Improving Occupational Safety and Health (OSH) in Human-System Interaction (HSI) Through Applications in Virtual Environments

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Abstract. Interactions between humans and system components of future work systems may be driven by digitalization, connectivity and agility. Though the design of future systems is not yet known or is not yet available or accessible, it would be desirable to ensure occupational safety and health (OSH) in early stages of development and design. It would also be helpful to learn about potential hazards and risks and prevent them before using work systems across their future life cycle. Since knowledge, experience and imagination might not be sufficient to predict human-system interactions (HSI) it should be possible to apply modeling and simulation such as virtual reality (VR) to overcome some of the challenges in analysis, design and evaluation of future work systems. Similar seems to be true for work systems too dangerous, too complex, or too resource demanding to investigate in reality. The concept on safety and usability through applications in virtual environments (SUTAVE) facilitates effective prevention through design in OSH to be addressed by means of innovative technology. Studies have been conducted to improve OSH in HSI supported by VR simulation; i.e. (a) risk assessments in planning stage, (b) task, interaction and information design in human robot interaction, (c) usability evaluation of safety measures in contexts of use, (d) near misses and course of events in accident investigations, (e) safety concept development. The results are encouraging to face future challenges in HSI as long as its design is taken into account early on and according to human factors and ergonomics principles.

Keywords: Occupational safety and health · Human system interaction
Virtual reality · Human information processing

1 Human-System Interaction

There is a growing concern due to digitalization in work systems design that occupational safety and health (OSH) requirements become less obvious and therefore less essential, although potential consequences may rather be sneaking in and become severe at the same time. Digitalization in smart manufacturing has a strong impact on human-system interaction (HSI) and seems to foster shifts in hazards (e.g. mechanical superimposed by mental) and in human task requirements (e.g. action implementation

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superimposed by perception and reasoning). Perspectives for prevention should adapt accordingly, in that design of human task and interaction interfaces referring to human factors and ergonomics principles become key performance indicators in mediating OSH. Modeling and simulation have a long tradition in research into future work systems as well as development of prospective design strategies and solutions. In the digital age it might be helpful to take simulations such as VR into account to facilitate prevention through design in future contexts of use while gaining experiences in introducing new technologies for the benefit of OSH in industry and services.

1.1 Occupational Safety and Health

According to the World Health Organization (WHO) occupational safety and health (OSH) refers to all aspects of health and safety in the workplace and should have a strong focus on primary prevention of hazards. Concepts on OSH may vary since OSH legislation differs across countries. The basis of the German social security system was formed in the 19th century and developed since to a comprehensive system with five pillars of insurances for health, pension, accident, long-term care and unemployment. OSH comprises all measures for safety and health of employees at work and other forms of activity. This includes the prevention of occupational accidents, occupational diseases and work-related health risks and the human centered design of working conditions. The national OSH system follows the conventions of the ILO and all legislation is harmonized with EU Directives [1].

Unlike legal requirements for OSH, the hierarchy of controls remains fairly similar across countries and provides some guidance for selecting effective measures for risk reduction and prevention in systems design. In Germany, a hierarchy of controls traditionally follows levels like (a) eliminating hazard (e.g. substitution), (b) technical measures (e.g. safeguard), (c) organizational measures (e.g. job rotation), (d) personal measures (e.g. personal protective equipment, PPE), and (e) instructional measures (e.g. warning sign). Albeit shorter, this hierarchy is similar to the ten level 'general principles of prevention' as listed in the EU OSH Framework Directive [2]. The hierarchy in OHSAS 18001 [3] also has five levels and contains similar content, however, with PPE listed lowest. Different perspectives on the hierarchy may also widen opportunities for interventions [4].

European and Australian OSH legislation with directives and guidelines are regarded especially useful in facilitating primary prevention. Manufacturers are required to design safe machinery that meet a set of minimal health and safety requirements and employers are held responsible for providing safe work equipment to employees [5]. As a consequence, technology and knowledge for designing safe equipment is accessible across countries; however, business decision makers and purchasers may not always value or request for it or manufacturers may not create demand for it by promoting it on the market [6]. Despite differences in OSH legislation across countries, OSH principles are equally important everywhere. The concept of primary prevention is a guiding principle for priority consideration of high level measures to combat hazards and risks at the work across the life cycle from early on with the consequence of lowering rates of occupational accidents and diseases.

1.2 Virtual Reality Simulation

Though work systems should not impair safety and health of humans interacting in these systems, they may not yet, readily, or easily available for investigating appropriate procedures for risk assessments or for developing and testing appropriate safety measures. Modeling and simulation of work systems seem to be solutions to provide support in terms of methods, tools and techniques. This opens up new and effective perspectives to face human factors and ergonomics challenges in work systems analysis, design and evaluation, in that it allows for systems to be investigated in temporal and spatial dynamics and across the life cycle from construction and development, over application in the context of use, up to modification and recycling [7, 8].

There is a long tradition also in OSH to use simulation techniques. Applications may refer to (a) procedures agreed on and established for testing product safety (e.g. laboratory heat stress testing for hydraulic pipes), (b) role plays in OSH trainings intending to simulate safety behaviour at the workplace, (c) retro-perspective accident analysis (e.g. cause effect and if what/when reasoning and analyses), and (d) investigations of unavailable, undesirable, inconvenient or future work scenarios (e.g. safety concept development to prevent from hazardous work equipment) [8, 9].

Over the past decades, VR has matured into a simulation tool for humans to interact with dynamic, three-dimensional virtual environments and into a methodology for different areas of applications. In industry and services VR allows applied research in human-machine system analysis, design, and evaluation for training, for demonstration, and for visualisation purposes [10]. VR has the potential to better bridge gaps between experimental research and traditional investigations at the shop-floor level while using specific advantages of simulation research [11] and being careful with human, material and financial resources. Improvements in technology and success stories from industrial applications attracted VR also to OSH. Applications often refer to rehabilitation and to qualification and training, with the latter placing an emphasis e.g. on safe behaviour at work or risk assessments [12, 13].

In OSH organisations VR is increasingly being used in studies on analysis, design and evaluation of task and interaction interfaces of work equipment such as machinery or tools with regard to improvements in human factors, ergonomics and safety [14–16]. Among these organisations, the Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA) established the concept ‘Safety and Usability Through Applications in Virtual Environments’ (SUTAVE) to facilitate effective prevention through design of HSI in OSH to be addressed by means of innovative technology. Information about current activities in the SUTAVE laboratory in general and technical information is given elsewhere (www.dguv.de/ifa/sutave).

1.3 Occupational Safety and Health in Human-System Interaction

HSI focuses on the understanding of how humans interact within work systems [17] while emphasizing human factors and ergonomics design requirements with regard to human information processing [18]. The four stages of HSI are closely related to OSH investigations and procedures, starting with identification of situational characteristics (i.e. information acquisition, sensation, determination of limits of process under investigation), analysis (i.e. information analysis, perception, hazard identification), followed by assessments (i.e. decision making, action selection, risk evaluation) and may result in redesign (i.e. action implementation, intervention, risk reduction).

Linking the design of HSI more closely to procedures for risk assessments should improve both human factors and ergonomics design quality of HSI as well as OSH in HSI. Work system components and their interactions would be designed as to safeguard operational safety, effectiveness and efficiency of HSI as well as to optimize human operator workload, which in turn will contribute to operational safety and health in work systems. As a consequence, design flaws, hazards and risks could be reduced and prevent from health impairments, near accidents or accidents. Application of human factors and ergonomics design requirements for HSI thus does not merely reflect the necessary compliance with legal regulations but also the pursuit of basic system goals. Projects conducted at the IFA will be used to inform about activities to improve safety and health through design of HSI in virtual environments.

2 Occupational Safety and Health Applications in Virtual Environments

2.1 More OSH in HSI When Planning Work Environments

Standardization of future river looks has been given high priority by the German Federal Ministry of Transport and Digital Infrastructure (BMVI) since it allows OSH improvements for future operations while accelerating modernization of waterway transport infrastructure and reducing costs across the life cycle. OSH is seen most effective early in design because redesign due to safety issues would be resource-demanding, if not impossible, when river lock construction has already been completed. Therefore, the German Social Accident Insurance Institution of the Federal Government and for the railway services (UVB) launched a project to strengthen the impact of OSH on the standardization of river lock components in its future contexts of use. IFA and UVB in cooperation with partners from BMVI, German Federal Waterways and Shipping Administration (GDWS) and German Social Accident Insurance Institution for Transport and Traffic (BG Verkehr) are developing a dynamic VR planning model of the river lock standard in its future contexts of use [19].

The new standard comprises a kit of standardized objects covering river lock requirements for professional inland navigation in Germany (e.g. chamber construction, lock gates). As a consequence, the VR planning model on standardized river locks also provides variations with regard to rise of water level (e.g. gates and chambers for 4 m to 25 m), to length of river barges (e.g. for up to 135 m or even 185 m river barges), and to type of water way (e.g. canal locks may have economizing basins), to name but a few. VR-Model development in 1:1 scale (see Fig. 1) refers to drawings of ongoing implementation planning of the first river lock according to the new standard.

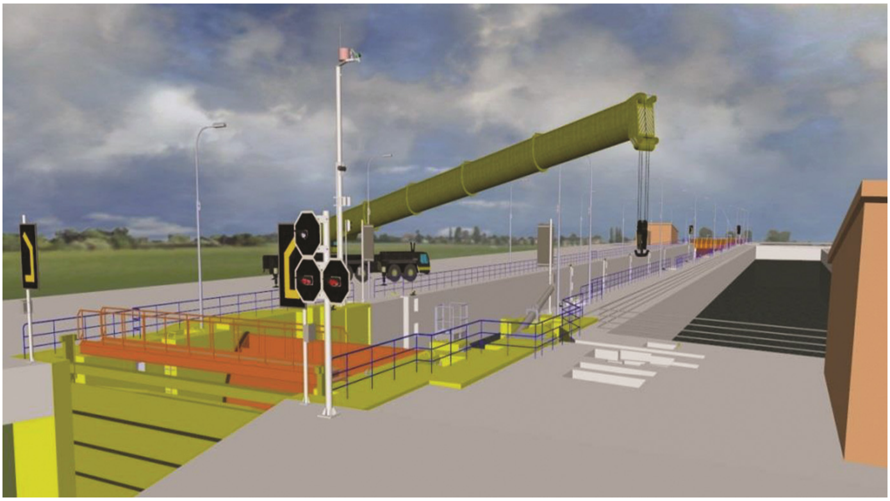

Fig. 1. VR simulation of maintenance work at standardized river lock for risk assessments.

With the aim to improve OSH, the VR model supports demonstration of about 75 different scenarios in a wide context of use across operational stages and the life cycle. Outcomes of risk assessments will result in documentations on

(a) design improvements of standardized objects to better match OSH requirements
(b) improved templates for conducting risk assessments [according to 20]
(c) new templates for conducting risk assessments [according to 2, 21, 22]
(d) design improvements for river locks currently under planning
(e) basic information for operation instructions for technical components
(f) basic information for working instructions for maintenance tasks at river locks
(g) references for risk assessments after successful construction.

Results have the potential to improve OSH in the process of standardization and in future work at river locks while at the same time immersing into future work scenarios in the context of use over next decades.

2.2 More OSH in HSI in Hazardous Work Environments

Investigations into work systems [17] should be conducted in protected simulation environments if these are too expensive to use in reality due to required downtimes or too dangerous or undesirable to face in reality. This also applies to empirical usability evaluations of prospective safety measures, as real contexts of use include hazardous and incident prone scenarios with near misses and accidents.

Mobile elevating work platforms (MEWP) enjoy increasing use and popularity and they provide flexible, easy and quick access to work places above ground level without setting up scaffolding. Unfortunately, the number of injuries and fatalities is still relatively high with most accidents referring to operators being crushed between MEWP rail guards and objects in the environment or being thrown from MEWP platforms [23].

Over the past years, efforts in MEWP safety [24] resulted in improvements, however, usable and effective safety measures are always required.

Among others, stop functions built into MEWP joysticks as new safety measure [25] have been assumed to be effective for accident prevention. Therefore the German DGUV Expert Committee ‘Trade and Logistics’, Subcommittee ‘Goods Handling, Storage, and Logistics’ in cooperation with the German Social Accident Insurance Institution for the trade and logistics industry (BGHW) as well as the German Social Accident Insurance Institution for the woodworking and metalworking industries (BGHM) have launched a research project at IFA to conduct a usability evaluation in VR before detailed recommendations for use of this additional protective measure would be given to manufacturers, rental companies or users.

In an industrial hall 22 naïve and experienced users performed on-site inspection tasks for about 2 h each [26]. Scenarios have deliberately been designed in a virtual environment to provoke accidents and near misses by constricting access to work places, reducing visibility in inspection areas, and adding obstacles in the environment. A MEWP in an industrial hall was set up in VR, except for MEWP controls and platform. MEWP drivers were required to perform driving and inspection tasks. Virtual near misses and accidents have occurred as rare events and as accidentally as in reality, i.e. collisions of the MEWP or its driver with objects in the hall.

As a result, near misses and collisions of the MEWP or the driver with objects in the environment occurred, similar to those reported in reality [23]. Surprisingly, the protective measure under usability evaluation has not been used in hazardous situations or during collisions. However, it has unintendedly been used in non-hazardous situations. Investigations into the use of controls in hazardous situations revealed that MEWP movements were always stopped by operators releasing their hands from the joysticks. In addition, system dynamics of joysticks with built-in safety function transformed linear joystick movements into exponential changes in MEWP movements, with the consequence that MEWP would always accelerate before coming to a stop, when using the safety measure. In conclusion, the given design of the measure has not been recommended for marketing, because the safety measure was not seen suitable to serve a measure for risk reduction and to prevent from severe accidents. Redesign suggestions have been documented accordingly.

Based on results of the VR usability evaluation, however, it has been possible to support accident investigations [27]. Post-hoc VR simulation of the VR usability study provided insights in the course of events by identification and reconstruction of near misses and accidents and by investigation of work system configurations, movements of the drivers and controls as well as MEWP movements in the work environment. Observations from variable locations and viewing angles disclosed potential impairments of human information processing through MEWP systems design during HSI. Recommendations for the development of measures of hazard and risk reduction could be given. In addition, the study illustrated how to detect potential accidents in future work scenarios and inform about development of measures for risk reduction early in design [28].

The IFA has also been requested by the German Social Accident Insurance Institution for Transport and Traffic (BG Verkehr) to develop a VR environment for accident investigations during unloading of vehicles with lifting platforms on loading ramps [29] (see Fig. 2). During unloading, the height of the vehicle body is adjusted continually, either automatically or manually, since the body of the vehicle would otherwise rise as the weight of the load decreases. Reports on slip, trip and fall accidents suggested that the lifting platform could shift horizontally causing the platform being in front of the loading ramp. A dynamic VR model was designed to foster reasoning, analysis and reconstruction of potential courses of events and may serve a basis for instructional support.

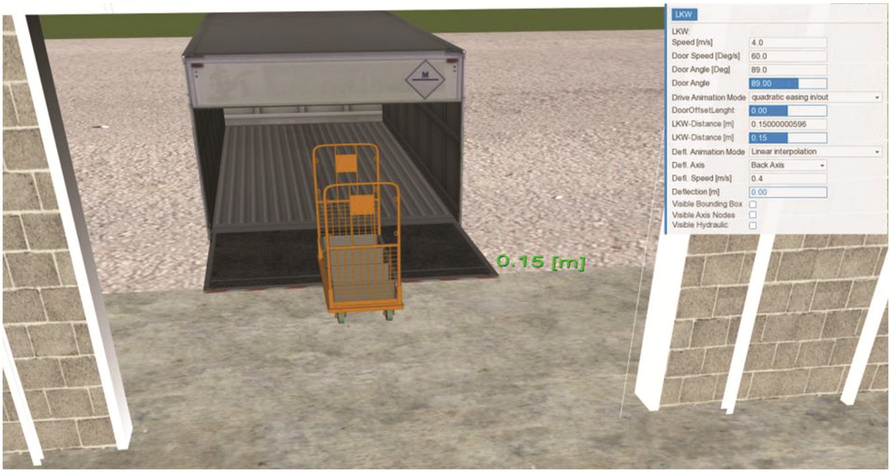

Fig. 2. Unloading of vehicles with lifting platforms on loading ramp in virtual environment.

2.3 More OSH in HSI in Work Environments Not Yet Available

In future industry and services, work equipment is required that is more flexible to use while at the same time being specific and very effective for different purposes. In recent years human-robot interaction has evolved to provide solutions, however, implications for health, safety, and well-being are not always clear. Since workplaces with humans interacting or even collaborating with robots in time or space on common tasks are still rare [30], VR simulation studies have been conducted to investigate human factors and ergonomics issues with regard to OSH in future work environments [31]. Human factors requirements on human-robot collaboration (HRC) in industrial settings have been conducted in VR referring to spatial distances between humans and robots, robot speed in proximity of human collaborators, and predictability of robot movement [32–34].

A human operator workplace was set up in reality in front of the VR presentation wall and integrated in a VR manufacturing environment [32, 33]. Task performance in human-robot collaboration overlapped in time and space with both individual human operator and robot task performance, respectively. Results yielded effects of distance (300 mm versus 1400 mm) between an industrial robot and a human operator in combination with effects of robot movement speed (250 mm/s versus 1500 mm/s). At relatively shorter distances participants reported higher levels of anxiety, while relatively lower robot speed was associated with slower and less accurate task performance of participants [32].

Another HRC study in VR [33, 34] used a similar setting, however, investigated the impact of robot speed in combination with predictability of robot movements on human performance in spatiotemporally overlapping workspaces. A lower level of predictability was associated with a decrease in task performance, while faster movements resulted in higher-rated values for task load and anxiety, suggesting demands on the operator exceeding the optimum.

Function allocation in human-robot interaction with regard to human-automation taxonomy was also addressed in VR [35]. Different levels of automation in combination with different modes for signaling demands for interaction between a single human operator and two simulated industrial robots were investigated regarding their impact on human operator task performance and work load (see Fig. 3). Industrial robots either asked the human operator to interact whenever required or adapted the request for interaction to idle times between individual operator tasks. Requirement for interaction were either audio-visually indicated or not. Interactions indicated and adapted to operator task sequences resulted in relatively less operator distraction from task performance and less impairment in operator workload. In human-robot interaction OSH may improve when interaction is audio-visually indicated and work equipment is adapted to the human operator.

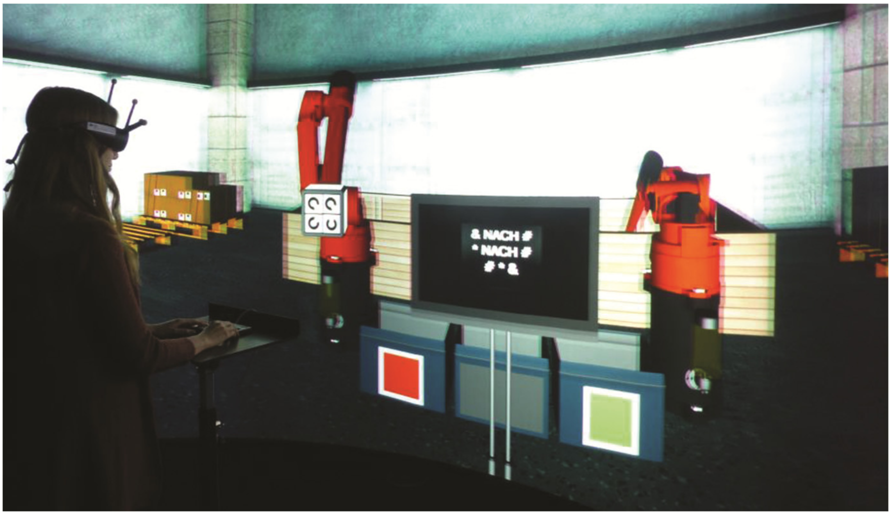

Fig. 3. Mixed reality manufacturing environment for human-robot interaction in STUAVE-Lab.

2.4 More OSH in HSI Through Safety Concept Development

With regard to safety concept development for HSI in manufacturing, VR studies have been conducted to investigate the design of tree-dimensional safety zones at work.

Electro-sensitive protective equipment (ESPE) such as safety light curtains, photoelectric switches, laser scanners and camera-based protective devices is used to protect workers from hazardous areas such as rotating parts of machinery [36]. Geometry of the detection zones and markings for identification by the human operator are among potential key differences in ergonomics design of ESPE with 3D and 2D safety zones. Therefore, a project has been launched by the German DGUV Expert Committee 'Woodworking and Metalworking' (FB HM), Subcommittee 'Machinery, Plants, Automation and Design of Manufacturing Systems' in cooperation with the German Social Accident Institution for the woodworking and metalworking industries (BGHM).

3D ESPE safety zones were explored in virtual manufacturing task scenarios on their effects on human performance, workload, and safety (see Fig. 4). Safety zones were varied in geometry (e.g. cuboid, spherical) and in modes for identification (e.g. warning zone, floor marking tape). Twenty participants performed manufacturing tasks on a machine with a rotary table. The machine was in operation while safeguarded by 3D ESPE when participants prepared materials for subsequent task sequences. Among others, results suggested that 3D safety zones in geometry should be adapted to contours of hazard zones (e.g. less edges and corners), as this yielded relatively fewer unintended breaches of detection areas for machinery safety. 3D ESPE floor marking tape is sometimes used to support operators in detecting invisible safety zones. Though useful in some situations to improve orientation for operators, it could not be identified as significantly increasing performance and improving workload in human system interaction [37]. In addition, VR revealed to be a helpful planning system for safety concept development and evaluation for a broad range of HSI settings at industrial workplaces.

Fig. 4. HSI in SUTAVE-Lab on machinery with rotary table; floor marking tape to support safety zone detection.

3 Improve OSH in HSI Through VR Applications

As demonstrated by examples presented, OSH becomes proactive and may draw benefits from VR in that a simulation environment facilitates analysis, design, and evaluation of HSI in work systems in industry and services for improving effective measures for prevention. Specific benefits refer to system interventions early in the design process (e.g. prevention through design) as demonstrated by the studies on risk assessments with regard to different perspectives in OSH legislation and different operational stages for work tasks at standardized river locks throughout the work system life cycle (see Sect. 2.1) [38]. VR has shown to support OSH in HSI design in situations too dangerous or undesirable to face in reality. Investigations in hazardous environments have extended the effective range of prevention in that realistic and more valid contexts of use could be applied in evaluation studies and in that the course of events in near misses and accidents could be investigated with regard to human information processing requirements (see Sect. 2.2) [28, 29]. Prevention in OSH intends to avoid detrimental consequences for operators before accidents are going to happen. VR modeling and simulation made this happen even though workplaces do not yet exist or have never been existed before and therefore predictions for potential hazards and risks are not necessarily met by knowledge, experience and imagination. In VR, systematic variations of standardized working conditions are available for investigations, even if testing is difficult, because their quality is subject to change (i.e. under heavy wear or degradation) (see Sect. 2.3). OSH in HSI will also improve when setting up new workplaces since reproduction of the same settings is as easy as it is to modify settings or scenario. Replication of contexts of use supports developing, testing and choosing among effective safety concepts for new interactions, machines and installations (see Sect. 2.4).

The presented studies go beyond VR simulations in that VR was used as a tool and method to improve OSH in HSI at work. OSH may take advantage of VR as future implementation of prevention measures can be accelerated early on. Given examples also provide support for the assumption that VR should be suitable to face future challenges for OSH in HSI in future systems evolving into smart factories, i.e. connectivity, optimization, transparency, proactivity and agility becoming main drivers that will be considered in OSH.

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