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VR-Based Investigation of Forklift Operator Situation Awareness for Preventing Collision Accidents

Minji Choi[1], Seungjun Ahn[2] and JoonOh Seo[3]

[1] Seoul Institute of Technology, Maebongsan-ro 37, Mapo-gu, Seoul, 03909, Korea, Email: mjchoi@sit.re.kr

[2] School of Natural and Built Environments, University of South Australia, City East Campus, Adelaide, SA 5001, Australia, Email: Jun.Ahn@unisa.edu.au

[3] Department of Building and Real Estate, Hong Kong Polytechnic University, 11 Yuk Choi Rd., Hung Hom, Kowloon, Hong Kong, Email: joonoh.seo@polyu.edu.hk

ABSTRACT

Forklifts are among the machines involved with the highest levels of occupational fatalities. As many accidents involved with a forklift can be attributed to the low situation awareness (SA) of the operator, it is essential to understand the factors influencing a forklift operator's SA for reducing forklift accidents, especially of collision type. Against this background, this research aims to investigate how a forklift operator's SA about other people around can be influenced by the type of subtasks they are carrying out. In this research, a virtual reality (VR) environment is used as the experiment environment, in which subjects perform a series of subtasks, such as driving, turning, reversing, loading and unloading, with a VR forklift simulation model. A SAGAT—an established SA measurement technique based on a series of queries targeting Level 1, 2, and 3 SA—is used as the main method to collect data about subjects' SA in the experiment. The analysis of the data reveals that a forklift operator is

likely to have a reduced SA about the workers around when he/she is performing a loading or unloading task due to attention narrowing, which occurs when a person concentrates on a cognitively demanding task. The findings provide insights into how forklift operator SA could be improved through an SA-oriented safety training program and also how sensing technologies might assist forklift operators with maintaining a good SA.

Keywords: Situation Awareness, Forklift, Operator, Safety, Construction Worker

INTRODUCTION

Forklifts are involved with high accident and fatality rates around the world (Stout-Wiegand 1987; Government of South Australia 2015; Marsh and Fosbroke 2015). In many cases, forklift accidents can be attributed to the operator's human errors, such as the lack of attention, misperception, or misjudgment (Miller 1988; Sarupuri et al. 2016). In other words, many forklift accidents are caused by the operator's reduced situation awareness (SA) (Miller 1988; Endsley 1995a; Sarupuri et al. 2016). This is evidenced by the fact that a significant number of forklift accident cases recorded by the US Occupational Safety and Health Administration (OSHA) report a reduced SA of the forklift operator as the main cause of the accident (OSHA 2018). For instance, a rough terrain forklift operator on a highway construction project ran over the legs of a flagger, who was controlling the traffic, without realizing the flagger was behind the forklift (OSHA 2018). There are many other accident cases like this in which the forklift operator 'did not see' or 'did not know' someone or something is around the forklift. The prevalence of this type of accident cases clearly highlights the importance of forklift operator SA, especially about the other workers around, for preventing collision accidents.

It can be particularly challenging for a forklift operator to maintain a good SA in a less organized workplace like a construction site due to the characteristics of this kind of work environment, such as multiple activities performed simultaneously, tight workspaces and narrow moving paths, congestion, and the dynamicity of the environment. In addition, a construction forklift operator often needs to operate the equipment in proximity to other individuals, materials, equipment and structures, which poses a major safety risk to the operator herself and others around. When carrying out a high-risk task, the operator needs to share attention to various elements of the environment (Endsley 2016), which is why maintaining a good SA is even more difficult when the person is carrying out a high-risk task in a less organized environment (Wickens et al. 2013; Endsley 2016). The importance of operator SA in forklift safety and the variability of operator SA under different circumstances necessitate research efforts to investigate how a forklift operator's SA can dynamically change under different circumstances and especially in a less organized work environment such as a construction site. Against the background, this research aims to investigate how a construction forklift operator's SA can be influenced by the type of tasks they are carrying out. This research especially focuses on forklift operator SA about other people around because maintaining a good SA about other people around is essential for reducing the likelihood of a collision accident.

The rest of paper is organized as follows. First, an extensive literature review is provided under the subheadings of *situation awareness and safety, situation awareness measures, and the use of virtual reality in situation awareness studies*. Then, the research processes are explained in a detailed manner, such as *forklift operation subtask breakdown,* *VR environment and scenario development, experimental setting and data collection, and data analysis*. Subsequently, the results, discussion and conclusions follow, including discussion on the theoretical and practical implications of the findings.

LITERATURE REVIEW

Situation Awareness and Safety

Endsley (1995a,b) provided a theoretical framework of SA, which has been widely accepted by many researchers and practitioners in the studies of human errors. SA is defined as "*being aware of what is happening around you and understanding what that information means to you now and in the future*" (Endsley 2016). Specifically, SA is defined as consisting of three different levels; the perception of the key elements in the situation (level 1 SA), interpretation of the perceived information in relation to the task goals (level 2 SA), and a projection on the system's near future state (level 3 SA) (Endsley 1988; Endsley 1995a; Jones and Endsley 1996; Stanton et al. 2001; Endsley 2016). The level 1 is the lowest level of SA and is directly associated with an individual's perception of information coming from the surrounding environment (Endsley 1988; Endsley 1995a; Jones and Endsley 1996; Stanton et al. 2001; Endsley 2016). Therefore, the errors in Level 1 SA can be related to reduced attention, failures in distinguishing relevant data, and the excessive gathering of irrelevant information (Alfredson 2007). At Level 2 SA, the operator comprehends the current situation based on the perceived elements (Endsley 1988; Endsley 1995a; Jones and Endsley 1996; Stanton et al. 2001; Endsley 2016). At this point, the person gains a clear picture of '*what is going on*', and an error can occur when there are discrepancies between the characteristics of the actual system and the operator's mental model (Endsley 1995a; Jones and Endsley 1996; Alfredson 2007). Lastly, Level 3 SA is related to an individual's ability to project the future status of the system (Endsley 1988; Endsley 1995a; Jones and Endsley 1996; Stanton et al. 2001; Endsley 2016). Overall, these three levels of SA offer a functional and practical model for assessing an operator's different levels of understanding and insight about the system (Stanton et al. 2001).

Over many years, the importance of SA in maintaining safe control of a system, such as an aircraft, has been discussed extensively (Stanton et al. 2001). It was found that poor SA of the operator was the main cause of over 200 aircraft accidents (Hartel et al., 1991; Stanton et al. 2001). Durso et al. (1998) found that most of the errors made by air traffic controllers were highly associated with an SA failure. For example, an air traffic controller may miss an important indicator that signals the current situation (i.e., Level 1 SA failure) or they perceive the signals but fail to comprehend or predict the situation accurately (i.e., Level 2 or 3 SA failure) (Stanton et al. 2001). When operating a complex system, people are often subject to 'attention narrowing' or 'attention tunnelling', which mean that they focus too much and too narrowly on certain features of the environment and drop their scanning behaviour (Endsley 2016). Also, people find it difficult to attend to all information available at once, and the ability to perceive and understand multiple items simultaneously is finite, which limits the amount of SA a person can achieve (Endsley 2016). As SA plays a paramount role in the safe operation of high-risk equipment, it is very important to understand the factors that can affect an operator's SA and design the system so that the likelihood of an operator SA failure can be minimized (Endsley 2016).

Situation Awareness Measures

In SA research, measuring an SA accurately is a challenging task (Endsley and Garland 2000). Given that SA is influenced by all the data coming from the outside environment (Endsley 2001), it is important to consider in which context an SA is assessed. Broadly speaking, previous approaches used for SA assessment can be categorized into three groups; post-accident investigation, direct system performance measures, and direct experimental techniques with simulation (Busquets et al. 1994; Endsley 1995a; Jones and Endsley 1996). Post-accident investigation and direct system performance measures have strength in measuring SA under real conditions, but these methods have limitations on investigating the influence of various potential factors that might affect SA (Busquets et al. 1994; Endsley 1995a). Additionally, direct system performance measures would most likely cause an interruption of the actual task. These limitations of the first two approaches have led to the wide adoption of the simulation-based experimental techniques in measuring SA (Endsley 1995a). This approach allows easy manipulation of the simulated environment and the detailed observation and measurement of SA-related variables. However, the limitation of this approach would be the limited realism of the simulated environment and tasks.

A number of specific SA measures have been developed, including physiological measures, performance-based measures, subjective measures, and questionnaire-based measures (Endsley 1995b; Salmon et al. 2006). Regarding physiological measures, P300 and other electroencephalographic measurements have been used to identify if certain information is cognitively perceived and processed in a human system (Endsley 1995b). However, these techniques have a limitation in determining whether the information is processed correctly or how much information remains in memory (Endsley 1995b). Performance-based measures involve objective measurement that can be assessed while the operator performs actual tasks, but these measures have been found to be quite sensitive to various internal or external factors (Endsley 1995b; Habibi & Shirkhodaie 2012). Subjective measures can be further divided into two types; self-rating and observer-rating (Endsley 1995b; Naderpour et al. 2016). In a self-rating assessment, the data on the subject's own SA can be collected cost-effectively (Endsley 1995b). Examples of this type of measurement techniques are Situational Awareness Assessment Technique (SART) (Taylor 2017) and Crew Awareness Rating Scale (CARS) (McGuinness 1999). However, the main limitation of these techniques comes from the fact that an operator usually has a limited ability to assess their own SA because they do not know whether or not their knowledge of the situation is complete or accurate (Endsley 1995b). The second type of subjective techniques, observer-rating, also has some limitations in assessing the mental processes of the operator (Endsley 1995b). Last, detailed information on a subject's SA can be collected using a questionnaire that would be administered at several points during a simulation (Endsley 1995b). The collected information can be regarded as objective data on the subject's SA because the questions asked are about specific information that can represent the person's SA at each moment. Often, a 'freeze' technique is used in conjunction with the questionnaire. It means that the simulation is stopped ("frozen") at several selected times during simulation, and subjects are asked about their knowledge of the situation at that moment (Endsley 1988; Endsley 1995b). Situation Awareness Global Assessment Technique (SAGAT) (Endsley 1988) is one of the most widely used methods to assess an operator's SA based on a questionnaire. The main advantages of SAGAT include; 1) it provides a global measure of a subject's SA because it includes all SA Levels in the measurement; 2) it measures the subject's knowledge about the situation while the memory is fresh; 3) it can be objectively collected and evaluated (Endsley 1988).

Use of VR in SA studies

Due to the significance of SA for safety in the context of equipment operation, the concept of SA has been widely used to understand human errors that can occur during equipment operation in various contexts, including driving (Gugerty 1997; Ma and Kaber 2005; Kass et al., 2007; Bellet and Banet 2012; Salmon et al. 2013), aviation (Endsley 1995a; Jones and Endsley 1996; Endsley 1999; Endsley and Garland 2000; Wickens 2002), military training (Wellens 1993; Eid et al. 2004; Entin and Entin 2000; Bryant et al. 2004) and behavioral science (Dinev and Hu 2007; Salas et al. 2017). Research has shown that an operator's ability to maintain a good SA can be achieved through effective training (Kaber et al. 2013; Patle et al. 2018). In addition, feedback on their behavior after training can help them understand the reasons and consequences of SA errors (Kaber et al. 2013). In this regard, virtual reality has been trialed as a training tool for improving operator's decision-making and situation assessment abilities (Lampton et al., 2006; Pleban et al., 2001; Kaber et al. 2013). This is because VR can provide a sense of realism regarding the situation, emergency condition, and possible accidents, in a risk-free setting (Patle et al. 2018). VR-based SA study has drawn much attention over the last few years because current VR technology not only provides a great variety of audiovisual effects but can also generate haptic and sensory effects that can enable operators to deeply engage in the simulated situation (Cibulka et al. 2018). With such advantages, VR simulators have been found more effective in SA studies and training than the conventional approaches based on only visual aids (Nazir et al. 2012; Manca et al. 2013; Nazir et al. 2013; Nazir et al. 2014; Nazir and Manca 2015; Cibulka et al. 2018).

RESEARCH METHODS

As abovementioned, the goal of this research is to investigate the changes in a forklift operator's SA about other people around when carrying out different tasks. In this research, the goal is addressed through the following steps (Figure 1): 1) analyzing the subtasks of forklift operation, 2) developing a simulation scenario and implementing an immersive virtual environment for the simulation, 3) running an experiment with subjects and collecting data about their SA as they go through the VR simulation using Situation Awareness Global Assessment Technique (SAGAT) and Retrospective Think-Aloud (RTA) methods, and 4) analyzing the collected. The following sections explain each of these research processes.

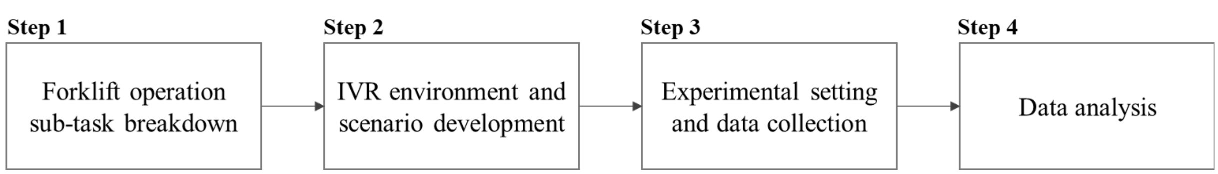

Figure 1. Research Methods and Process

Forklift Operation Subtask Breakdown

In SA research, creating a breakdown structure of tasks and subtasks is essential so that the specific context of SA (e.g., what specific things the operator needs to be aware of in performing a specific task) can be developed for each task. In this regard, a Goal-Directed Task Analysis (GDTA), which is a cognitive task analysis for listing the requirements of operator SA in a breakdown structure, is often used as the first step of SA study (Endsley et al. 2003; Naderpour et al. 2014; Naderpour et al. 2016). The main focus of a GDTA is identifying an operator's comprehensive goals that need to be accomplished, the decisions that need to be made to achieve the goals, and information required to make appropriate decisions (Endsley et al. 2003).

In this research, a GDTA was developed based on forklift operation safety guidelines, such as High-Risk Work – A Guide to Forklift Safety (SafeWork SA, 2015), as well as forklift accident reports extracted from the US OSHA accident database (i.e., OSHA Fatality and Catastrophe Investigation Summaries, https://www.osha.gov/pls/imis/accidentsearch.html). Forklift safety guideline documents and the accident case reports provided detailed information regarding the goals and tasks to be achieved by a forklift operator (Endsley et al. 2003; Naderpour et al. 2014), as shown in Table 1. Among the subgoals identified, the second subgoal, 'handling loads without any accident', was focused in this research. This subgoal (i.e., the safe operation of a forklift) is related to three decisions, each of which is related to an accident type, such as hitting, tip-over, and having someone caught in moving parts of the equipment, respectively. This categorization of different types of forklift accidents is based on accident case reports included in the OSHA's accident database. The authors identified 158 forklift operation-related accident cases by analyzing frequencies of word usage of the term "forklift" in the database. A further investigation on the identified cases revealed that 41 cases (25.94%) among them were directly associated with a SA error by the operator, and the majority of them was of the type that someone was hit by a forklift in motion (63.41%). Further categorization of these accident cases revealed that such collision accidents occurred while the operator was driving straight without any load (36.58%), backing up (31.70%), making a turn (14.63%), driving with load (9.75%), or loading (7.31%).

Table 1. Goal-Directed Task Analysis (GDTA) for Construction Forklift (The sub-goal focused in this research are in bold fonts)

Goal: Lift and transfer loads accurately, efficiently and safely
Subgoal 1: Lift and transfer loads accurately and efficiently (efficiency-related subgoal)
Decision 1-1: Are loads lifted/transferred accurately?
Decision 1-2: Are loads lifted/transferred quickly?
…
Subgoal 2: Lift and transfer loads safely
Decision 2-1: Is the risk of hitting someone or something minimized?
SA 1: Is there any other worker working near the forklift? **SA 2: How close is the forklift and the person? How are the person and the forklift moving?** **SA 3: Is there any chance that the forklift can hit the person?**
Decision 2-2: Is the risk of tip-over minimized?
Decision 2-3: Is the risk of having anyone caught-between moving parts of forklift minimized?
…

Among the subgoals identified in the GDTA, this research particularly focuses on the collision type accidents (i.e., Decision 2-1 in Table 1) due to the frequency of this type of accidents reported. Then, the three levels of SA that would be required for the forklift to avoid any collision accidents were also identified. In this context, Level 1 SA pertains to whether the operator perceives other workers in proximity. Level 2 SA pertains to whether the operator correctly comprehends the situation regarding the movement of the forklift and the other workers, and Level 3 SA pertains to predicting whether there is any chance to hit the worker with the forklift.

IVR Environment and Scenario Development

As a next step, a simulation scenario of forklift operation was developed. Based on an interview with a licensed forklift operator, the accident reports and the forklift operation guidelines, four main subtasks of forklift operation for material handling were included in the final scenario: 1) driving forward without a load, 2) driving reverse with a load, 3) making a turn, and 4) lifting a load. Notably, these four subtasks possess different characteristics in terms of task complexity (e.g., driving straight/curved path, forward/backward, and with/without load) and require different levels of mental workload for maintaining a good SA, as illustrated in Figure 2. As mentioned above, the scope was determined to be the forklift operation for material handling, and other types of use of forklifts, such as using a forklift as a lift, were excluded in this research.

Figure 2. Example of Different Task Complexity (With/without a load on a fork)

As the next step, this research developed an immersive virtual environment (IVR) for an experiment. An IVR can offer a sense of existence within a 3D multi-physical environment with physical risk-free settings (Setareh et al. 2005). Additionally, the use of a VR environment also allowed the investigation of the changes in operator SA because SA can be measured at any point in time during the simulation.

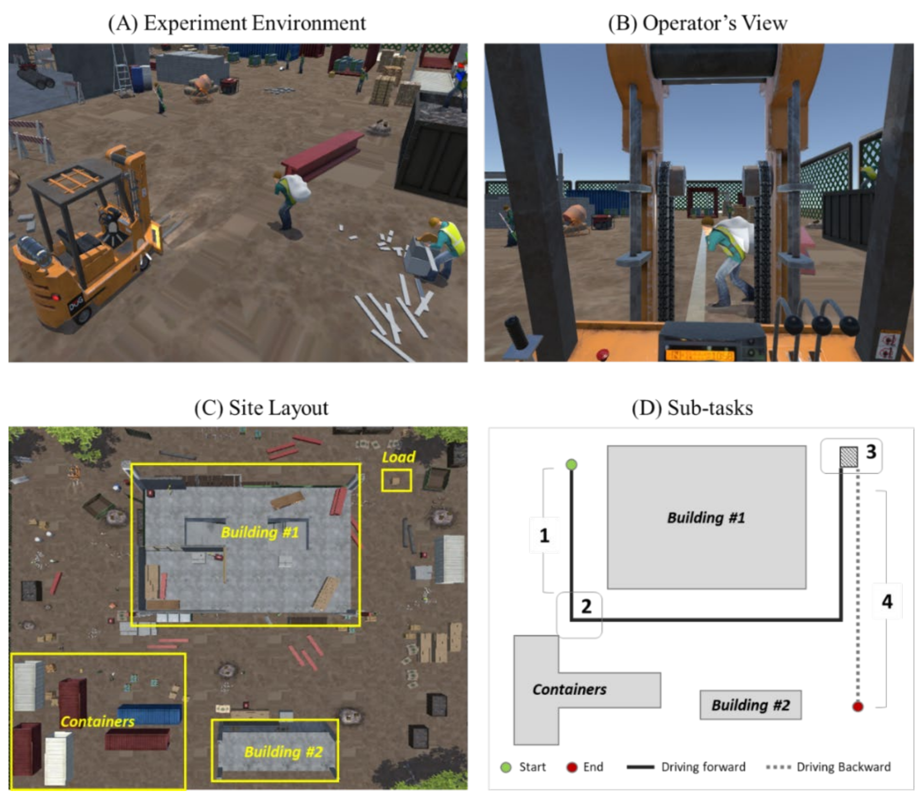

Figure 3. Virtual Construction Site Model Developed for Experiment

A model for the immersive virtual environment for the forklift operation simulation as described above was constructed using a game engine with C#-based scripting API for three-dimensional games, Unity. The model was specifically developed to represent a busy construction site where many construction workers and various activities are present simultaneously, as shown in Figure 3. In this VR environment, the operation scenario includes four subtasks such as driving forward without a load (Task 1), making a turn around a corner of a building (Task 2), lifting a load (Task 3), and driving reverse with a load (Task 4), in sequence, as shown in Figure 3(D).

In order to set up an experiment setting that would allow a realistic behavioral response from a subject (Freeman et al. 2000; Kuliga et al. 2015), this research utilized a head-mounted display device, HTC Vive. Such an immersive virtual experience facilitated by a head-mounted display is known to support a high level of behavioral realism (Kuliga et al. 2015), especially about viewing or information search behavior, while having some weakness in reproducing the user control interface (e.g., the difference between an actual motion for moving an object in the real environment and a hand gesture to mobilize an object in VR). However, as the focus of this research was on people's perceptive and cognitive process and how they can maintain a good SA, and not directly related to the motor control aspect of forklift operation, and also the familiarity of the control device is very important for user performance in VR (McMahan et al. 2012), a keyboard-based control of the forklift movement and operation was deemed acceptable for the purpose of experiment.

Lastly, the virtual construction site model included a number of construction workers as 'SA target objects', which means that an operator should be aware of where they are, how close they are to their forklift, and whether there is any potential risk of hitting any of them with the forklift. Those virtual workers were designed to be performing an activity, such as carrying an object, ground sweeping, compacting, and pulling a cart, near the travel path of the forklift (Figure 4).

Figure 4. Examples of SA Target Objects

Experimental Setting and Data Collection

A total of 20 subjects were recruited and participated in the experiment. All of the participants were undergraduate or graduate students in Hong Kong Polytechnic University majoring in construction engineering. Equal number (n=10 for each) of male and female students volunteered for the experiment. None of the subjects had previous experience of operating a forklift. However, 65% of the participants already had some previous experience with VR technology. After an introduction of the experimental procedure, they were requested to provide informed consent forms as required by the Human Subject Ethics Subcommittee of the Hong Kong Polytechnic University (HSEARS20181108003). Then, the participants received general driving and safety instructions for forklift operation using a forklift operation manual book (Clark 2017) and were instructed about how to operate a forklift to perform subtasks in the virtual environment. A training session without any SA target objects was organized before the actual experiment so that the participants can get familiarized with the environment and learn how to operate the virtual forklift model.

In this research, SAGAT was used as the main method to measure the subjects' SA in various situations in the VR simulation. SAGAT is an objective assessment of operator SA—it does not require subjects or observers to make a subjective judgment on how high an SA is—and has been validated for its effectiveness for measuring all types of operator SA, including Level 1 SA (perception), Level 2 SA (comprehension), and Level 3 SA (projection of the near future), comprehensively (Endsley 2017). As SAGAT directly measure the constructs of the different Levels of SA instead of inferring the operator's SA from their behaviors, it is categorized as a direct measure of SA (Endsley 2017). Additional advantages of SAGAT include that the data is collected from the subject immediately as the situation is occurring, and therefore, measurement error is reduced.

Following the standard procedure of SAGAT, the subjects were asked to stop at a few points (i.e., 'SA freeze') during the simulation, and then they were asked about his/her perception (Level 1 SA), interpretation (Level 2 SA), and projection (Level 3 SA) of the situation regarding other people near the forklift. An SA freeze took place during each task, as shown in Figure 5, and data was collected with verbal answers on each of the SAGAT questions. Therefore, there were a total of 4 freezes, and each of them took an average of 25 seconds for answering simple yes or no questions on the state of the target object. The average duration for completing all four tasks was 6 minutes 38 seconds. To minimize the predictability of when and where the SA queries are given, the actions and moving directions of the SA target objects were randomized, as shown in Table 2.

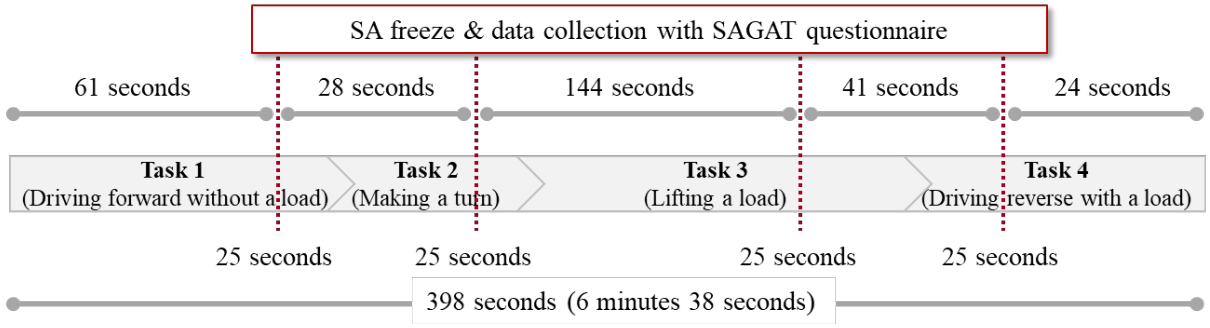

Figure 5. SA Freeze Moments and Average Durations during Experiment

Table 2. SA Target Object's State and Freeze Moment for Each Sub-task

Sequence	**Sub-task**	**SA Object's State**		**Moment of SA Freeze**
		Action	**Moving Direction**	
1	Driving forward without a load	Carrying a wood piece	Toward forklift from front	Just before passing the object
2	Making a turn	Ground solidifying	Across forklift's travel direction	Just after passing the object
3	Lifting a load	Carrying a heavy sack	Toward forklift from front	Just after loading the pallet
4	Driving reverse with a load	Ground sweeping	Same as forklift from behind	Just before passing the object

In SAGAT, the queries should be relevant to the operator's SA and should be similar to how the person would perceive and process information about the situation (Endsley 2017). To meet these requirements, SA queries were developed based on the GDTA result. As described in Table 1, the GDTA identified the queries that are most relevant to each SA Level required for avoiding a collision with a worker, as the followings: 'Is there any other worker working nearby the forklift?' (Level 1 SA); 'Is the person moving?' and 'If the person is moving, is s/he approaching me or not?' (Level 2 SA); 'What will happen to the forklift and the coworker if I continue moving on my direction?' (Level 3 SA). Based on these queries, more detailed SA queries as SAGAT questionnaire items were developed, as shown in Table 3.

Table 3. SAGAT Questions for 3 SA Levels

SA Level	SAGAT Questions
1 (Perception)	1. Did you see any coworker walking? 2. Was there any coworker approaching you?
2 (Interpretation)	1. Was the coworker's moving direction same as yours? 2. What was the moving direction of the coworker? 3. From forklift's position, where was the coworker?
3 (Projection)	1. Do you think there is a chance that you can hit the coworker after this stop? 2. Do you think the coworker will move closer to you after this stop?

In addition to SAGAT, an RTA method was used as a supplementary method to investigate the possible reason for SA errors and any unexpected responses. In RTA, a subject is asked to verbalize the process after the completion of the assigned task (Guan et al. 2006). Specifically, a cued retrospective think-aloud (C-RTA) technique was used in this study. In C-RTA, a visual cue, such as an eye-tracking video (Van Cog et al. 2005) or a recording of gameplay (Tan et al. 2014), is provided to help the subject recall what happened (Van Den Haak et al. 2003; Guan et al. 2006). C-RTA has been proved to be an effective method for capturing perceptual and cognitive processes while minimizing the disruption of the processes caused by measuring (Salmerón et al. 2017).

Following the standard procedure of C-RTA, a video record of the forklift operator's view from the simulation was shown, and the subject was asked to verbalize 'what was going through in their mind' as they watch the video replay of what they were doing. If the subject's description did not provide enough information about a possible reason for a SA failure, probing questions, such as "what was the reason that you did not see the person?" or "where were you paying your attention at the moment?", were asked additionally.

RESULTS

The collected data from the experiment was first analyzed by calculating the mean percentages of correct responses to the SA queries for each subtask. This was to investigate how many times the subjects maintained or failed to maintain a good SA about the workers nearby while performing the different subtasks. Then, an Analysis of Variance (ANOVA) was conducted to see if there were statistically significant differences on each Level of the subjects' SA between the subtasks. A null hypothesis of "*H_0=a group mean of level 1, 2, and 3 SA for other workers around is the same for all four subtask groups*" was, therefore, first tested using the data. Then, a Tukey test, a post-hoc test for comparing a mean difference between groups, was conducted to test the difference in the mean scores of each Level of SA between each pair of subtasks.

Figure 6 and Table 4 provide the mean percentages and descriptive statistics of correct responses to Level 1, 2, and 3 SA queries for different subtasks. For all four subtasks, the subjects showed the highest level of scores for Level 1 SA while Level 3 being the lowest—which imply that most of the subjects successfully perceived all SA target objects, i.e., workers around the forklift, but fewer subjects correctly interpreted the situation regarding the distance between the worker and the forklift or the direction of the worker's movement, and even fewer subjects correctly predicted potential possibilities of a collision accident. More specifically, the subjects maintained the highest level of Level 1 SA, the perception of other people around, during the first (i.e., 'driving forward without a load') and second (i.e., 'making a turn') subtasks. In both subtasks, the subjects had the same level of correct responses to Level 1 SA queries (M=0.85 for both subtasks). While a few subjects (N < 3) mentioned that the mast of the forklift sometimes blocked their sights, the majority reported during RTA sessions that they did not experience any difficulties in observing the SA target objects and other obstacles on their moving path throughout the subtasks 1 and 2. However, a difference was observed between Subtask 1 and 2 for Level 2 and 3 SA queries. There was a more significant decrease in Level 2 SA (M=0.75) and Level 3 SA (M=0.55) for the 'driving forward without a load' subtask than it is for the 'making a turn' subtask (M=0.80 for Level 2 SA and M=0.70 for Level 3). The RTA revealed that several subjects decreased their speed when making a turn, and this could be a possible reason why their Level 2 and 3 SA scores were higher for the subtask of making a turn rather than it was for driving a straight line.

Most importantly, it was observed that the operator's SA for other people around was most significantly reduced when performing Subtask 3, 'lifting a load'. All Level 1, 2, and 3 SA scores decreased dramatically for this subtask (M=0.35 for Level 1 SA, M=0.35 for Level 2 SA, and M=0.3 for Level 3 SA) when compared to other subtasks. Next to the loading subtasks, the subject's SA scores for all Levels were second-lowest (M=0.7 for Level

1 SA, M=0.55 Level 2 SA, and M=0.5 for Level 3 SA) for the ‘driving reverse with a load’ subtask.

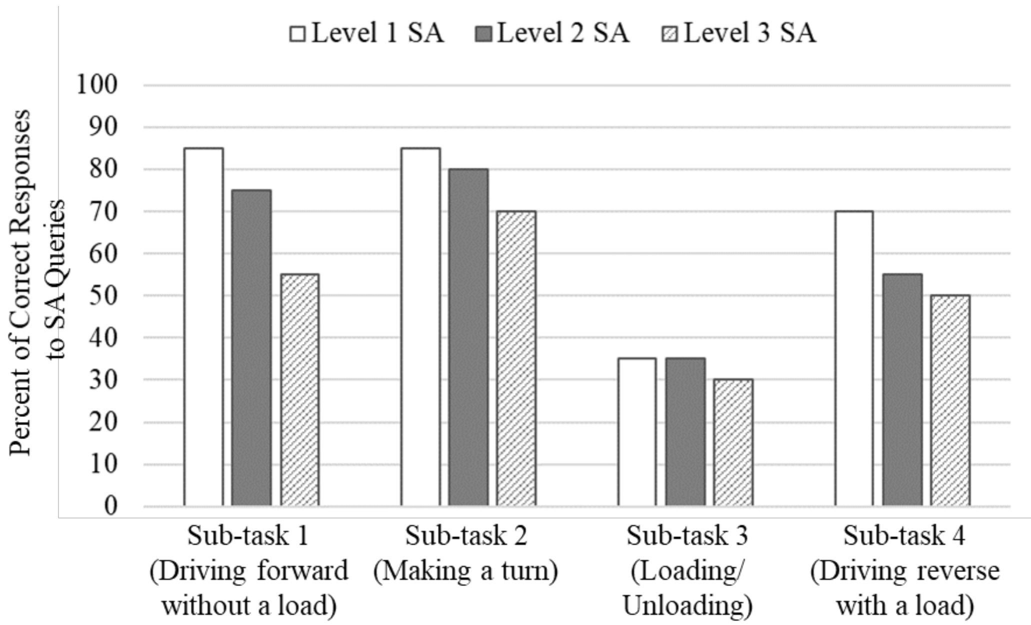

Figure 6. Mean Percent of Correct Responses to SA Queries during Each Subtask

Table 4. Descriptive Statistics for Correct Response Rate for Different SA Levels and Different Subtasks

Level 1 SA						
Subtask	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
1	20	0.850	0.366	0.081	0.678	1.021
2	20	0.850	0.366	0.081	0.678	1.021
3	20	0.350	0.489	0.109	0.121	0.579
4	20	0.700	0.470	0.105	0.480	0.920
Level 2 SA						
Subtask	N	Mean	Std. Deviation	Std.	95% Confidence Interval for Mean	

				Error	Lower Bound	Upper Bound
1	20	0.750	0.444	0.099	0.542	0.957
2	20	0.800	0.410	0.091	0.607	0.992
3	20	0.350	0.489	0.109	0.121	0.579
4	20	0.550	0.510	0.114	0.311	0.788

Level 3 SA

Subtask	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
1	20	0.550	0.510	0.114	0.311	0.788
2	20	0.700	0.470	0.105	0.480	0.920
3	20	0.300	0.470	0.105	0.080	0.520
4	20	0.500	0.512	0.114	0.259	0.740

Also, there were some differences in the pattern of changes between Level 1, 2, and 3 SA for different subtasks. Subtask 1: 0.85 (Level 1 SA)→0.75 (Level 2 SA, -11.76%)→0.55 (Level 3 SA, -26.67%). Subtask 2: 0.85 (Level 1 SA)→0.85 (Level 2 SA, -5.88%)→0.7 (Level 3 SA, -12.5%). Subtask 3: 0.35 (Level 1 SA)→0.35 (Level 2 SA, 0%)→0.3 (Level 3 SA, -14.28%). Subtask 4: 0.7 (Level 1 SA)→0.55 (Level 2 SA, -21.42%)→0.5 (Level 3 SA, -9.09%). This result indicates that the decrease from Level 1 to 2 SA was the most noticeable for Subtask 4 (-21.42%) when compared to other subtasks. For Subtask 3, which had the highest level of SA failures for all Levels 1, 2, and 3 SA, there was not much change between Level 1 and 2 SA—which may imply that most SA failures occurred at Level 1 SA for this task.

The result of ANOVA confirmed that the collected data rejected the null hypothesis that the mean value of the forklift operator's SA scores will not be different among the subtasks. Specifically, there were statistically significant differences among four subtasks for level 1 SA (F(3,76) = 6.105, p=0.001) and level 2 SA (F(3,76) = 3.908, p=0.012), and a marginally observable difference for level 3 SA (F(3,76) = 2.261, p=0.088). In addition, the result of a Tukey test (Table 3) confirmed that the subjects' Level 1 SA scores were statistically significantly lower for Subtask 3 (M=0.35) compared to Subtasks 1 and 2 (M=0.85, p=0.002) and marginally so when compared to Subtask 4 (M=0.7, p=0.054). A similar pattern is observed for Level 2 SA too; Level 2 SA scores were significantly lower for the loading subtask (M=0.35) than it is for Subtask 1 (M=0.75, p=0.040) or Subtask 2 (M=0.80, p=0.016), but no significant difference from that of Subtask 4 (M=0.55, p=0.528). However, there was no statistically significant difference in the means of Level 3 SA scores between the subtasks in the dataset.

Table 3. Summary of Tukey Test Results

(I) Task		Mean Difference	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Level 1 SA						
1	2	0.00000	0.13500	1.000	-0.3546	0.3546
	3	0.50000*	0.13500	0.002	0.1454	0.8546
	4	0.15000	0.13500	0.684	-0.2046	0.5046
2	3	0.50000*	0.13500	0.002	0.1454	0.8546
	4	0.15000	0.13500	0.684	-0.2046	0.5046
3	4	-0.35000	0.13500	0.054	-0.7046	0.0046
Level 2 SA						
1	2	-0.05000	0.14712	0.986	-0.4365	0.3365
	3	0.40000*	0.14712	0.040	0.0135	0.7865
	4	0.20000	0.14712	0.528	-0.1865	0.5865
2	3	0.45000*	0.14712	0.016	0.0635	0.8365
	4	0.25000	0.14712	0.331	-0.1365	0.6365
3	4	-0.20000	0.14712	0.528	-0.5865	0.1865
Level 3 SA						
1	2	-0.15000	0.15539	0.769	-0.5582	0.2582
	3	0.25000	0.15539	0.380	-0.1582	0.6582
	4	0.05000	0.15539	0.988	-0.3582	0.4582
2	3	0.40000	0.15539	0.057	-0.0082	0.8082
	4	0.20000	0.15539	0.574	-0.2082	0.6082
3	4	-0.20000	0.15539	0.574	-0.6082	0.2082

* The mean difference is significant at the 0.05 level

Discussion

The analysis results demonstrate that a forklift operator's SA is significantly influenced by what task the operator is carrying out at the moment. Specifically, the analysis tells us that a forklift operator will have a reduced SA regarding the workers around when he/she is performing a loading or unloading task. This implies that the operators' attention may be narrowed when he/she performs a loading or unloading. In the RTA session, those subjects who failed to maintain a good SA during these tasks reported that they did not see a worker approaching the forklift because they were focusing on carrying out the task accurately. In other words, the subjects were experiencing a higher mental workload due to the complexity of the task. This kind of attention narrowing when performing a complex task and the resulting reduction of situation awareness has been reported in the various contexts of high-risk machine operation (e.g., Sneddon et al. 2006).

A good understanding of such conditions under which forklift operators will have a reduced SA about the surroundings can provide important insights into how an SA reduction can be mitigated through an improvement of people's skills (e.g., more training on how to maintain a good SA in various operation situations) or an improved design of the machine (e.g., proximity sensors to alert the operator or the workers). Therefore, the results of this research suggest that there may be a need for developing training programs aiming to mitigate a reduction in SA in specific circumstances. For example, safety training programs teaching the most common type of SA failures can help both forklift operators and other workers who will work near the equipment to recognize the safety hazards more clearly. Especially, Level 2 or 3 SA may require such training. This is because there was a noticeable drop in Level 3 SA when compared to Level 1 or 2 SA in the research. Even if an operator is aware of the presence of other workers nearby (Level 1 SA), a misjudgment on the current (Level 2 SA) or future status of the situation (Level 3 SA) can lead to a critical accident. Therefore, forklift operation training programs should be able to teach not only what kind of things need to be searched and found in the surrounding environment but also how to make an accurate prediction of the situation in various scenarios and circumstances (e.g., good mental models).

Another perspective to think about how to address the issue of reduced SA under specific circumstances would be how other controls measures can be used to mitigate the safety risks increased due to reduced SA. According to the Hierarch of Control model, the most effective safety measure would be to physically remove the hazard (elimination), while the least effective one would be personal protective equipment (PPE) (NIOSH 2015; OSHA 2016; HSA 2019). However, in reality, the more effective forms of safety measures, such as eliminating or substituting the hazard, are often the most difficult and costly (NIOSH 2015). In the context of enhancing a forklift operator's SA for safety, technologies such as a sensing-devices-based alert system (i.e., an engineering control) can be a cost-effective solution for the operator to maintain a good SA throughout the operation.

As many forklift collision accidents occurred due to a SA failure of the operator, such an improvement in the forklift design or in forklift operators' safety skills will ultimately contribute to the reduction of collision accidents involved with forklifts, especially the ones caused by human errors made by a forklift operator. However, it needs to be also noted that forklift collision accidents are not only caused by reduced SA. While the results of this research suggest that the operator's SA about workers around is lower when they are doing loading or unloading than it is when they are driving forward without a load or turning, a lower number of forklift collision accidents have been reported as involved with loading or unloading activities than involved with driving forward. An explanation for this discrepancy could be the different portion of forklift operation time for performing different tasks; if forklift operators spend more time with driving than with loading/unloading, there can be a greater chance that an incident occurs when a forklift is traveling without a load. Another explanation could be the potential difference in the operator SA between the training situation (such as the case of this research) and the normal working situation. According to the accident causality models, there are many human behavioral factors besides SA that can potentially contribute to an accident, such as mental/physical fatigue and the lack of due care. A further investigation would be necessary to clarify how large portion of forklift collision accidents are caused by reducing SA and what other factors can interact with the SA factor in the causality of forklift collision accidents.

CONCLUSIONS

This research investigated how a forklift operator's SA for safety can be influenced by the task being carried out, focusing on four different subtasks (i.e., driving forward without a load, making a turn, loading, and driving reverse with a load). Especially, this research focused on an operator's awareness of other people around the forklift as such awareness is critical to prevent any collision accidents involved with forklifts. The research findings reveal that a forklift operator's SA about other workers around is significantly affected by the complexity of the subtasks being carried out at the moment. Specifically, the loading and driving reverse with a load tasks significantly reduced the operator's ability to perceive or interpret the status of workers moving nearby and/or project the future status of the situations. Based on the findings, the use of additional control measures such as sensing devices and situation signifiers (an engineering control) or more SA-oriented, detailed safety training for both operators and other workers (an administrative control) can be proposed to reduce SA-related human errors in forklift operation.

This research and its outcomes are expected to create novel opportunities for both research and practice. Understanding equipment operator SA for safety in construction site would open a new door to revealing cognitive aspects (i.e., human errors) related to equipment accidents, which have not been fully investigated in the construction domain. Also, assessing operator SA by varying the influencing factors can help with identifying more effective interventions (e.g., construction workplace best practices and equipment design) as well as training strategies to reduce the number of accidents involved with the operation of mobile plants on construction sites.

This research is not without limitations. Additional research will be required to confirm the validity of the findings in a real-world setting. Future research plans also include assessing the impact of a wider range of factors such as environmental or individual factors on forklift operators' SA for safety. In addition, operator SA for other types of mobile equipment (e.g., excavator, bulldozers) that are frequently used on construction sites will also be examined. Also, even though the student subjects were fully trained to operate the forklift in VR before participating in experiments, a lack of field experiences of those subjects could lead to higher mental demands that might negatively affect their SA (Endsley and Garland 2000). Investigating and comparing SA between novice and experienced forklift operators would be needed for understanding how working experience can affect one's capability in interpreting the current situation and making a correct decision for safe operation of a forklift.

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