Department of Civil & Natural Resources Engineering, University of Canterbury, New Zealand
[b]Department of Civil and Environmental Engineering, University of Auckland, New Zealand
[c]School of Built Environment and Architecture, London South Bank University, UK
[d]Faculty of Civil Engineering and Mechanics, Jiangsu University, China
E-mail: zhe.zhang@pg.canterbury.ac.nz, brian.guo@canterbury.ac.nz, yan.chang@auckland.ac.nz, jinr@lsbu.ac.uk, hanyu85@yeah.net

Abstract

Construction sites are complex and dynamic, and this tends to increase the cognitive loads for construction workers. Developing and maintaining an adequate level of situation awareness (SA) at different levels (e.g., workers, supervisors, and project managers) is essential to improve the individuals' capability of managing site safety. Despite the fact that there have been studies that applied SA to construction safety, SA is still an under-researched concept in construction safety. It remains unclear how SA impacts safety behaviours, site safety management processes, and accident prevention strategies. To fill the research gaps, a critical literature review is conducted to: (1) identify and analyse current studies that integrate the concept of SA for managing construction safety, (2) investigate the conceptual linkages between SA, DT, and construction safety, and (3) recommend future research directions towards building a digitalised situation-aware construction safety management system. A five-step systematic review method was adopted, including literature search, selection, coding, data analysis, and discussion. Previous research on (1) elements of SA related to construction safety, (2) SA measurement, (3) digital technologies for SA, (4) SA and safety behaviour and hazard identification was reviewed and summarised. This paper recommends four specific future research directions to advance the research on SA for managing construction safety. Apposite utilization of the findings can assist digitalization revolution on construction safety management for both research and practice.

Keywords –

Construction safety; Digital technology (DT); Situation awareness (SA)

1 Introduction

The construction sites are highly hazardous, due to the dynamic and complex nature of the construction activities. The construction industry has been suffering from a high injury rate at the global level. For example, from 2011 to 2017, the New Zealand construction industry has seen yearly increasing work-related injuries, ranging from 26,394 to 37,659 [1].

Over the past decade, the construction industry has started using digital technology (DT) in managing various aspects of project management. There has been increased research interest in applying DT for managing construction safety in this ongoing shift towards digitalisation. For example, Guo et al. [2] reviewed DT for construction safety and discussed the conceptual linkages between safety planning, real-time hazard management, and safety knowledge engineering.

Given the fact that construction sites are complex and dynamic, and this tends to increase the cognitive loads for construction workers [3, 4] and create information gaps between individuals (e.g., frontline workers, supervisors, and managers) and site conditions [5, 6]. As a result, workers are often unaware of new hazards that emerge from interactions among activities and thus unable to predict possible hazardous scenarios, which are often beyond their cognitive capacity and boundary. Traditional construction safety practices focus mainly on pre-activity safety planning and are ineffective in bridging the information and awareness gaps caused by the site dynamics. Developing and maintaining an adequate level of situation awareness (SA) at different levels (e.g., workers, supervisors, and project managers) is essential to improve the individuals' capability of managing site safety.

SA was defined as "the perception of the elements 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" [7]. It is a multi-dimensional concept that first originated from the military aviation domain during the First World War. Endsley proposed a model of SA, which defines SA at three ascending levels: perception, comprehension, and projection [7]. Since then, the concept has received attention from researchers in different domains, such as engineering [8], computer science [9], psychology [10], and military [11].

Many researchers have applied the concept of SA to enhance the understanding of safety awareness and behaviours [12-14]. Despite these efforts, SA is still an under-researched concept in construction safety. It seems that SA is an important concept that has shown the potential to conceptually link DT and safety management and science. However, it remains unclear that how SA impacts safety behaviours, site safety management processes, and accident prevention strategies. Therefore, more research is needed to investigate the fundamental linkages to site safety.

To fill the research gaps, a critical literature review is conducted to: (1) identify and analyse current studies that integrate the concept of SA for managing construction safety, (2) investigate the conceptual linkages between SA, DT, and construction safety, and (3) recommend future research directions towards building a digitalised situation-aware construction safety management system.

2 Methodology

The study adopted the systematic review method. The method consists of five main steps: literature search, selection, coding, data analysis, and discussion. Scopus was selected for literature search due to its comprehensive coverage of relevant peer-refereed academic papers. The search keywords and terms are presented in Table 1.

The 1st, 2nd, and 3rd rounds of search identified 71, 64, and 14 papers, respectively. Only articles, book chapters, and conference papers were kept for data analysis during the screening and selection stage. In addition, papers that are irrelevant to the construction industry were excluded. Duplicate articles that were identified in the three rounds of the search were also excluded. As a result, a total of 74 papers were kept for further analysis.

The authors, title, year, country or region (country of the first author's unit), cited by, industry, SA aspect, technology used, equipment, SA measurement methods, statistical analyses method used, and statistical analyses indicator were coded, the coding results are presented in Table 2, Table 3, Table 4, and Table 5. The emphasis was placed on the elements, measurement of SA for construction safety, the relationships between SA, construction safety, and DT.

Table 1. Search keywords and terms

Round of search	Keywords
1st	"situation awareness" AND "construction" AND "safety" OR "hazard" OR "accident" OR "risk" OR "health"
2nd	(("situation awareness") AND (construction) AND ((stakeholder) OR ("digital technology") OR ("digital") OR ("technology") OR ("real-time location system and proximity warning") OR ("building information modeling") OR ("augmented reality") OR ("virtual reality") OR ("game technology") OR ("e-safety-management-system") OR ("case-based reasoning") OR ("rule-based reasoning") OR ("motion sensor") OR ("action recognition") OR ("object recognition") OR ("laser scanning") OR ("physiological status monitoring") OR ("virtual prototyping") OR ("geographical information system") OR ("ubiquitous sensor network")))
3rd	(("situation awareness") AND (construction) AND (safety) AND ((stakeholder) OR ("digital technology") OR ("digital") OR ("technology") OR ("real-time location system and proximity warning") OR ("building information modeling") OR ("augmented reality") OR ("virtual reality") OR ("game technology") OR ("e-safety-management-system") OR ("case-based reasoning") OR ("rule-based reasoning") OR ("motion sensor") OR ("action recognition") OR ("object recognition") OR ("laser scanning") OR ("physiological status monitoring") OR ("virtual prototyping") OR ("geographical information system") OR ("ubiquitous sensor network")))

3 Key review results

3.1 Temporal distribution of publications

According to Figure 1, the earliest relevant paper was published at the International Conference on Computational Intelligence and Security in 2006. The number of relevant studies remains low until 2017. Starting from 2017, the topic of self-awareness was under the spotlight, and the number of relevant papers began to increase and reached its peak in 2020.

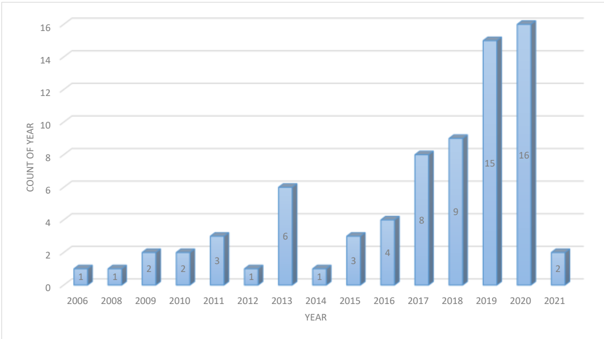

Figure 1. Distribution of publications by year

3.2 Elements of SA related to construction safety

The element of SA is about what constitutes SA at three different levels (i.e., perception, comprehension, and projection). It is a question of what are the essential data/information elements that enable an individual to develop an appropriate knowledge state for perceiving, comprehending, or predicting site safety-related scenarios. In general, no study has been conducted to explicitly identify a comprehensive set of elements of SA for construction safety. Nevertheless, there are fragmented studies that link SA to a specific aspect/object of construction projects.

SA elements of interest mainly cover three main dimensions: people, machinery, and environment from a safety management perspective. SA elements of people can be further categorised into physical and psychosocial aspects. SA elements of people identified from the literature review are presented in Table 2.

Data and information regarding machinery are also essential for site safety management, as they tend to create various hazards. Attention has been paid to location [15, 16], motion/behaviour [15, 17-19], and conditions [20, 21] of machineries.

At the environment level, physical and psychosocial conditions are of interest for safety purposes. SA elements of environment identified from the literature review are presented in Table 3.

Table 2. SA elements of people

Category	SA Elements	Study
Physical	Location	[16, 22]
	Movement	[22-24]
	Behaviour	[17, 23]
	Roles	[25]
Psychosocial	Stress; fatigue	[24]
	Time pressure	[18]
	Mental/cognitive load	[18, 26, 27]
	Areas of interest (AOI)	[27, 28]
	Emotional stability	[28]

Table 3. SA elements of the environment

Category	SA Elements	Study
Physical conditions	Temperature	[22]
	Weather	[15]
	3D model of the site	[15, 19]
	The geometry and location of existing structures	[16, 20]
	The geometry of site topology	[20]
	Hazards	[16, 18, 22]
Psychosocial conditions	Safety climate	[24]

3.3 SA measurement methods for construction safety

Several SA measurement methods were developed for construction safety, based on existing ones developed in other domains. A summary is presented in Table 4.

For instance, Fang et al. developed a query-based SA measurement method inspired by Situation Present Assessment Method (SPAM) to quantify SA [21]. Javier and Masoud applied the Goal-Directed Cognitive Task Analysis (GDTA) technique to investigate the key goals and SA requirements and develop SA-centered construction management methods and an IT tool to improve stakeholder decision-making processes [29].

3.4 Digital technologies for situation awareness

Various DTs have been applied to measure, develop, and maintain SA at different levels (i.e., perception, comprehension, and projection). A summary of DT technologies for SA is presented in Table 5.

VR was adopted to investigate the impact of tasks intricacy on forklift driver's SA [30]. The research indicates that the task complexity will significantly influence the forklift operator's SA [30]. The result manifests that the characteristic of mission on-site can be one diminution of SA.

Seokyon employed Ultra-wideband (UWB) technology and Angle-of-Arrival, Time-of-Arrival and Time-Difference-of-Arrival methods, axial-rotation and random-move collision preventing strategies was proposed to improve equipment operator's SA to avoid unexpected collisions [31]. This research demonstrates that UWB is an advanced real-time site object spatial data collection method.

Table 4. SA measurement methods

SA measurement methods	Study
Use eye-movement metrics, human errors, attention to measure cognitive processes	[32]
Direct measures of SA (eye-tracking) and Subjective SA measurement using Participant subjective situation awareness questionnaire (PSAQ) and Situation awareness rating technique (SART)	[33]
GDTA	[34]
Direct measures of SA (eye-tracking), AOI, and big five personality questionnaire	[28]
Direct measures of SA (Bluetooth energy power, position, temperature, battery volume and acceleration from BLE sensor)	[22]

Table 5. Digital technologies for SA

DT	SA Elements	Study
IoT sensors	Locations,	[35]
	Human activities	[23]
	Machinery activities	[18]
Computer vision	Human behaviour	[23]
MAR	Cognitive load	[36]
Sensors, UWB	Machinery behaviour	[31]
VR/AR/MR	3D model of the site	[30]
	The geometry and location of existing structures	[37]
	The geometry of site topology	[38]
BIM	Visual awareness	[35, 37]
Web technologies	Logistics	[39]

3.5 SA and safety behaviour

Previous research on safety behaviour was mainly focused on identifying and testing antecedents (e.g., safety motivation, safety knowledge, management commitment to safety) based on existing behaviour and motivation theories (e.g., theory of planned behaviour).

The literature review results suggest that research on the impact of SA on safety behaviour in the construction domain has been limited. There is no research conducted to statistically test the relationship between SA and safety behaviour in the construction industry.

Sneddon et al. [12] tested the relationships between actors (i.e., sleep disruption, fatigue, stress), worker's SA, and unsafe behaviours, accidents, and near-miss accidents, based on the data collected in the oil and gas industry. The results indicated that SA is significantly related to unsafe behaviour. Mohammadfam [13] performed a path analysis to investigate the relationship between SA and human errors based on the survey data collected from multiple industries. The results suggested that the relationships between factors (i.e., sleepiness, fatigue, safety knowledge, and safety locus of control) and SA are statistically significant. SA was also significantly correlated to human error and safety behaviour.

SA has been applied as a concept that links digitalisation and automation in crane operation to safety performance. For example, Fang [18] developed a cognitive-based real-time crane operation assistance system to perform autonomous hazard identification. This research proposes a measurable cognitive-based effectiveness validation approach that demonstrates the potential of an evaluating method to examine the relationship between the system design vision and system actual performance. Utilizing real-time motion sensing and 3D modeling technology, Fang et al. [19] proposed a mobile crane operator-assistance system to improve the SA of operators. In addition, a collision-prevention strategy and UWB-based algorithms were created by Seokyon. The system can perform equipment collision detection [31]. By leveraging eye-tracking and task observation technology, a field experiment was conducted by Markus to investigate the operator visual information acquisition process [40]. Employ VR environment, Choi et al. applied SAGAT to examine the impact of subtasks on forklift operator's SA [30].

3.6 SA and hazard identification

Research efforts were made to investigate the impacts of SA on workers' ability of hazard identification. Hasanzadeh et al. [32, 33] suggested that eye movements can be a reliable indicator of workers' attention and comprehension of construction hazards. The research used eye-tracking technology to measure SA. The results indicated that SA varies significantly depending on workload, state of the area of interest, and experience.

Several studies [26, 27, 36] have been conducted to identify that mental load will significantly affect worker's SA. In addition, Eskandar et al. [24] identified that the high production and coordination pressure might influence the stakeholder's response. One of the first efforts adopting mobile eye-tracking technology to investigate the relationship between SA and worker's attention was conducted by Hasanzadeh [41]. Li et al. [42] revealed that knowledge sharing and construction safety awareness are critical to hazard identification.

4 Discussion

The critical review aims to investigate the current conceptual position of SA in site safety and analyse the impact of DT on improving or maintaining SA.

4.1 A digitalised situation-aware site for safety

Although DT has been well researched and implemented for managing construction safety, there are conceptual gaps in the role of DT in accident causation models and safety science. Few studies have been conducted to conceptualise the role of DT. Due to the limitation of human cognition capacity, workers cannot process all relevant information for site safety. Accidents and near misses can be attributed to this limitation. DTs have demonstrated significant potentials to address the limitation by capturing data, generating new information and knowledge, and facilitating information flow.

An assumption behind using the concept of SA is that if workers and managers can access an adequate amount of right information at the right time regarding site safety, accidents can be prevented. This assumption has been implicitly applied to justify most of the previous studies on DT for construction safety. The results of the literature review suggest that there is a solid conceptual basis underpinning the assumption. The conceptual basis is formed based on the theoretical linkages among SA, DT, and construction safety management. First, SA and attention are fundamental concepts of human behaviours. SA is a concept that has been applied to link human behaviour and hazards, which are two main contributing factors in accident causation models (e.g., Domino model by [43]). Second, there is solid evidence that DT can provide relevant information and knowledge to develop and maintain SA at the individual and group level. As such, SA is a helpful concept that links DT and construction safety management and safety science.

DT can be developed, selected, and integrated into a coherent platform to provide a comprehensive situation picture (SP) following the same rationale line. Kärkkäinen et al. [44] defined SP as "A state where the scope, quality and accessibility of produced operational information is adequate for controlling the workflow and improving production processes.". Another working definition of SP from a safety management perspective can be:

"A state where the scope, quality and accessibility of all relevant information produced by DT is adequate for making informed decisions and improving safety performance." To realise this ideal state, it is essential to understand what the relevant information is, how to capture and communicate the information to the right people at the right time, and how the construction site can be (re)designed to facilitate the information capturing and communication. This design thinking can create various interfaces between humans and the environment. The interfaces help an individual or a group to get the right information at the right time. Knowing something will never guarantee safe behaviour [45], however, the information and knowledge generated from the interfaces can significantly enhance the capability and capacity of individuals and groups to manage the dynamics and complexity of construction activities. The theoretical stance is that DTs do not improve safety level directly; instead, they improve the safety level by empowering people.

4.2 Future research directions

The application of the concept of SA for managing construction safety is still in its infancy. More research is needed to further develop its conceptual linkages to construction safety. The efforts should be focused on conceptualising the role of DT in construction safety management and science. Three specific future research directions are recommended as follows.

First, research efforts are needed to identify elements of SA by levels (e.g., perception, comprehension, and projection), stakeholders (i.e., individual workers, team, supervisors, and project manager), and tasks. The results of the recommended research can potentially help design and integrate a network of DT and techniques to develop and enhance SA in various scenarios.

Second, based on the results from this research, an ontology (or taxonomy) of SA is needed to represent the knowledge of safety information in the construction domain. The ontology can help people understand what information/knowledge is relevant to site safety and capture the relations of concepts for reasoning from a low level of SA (i.e., perception) to higher levels (i.e., comprehension and projection).

Third, as aforementioned, there is a need for research on investigating the statistical relationships between SA and safety behaviour. SA can be measured at the worker level using either subjective or experimental measurements. Statistical testing methods such as factor analysis can be performed to explore the structure of SA. A structural equation model can be conducted to test the relationship between SA and other safety factors (e.g., safety behaviour, stress, management commitment to safety, social support). The statistical results can provide significant empirical evidence regarding the usefulness of the concept of SA in construction safety management.

Finally, future research efforts should be made to conceptualise the role of DT in accident prevention strategies (e.g., safety management system, safety culture/climate, resilience engineering). SA seems useful in connecting DT with classical accident causation models (e.g., Swiss cheese model). These efforts can lay a scientific foundation to integrate various DT into a platform to achieve a zero-harm vision.

5 Conclusions

By using a systematic review methodology, this paper reviewed studies that investigate the concept of SA for construction safety. The results suggested that SA elements can be divided into three categories: human, machine, and environment. A more comprehensive SA taxonomy remains an undeveloped domain. Several SA measurement methods were identified. The selection of method is highly dependent on the researcher's experience and the system architecture on measuring SA. A comprehensive understanding of SA is essential for improving SA measurement efficiency and effectiveness. The relationship between SA and DT, SA and safety behaviour, SA and hazard identification attract considerable attention. Furthermore, further efforts on developing an innovative digitalised situation-aware site that can deliver the right information to the right people at the right time were proposed by this research.

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