SAFETY SCIENCE Monitor

Issue 1 2013 VOL 17

Article 2

A VIRTUAL REALITY PILOT STUDY TOWARDS ELEVATING WORK PLATFORM SAFETY AND USABILITY IN ACCIDENT PREVENTION

PETER NICKEL

Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA), Alte Heerstraße 111, D-53757 Sankt Augustin, Germany, firstname.name@dguv.de Corresponding author: Tel. +49 2241 231-2832, Fax +49 2241 231-2234, E-mail address: peter.nickel@dguv.de

ANDY LUNGFIEL

Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA), Alte Heerstraße 111, D-53757 Sankt Augustin, Germany, firstname.name@dguv.de

GEORG NISCHALKE-FEHN

Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA), Alte Heerstraße 111, D-53757 Sankt Augustin, Germany, firstname.name@dguv.de

ROLF-JÜRGEN TRABOLD

DGUV Expert-committee 'Trade and Logistics', Sub-committee 'Goods Handling, Storage and Logistics', German Social Accident Insurance Institution for the trade and distribution industries (BGHW), 68145 Mannheim, Germany, rj.trabold@bghw.de

ABSTRACT

Analyses of accidents with mobile elevating work platforms (MEWPs) identify falling and crushing as major hazards with a high level of annual fatalities. Operator training and MEWP safeguards design as measures to prevent accidents take long to become effective at the shop-floor level. In order to avoid the risk of placing operators and others in danger, safety measures under development should not be evaluated in hazardous situations and are often constricted to functional testing. Development and testing of a mixed reality scenario is presented to inform about its suitability for evaluations of MEWP safeguards under development and in the context of use. Initially, contributory conditions to crushing as a major hazard have been identified and a work environment for MEWP has been set up in virtual reality (VR). A pilot study required an MEWP operator to perform inspection and driving tasks in normal and hazardous work situations. High ratings for immersion and presence in the VR environment suggested the scenarios were perceived rather natural. While operator task performance was high, the level of operator task load varied according to potential hazards during driving and inspection tasks. Risk perception in virtually hazardous situations may not necessarily be as high as in reality and needs further investigation. It has been concluded that VR simulation is a promising tool for studying the usability of safeguards under development; it has the potential to reduce the effort of field studies without being able to replace them. Occupational safety and health may take advantage of VR as future implementation of prevention measures can be accelerated early on.

Keywords
Mobile elevating work platform (MEWP), Safety measure, Virtual reality, Usability, Accident prevention, Human Factors

1. INTRODUCTION

Mobile elevating work platforms (MEWP) are frequently used in many industries, including construction and manufacturing, and for a variety of maintenance applications to elevate workers to work places above ground level. MEWPs become more and more popular because of their flexibility and easy and quick access to any place without setting up scaffolding from the ground. Although MEWP manufacturers, rental companies, users, and occupational safety and health organisations have made continuous efforts to improve MEWP safety (e.g. EN 280, 2010; Strategic Forum for Construction, 2010), the number of injuries and fatalities with MEWPs involved seemed to increase or at least to maintain at a relatively high level. German Social Accident Insurance Institutions report about six fatalities per year (BGI 720, 2013) and NIOSH of the USA reports about 30 fatalities per year for a similar decadal period (NIOSH, 2009), with a tendency of increases in death involving MEWP use. Reliable numbers of injuries are not available, because official accident reports do not necessarily indicate whether work with MEWPs has been involved or may have caused an accident. Countermeasures and intervention strategies developed for accident prevention often are faced with the situation that they take long to become effective and those measures under development cannot be tested in the context of use (i.e. accident situations) to avoid placing operators or others in danger. The German DGUV expert-committee 'Trade and Logistics', sub-committee 'Goods Handling, Storage, and Logistics' in cooperation with the German Social Accident Insurance Institution for the woodworking and metalworking industries (BGHM) as well as for the trade and distribution industries (BGHW) have recently initiated a research project to address this issue. The usability of a prototype MEWP safety measure (Nischalke-Fehn & Bömer, 2011) should be evaluated in virtual reality (VR) before detailed recommendations will be given to manufacturers or users. In the SUTAVE laboratory of the IFA (Huelke et al., 2010; Nickel et al., 2012b), therefore, virtual scenarios with normal and hazardous work situations will be developed to allow operators to use a real control panel with the built-in safety measure in a virtual MEWP.

1.1 Virtual reality in occupational safety and health

Over the past decades, VR cleared its way for industry and services. It has grown into a simulation tool for humans to interact with dynamic, three-dimensional virtual environments and into a methodology for applied research in human-machine system design and evaluation as well as for training, for demonstration, and for visualisation purposes (Stanney, 2002; Miller et al., 2012). VR has also been matured to facilitate efficient investigations with the potential to better bridge gaps to more traditional research at the shop-floor level while using specific advantages of simulation research and being careful with human, material and financial resources (Chapanis & van Cott, 1972; Stanney & Cohn, 2012). Improvements in technology attracted VR to occupational safety and health. Applications often refer to qualification and training (Cobb et al., 2002) with regard to safe behaviour at work or risk assessments (e.g. BG Chemie, 2003; Leskinen, 2005; Simeonov et al., 2005; Saulewicz et al., 2005), to name but a few.

In occupational safety and health organisations, VR is increasingly being used in studies on design and evaluation of human-machine interfaces with regard to improvements in ergonomics and safety (e.g. Helin et al., 2007; Määtä, 2007; Marc et al., 2007; Aromaa & Helin, 2011; Naber et al., 2012; Nickel et al., 2012a). VR has the potential to widen the scope for usability investigations, addressing the "extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" (EN ISO 9241-11, 1998, p. 2). In the given context, usability should refer to work system design (EN ISO 6385) in that interaction between humans and system components (i.e. work task, equipment, place, and environment) should serve appropriate task performance and consider ergonomic design strategies and principles (Wickens et al., 2004; Helander, 2006). With regard to safeguard of machinery, however, it is important to take into account both sides of the story. Safety measures are an integrated component of work system design when they effectively prevent accidents, while at the same time do not hinder or compromise operations in non-accident situations. The latter refers to studies indicating about one third of safety measures being permanently or temporarily tampered or defeated (Schaefer & Lüken, 2005; Apfeld, 2010). Therefore, an essential issue in evaluations of safeguard measures is the specification of the focus of usability assessments (e.g. the functionality of the product or its purpose of use) and the description of the context of use (EN ISO 9241-11, 1998). For the given research project more detailed information about accidents are necessary to allow for developing and testing MEWP safeguards in relevant and appropriate scenarios. Some of the reasons of fatalities and injuries in the work with MEWPs especially in Germany should be considered relevant in evaluation studies.

1.2 Major hazards and potential causes

Reasons for the relatively high but varying number of fatalities and accidents are manifold (McCann, 2002; Pan et al., 2007; Stocker et al., 2012). First, this may have been caused by the still increasing number of MEWPs in operation. Secondly, MEWPs may be used more often and therefore potentially more hazards may have to be taken into account. Thirdly, since long MEWP manufacturers, rental companies, users, and occupational safety and health organisations (e.g. BGHM, BGHW, IFA, IPAF, NIOSH) have been engaged in efforts to improve MEWP safety, however, newly developed safety equipment and safety procedures take long to become effective in everyday work and in MEWPs already in use. Finally, it is not always easy to investigate the effectiveness of safety devices and procedures in the context of use, in order not to place operators in danger.

Efforts in accident prevention and accident analysis yielded some information on endangering and contributory conditions. This information may also be helpful for the development of work scenarios in simulation studies for an assessment of safety measures. From analyses of the accident insurance statistics from 1996 to 2000, Jäger (2002) and McCann (2002) drew attention to the rising number of accidents with MEWPs. Although pointers to possible causes of accidents can only be derived from the statistics to a limited extent, the main hazard proved to be that of collapses or tip-overs of MEWPs. Similar results were revealed by a compilation by Schilling (2007) that illustrated hazards based on accident events and additionally identified prevention measures. Some of the safeguards and protective measures have already been included in standards and technical information (e.g. EN 280, 2010).

According to analyses of fatal accidents, reported to the German FIOSH from 1992 to 2008, the risk of crushing has become apparent as a key accident factor or major hazard in addition to the risk of falling (Deuchert, 2010). In such accidents, the operator is trapped between the MEWP's guardrail and parts of the surroundings (e.g. joists, beams, steel roof structures) (BGI 720, 2013). Attributing the accident solely to MEWP operator behaviour, classified as operator error, easily leads to an underestimation of the effects of equipment design on human-system interaction in the work process. Combinations of primary prevention measures, such as protective measures (BGI 720, 2013; NN, 2012), and secondary prevention measures, such as operator training on the safe use of MEWPs (BGG/GUV-G 966, 2010; Strategic Forum for Construction, 2010), may have good prospects for preventing accidents.

In summary, analyses and reports of accidents due to crushing or trapping fail to reveal any straightforward systematic in the causal conditions (e.g. design of specific MEWP component, working height). Nevertheless, they do each show varying combinations of contributory conditions (e.g. irregular steel structure of the ceiling, obstacles, MEWP boom rotation angle > 90°, insufficient lighting of the work area; Stocker et al., 2012), most of which are documented as hazards in EN 280 (2010) or in Strategic Forum for Construction (2010). Combinations of such hazards are decisive for the development of work scenarios for usability evaluation studies. The development and testing of mixed reality work scenarios will be an essential step to inform about its suitability for an evaluation of MEWP safeguards under development and in the context of use. Based on contributory conditions to crushing as a major hazard, scenarios for MEWP operations will be set up in a mixed virtual environment. In a pilot study, operator performance measures will be taken to provide information about operator behaviour in hazardous situations relevant for usability evaluations of MEWP safety measures.

2. MATERIAL AND METHODS

2.1 Testing environment

The pilot study was scheduled in the VR laboratory of the IFA (www.dguv.de/ifa/sutave) equipped with a 7 m² operating space in front of a curved presentation wall of 24 m² (3 m x 8 m). The wall represents a 164° circle segment of 2.8 m arc radius. The physical dimensions allowed the workspace and projection area big enough to fully cover the human field of vision for stereoscopic depth perception when facing the projection wall. Dimensioning also facilitated interaction of human operators with large stationary machinery. Interference filter technology (Infitec®, Infitec GmbH, Germany) was applied to 3D rear projection with three pairs of high luminance projectors (F2 series, projectiondesign as, Norway) and to operator 3D glasses to experience depth cues in three-dimensional space. Four infrared cameras for motion capturing (VICON®, OMG plc, UK) mounted on top of the projection wall served a dynamic match in real-time between operator body and head movements and the adaptation required for visualisation of the virtual environment (Huelke et al., 2010). This way, operator movements and movements in the environment were optimally and in real time adjusted to the vision of an individual operator. In addition, the operator experience of presence and immersion in the mixed virtual environment were supported.

In the laboratory, the scenarios for the study were set up in mixed VR. A real work platform of a MEWP, designed according to EN 280 (2010), including a real control panel was placed in the operating space in front of the virtual environment projection. The work platform and control panel allowed the operator to get a haptic feedback when leaning against and touching the railing of the platform as well using the joysticks, dials, knobs, and buttons of the control panel (see Figure 1). The control panel for the MEWP was similar to industry standard, but especially designed to match the specific functionality required and to fit the purpose of the study. Two joysticks served lowering, rising, rotating, slewing, and travelling of the MEWP (EN 280, 2010). Safety functions in the form of emergency stops (Nischalke-Fehn & Bömer, 2011) were added to both joysticks. It was assumed that in some circumstances an emergency stop at maximum level of deflexion of the joystick lever might contribute to avoidance of crushing accidents or at least to reduce the level of severity of injuries caused by these accidents (Nischalke-Fehn & Bömer, 2011).

Figure 1: Operator driving and inspection task performance in the mixed reality work scenario (VR projection adjusted to operator view and not to camera perspective)

The virtual environment encompassed the remaining parts of the MEWP such as the chassis and the extending structure and a shopping centre. The work scenario was designed with Python (Python Software Foundation, USA) and was presented by the Vizard Virtual Reality Toolkit (WorldViz LLC, USA). The MEWP used in this study was based on a 3D model of a Haulotte HB40 boom lift (TurboSquid Inc., USA). The chassis of the model was modified in shape, size and texture. This was done to improve the fit to the VR system and to the work scenarios used in the present study (see Figure 1). In addition, physical models of gravity, of movement and moving parts, of collision, of sound and shadow were integrated to allow for realistic appearance and movements and for safety features of a standard MEWP as described in EN 280 (2010). The roof of the virtual shopping centre was built on top of a steel construction with binders attached to 12 bearing pillars (see Figure 1). The shopping centre and the distances between pillars required to use a MEWP for appropriate performance of inspection tasks. Real and virtual objects co-operated in real-time during human-machine interaction. During interaction real and virtual worlds merged, i.e. movements of real control actuators by the operator directly controlled movements of the virtual MEWP within the virtual work scenarios.

2.2 Operator tasks and measures taken

In order to investigate the suitability of the work scenarios for usability evaluations of the safety functions supplemented to the MEWP joysticks (Nischalke-Fehn & Bömer, 2011) it was required to perform inspection and driving tasks in the work scenario. The key purpose of the safety functions was to avoid crushing accidents. Because of the mixed VR used for scenario design, it should not only be possible for operators to behave as in real work environments. They should even be able to experience dangerous or hazardous situations, without being placed in danger. This allowed testing the safety functions in the context of use facing demands of close to reality work scenarios. A usability evaluation in these situations would refer to whether, to what extent and result, when and how operators were being able to take advantage of the safety functions.

An important requirement of safety functions in order to be effective is to avoid its inadvertent use in non-hazardous situations. Based on studies in industry with regard to safeguard of machines it was found that about one third were permanently or temporarily defeated (Apfeld, 2010). Among others, reasons for tempering safeguards could often be seen in non-ergonomic design of task procedures and work equipment caused by safeguards themselves (Schaefer & Lüken, 2005). An evaluation of the usability of the MEWP emergency stop functions would require considering its use in non-hazardous situations. It would be relevant to know whether, to what extent, when and how the safety functions were used in an inadvertent manner. Whenever the operator experiences dangerous or hazardous situations, he/she should feel free to use the built-in safety function.

The operator main task was to inspect compounds of the ceiling construction by using a MEWP. The inspection referred to 12 binders attached to the pillars specified in the operator work instructions. The operator was asked to check for proper bolting and for corrosion of the binders connecting the bearing pillars with the roof of the shopping centre (see Figure 1) and if necessary, make notes about maintenance work required. The inspection and driving tasks required the operator to stay as close as possible to the specified steel compounds. The number of successful inspections determined inspection task performance.

Driving the MEWP was another operator task. Driving parameters such as speed, movements and angularity of the MEWP chassis and the extending structure were taken as measures for task performance. Records were also taken for the use of MEWP controls, the route taken in the shopping centre, the number of collisions, the number of triggered emergency stops, and the time required to get to the inspection points close to the ceiling. The operator was asked for sustained attention because of elevated crossings in the middle of the two-floor shopping centre and because inspection points were close to the ceiling. While measures of operator task performance would serve an effectiveness assessment of usability, task load measures were taken to assess the efficiency and the satisfaction of the use of the safety function in work scenarios. Heart rate variability (HRV, coefficient of variation of inter-beat intervals; Zeier, 1979; Manzey, 1998) and the NASA Task Load indeX (NASA TLX; Hart & Staveland, 1988) provided information about the effort required for task performance in the work scenarios.

2.3 Experimental procedure

The procedure was more elaborated because the pilot study served as a test-bed and should inform about the suitability of the experimental design. At the beginning of the experimental session, the participant was asked to fill in a questionnaire on demographic information, health, visual acuity, handedness and physical fitness. This information served to check among others for detrimental effects on psychophysiological measures. The Polar® RS800 (Polar Electro Oy, Finland) device was attached for continuous recording of inter-beat intervals of the electrocardiogram and questionnaires for initial operator state assessment were presented. Baselines were taken for Simulator Sickness (SSQ; Pfendler & Thun, 2001), Immersive Tendency (ITQ; Witmer & Singer, 1998) and the NASA TLX. A period of about 10 min served to become familiar with the mixed virtual environment, wearing Infitec® glasses for 3D perception, and using the MEWP controls. During this period, the operator used the safety function of the control panel for testing purposes. Afterwards, operator instructions were discussed and he/she was asked to perform the inspection and driving tasks according to instructions. In the debriefing section the SSQ, NASA TLX and the Presence Questionnaire (PQ; Witmer & Singer, 1998) were presented for final operator state assessment.

3. PRELIMINARY RESULTS OF THE PILOT STUDY

The inspection task required the operator of the self-propelled MEWP to check for proper bolting and for corrosion of the binders, which connected the bearing pillars and the roof of the shopping centre (see Figure 1). The operator managed to approach individually all twelve binders and could assess each binder, thus has been able to perform appropriately the inspection task in all cases. The distances between the pillars, the construction of the ceiling, and the location of the binders close to the ceiling made it necessary to change frequently location of the MEWP chassis. After having reached a suitable location on ground level close to a pillar, the extending structure and the work platform of the MEWP was to be raised, lowered, and rotated to approach an individual binder. Driving task performance, therefore, required extensive control activities to approach and to assess all 12 binders. The angularity continuously taken from the single boom of the MEWP indicated its movements for a 20 min sequence of task performance, as illustrated in Figure 2. The boom was at highest altitude level at an angularity of about 60°. At less than 10° the boom was close to ground level in transport position. A step function consisting of 12 high plateaus marked relatively short time intervals when the MEWP operator inspected the binders close to the ceiling. As a result, the time for the inspection task, i.e. to approach and to assess individual binders, was about 15 % (3 min) of the total time required for the driving tasks.

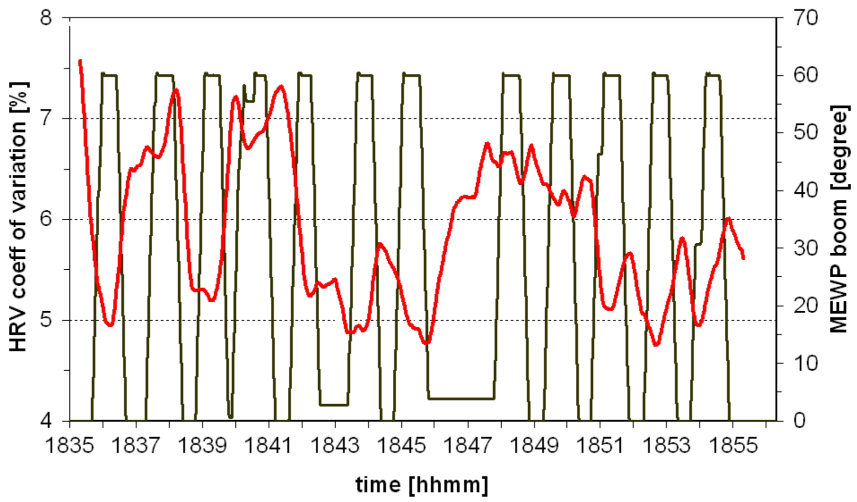

Figure 2: HRV (bold red line; left) and MEWP boom angularity (fine black line; right).

In order to explore the control activities of the same 20 min task sequence, also speed measures were taken from the MEWP chassis and from the work platform. According to the results indicated in Figure 3, the MEWP came to a rest when speed measures indicated levels neither being positive (e.g. moving forward or upwards) nor negative (i.e. moving backwards or downwards). The remaining periods in Figure 3 are congruent with the high plateaus for boom angularity in Figure 2. Therefore, the measures also pointed out time intervals of inspection periods close to the joists or steel roof structures at the ceiling. This indirectly provides information about control activities with the joysticks of the MEWP control panel.

Results presented in Figure 3 also indicated that the MEWP was driven at all levels of speed available (i.e. min to max level). For shorter time intervals, the MEWP even remained at highest level of speed. This is in accordance with measures taken from the MEWP joystick. Control actuations were continuously recorded in order to inform about the position of the joystick control lever (e.g. neutral, MEWP movement, emergency stop at max deflexion). The analysis of the control performance of the operator revealed that at no time the safety function of the joystick was triggered. The operator used the safety function only during the training period for testing purposes of the controls and for familiarisation. No collision or accident occurred during task performance, although the operator was required to get close to the inspection points in order to assess binders and the risk of collision was high. Consequently, there was no need for the operator to use the emergency stop that would have triggered a safety function.

It was also interesting to know whether and to what extent the safety function would be used inadvertently. During MEWP movements, the level of deflexion of the control levers remained within normal boundaries and no indication is given for inadvertent use of the safety function. This suggests, that the safety function of the joystick and the level of a force required for actuation of the emergency stop seemed to be well designed to avoid inadvertent release of the supplementary safety related measure built-in the joysticks of the MEWP control panel. Despite the measure being effective to avoid defeating the measure, however, operator feedback indicates that the level of force required may have been too high to be used in crucial or hazardous situations.

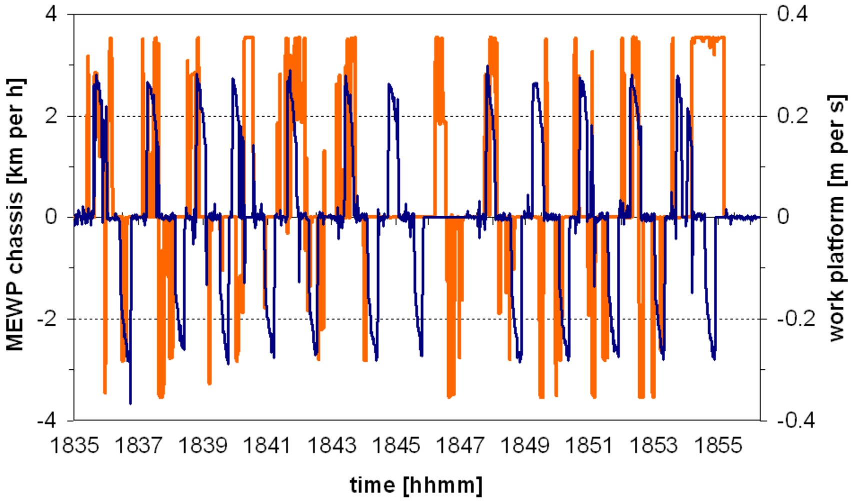

Figure 3: MEWP chassis speed (bold orange line; left) and platform speed (blue line; right).

At about mid sequence of the time scale in Figures 2 and 3 a longer gap occurred for MEWP platform movements. This was because of two reasons. First, in the middle of the shopping centre an elevated crossing connected left and right side of the first floor and resulted in a longer distance between pillars (see Figure 1). Second, the operator was instructed to approach the binders in a predefined sequence. In the middle of the shopping centre he headed for a pillar not indicated as next in the instructions, however, realised the mistake before moving upwards and relocated the MEWP chassis to the pillar according to instructions. Apart from the detour, operator driving task performance was maintained at high level and no collisions occurred during MEWP movements in the shopping centre. Driving task performance data in combination with the topographical representation of the work environment would also allow for documentation of movements and near collisions within a 3D space.

The MEWP operator task load as indicated by the NASA TLX yielded a moderate level at about 62 (out of 100) on average for the 20 min task sequence. Analysis of HRV, however, allowed for continuous information about operator task load and suggested variations in parallel with operator inspection and driving tasks (see Figure 2). Increases in level or relatively higher levels of HRV indicate reductions and relief in operator workload or effort, whereas decreases and relatively lower levels rather suggest elevations in effort expenditure and activation. According to the results presented in Figure 2 increases and peaks in HRV (i.e. decrease in effort level) seemed to coincide with leaving inspection points and moving down to ground level. More importantly, increases in effort expenditure and activation (i.e. HRV decrease) went along with approaching inspections points, requiring complex control activities in order to avoid collisions with joists or steel roof structures at the ceiling or hazardous incidents at height.

4. DISCUSSION AND CONCLUSION

Work scenarios for MEWP operations have been successfully developed in a mixed VR simulation setting and results of the pilot study suggest that, in principle, the simulation environment is suitable for usability assessments of MEWP safeguards under development and in the context of use. All functionality of the MEWP controls has been used to manoeuvre the platform of the MEWP in the shopping centre and to individual binders close to the steel construction of the ceiling. During the remaining session time, inspections have been performed according to instructions. Results obtained from simulation sickness ratings (SSQ) for the session showed negligible symptoms only, referring to sickness scores much lower than reported on average across simulation studies (Stanney et al., 1997) and arguing in favour of the mixed VR work scenarios used in the pilot study. Interactive task operations in the scenarios also resulted in high ratings for perceived immersion and presence; above average when compared to results obtained from other studies (Witmer & Singer, 1998). Since the binders were close to the complex steel construction of the ceiling, approaching and leaving inspection points could be assumed more dangerous. Results of the psychophysiological measure suggest that task performance in potentially hazardous situations may have costs in terms of increases in effort, activation, or threat of collision. The application of operator performance, psychophysiology, and ratings as efficiency measures seem promising as they tap relevant dimensions of human behaviour when interacting with complex systems (Wickens et al., 2004) and have the potential to provide evidence for the effectiveness and efficiency of the usability of the safety measure.

A comparison between VR and real work environments has not been the focus of the present study, but safety research provides some evidence for comparable results in both environments (Simeonov et al., 2005; Marc et al., 2007; Nickel et al., 2012c). However, some studies also report, that behavioural responses in simulation environments may not always be as clear-cut or affective as in reality (Stickland et al., 1997; Stanney, 2002). While the results suggest effective and high quality work scenarios for the present study, it has not been possible to test the emergency stop during MEWP operations. Collisions with obstacles or other components around the MEWP occurred neither in hazardous work situations when operating the MEWP close to the ceiling, nor in normal work situations when driving in transport position. Similar to accidents or errors, collisions are rare events, are not easy to predict and do happen surprisingly. It is therefore concluded, that for usability evaluation of safety measures, more effort is required to better design a risk for collisions in hazardous work scenarios.

Usually, during normal operations no use of the safety function built-in the MEWP joysticks in form of an emergency stop could be interpreted as a positive result. This would indicate that inadvertent actuations of the function were avoided and the joysticks, with the additional safety function, do not hinder, disrupt or disable the normal workflow (Schaefer & Lüken, 2005). However, this interpretation would have only been possible with emergency stops detected, because too much force could have been required to trigger the safety function built-in the joysticks. Future investigations into this type of safety measures, therefore, should include the force required as a variable relevant for the usability evaluations in different contexts of use.

Although the empirical basis is too small to draw general conclusions, the results provide evidence for an appropriate quality of the mixed VR simulation environment for usability evaluations of a supplementary safety measure in form of an emergency stop built-in the joysticks to control MEWP operations. This provides a sound basis for guiding more elaborated usability studies along the lessons learned and experiences gained in the pilot study. Occupational health and safety should therefore proceed in follow its long tradition in simulation research to use its specific advantages. It will not substitute traditional techniques for analysis, design and evaluation in laboratories or in the field, but bridging the gap between them (Chapanis & van Cott, 1972). Applied research in human-system interaction in the context of accident prevention and product safety, as already initiated by accident insurance institutions, may therefore be extended to simulations of hazardous work scenarios without placing operators in danger or to simulations of future work scenarios for today's prevention through design.

ACKNOWLEDGEMENTS

This work refers to project IFA5118 initiated by the DGUV Expert-committee 'Trade and Logistics', Sub-committee 'Goods Handling, Storage and Logistics' in cooperation with German Social Accident Insurance Institution for the woodworking and metalworking industries (BGHM) and for the trade and distribution industries (BGHW). Results of the study were presented, in part, at the 6th International Working on Safety Conference "Towards Safety through Advanced Solutions", Sopot, Poland, in September 11-14, 2012. We would like to thank anonymous reviewers for valuable comments on an earlier draft of the paper.

REFERENCES

Apfeld, R., 2010. Stop defeating the safeguards of machines. Proceedings of the 6th International Conference on Safety of Industrial Automated Systems (SIAS 2010) (F6001, 1-6), June 14-15, 2010, Tampere, Finland. Finish Society of Automation, Helsinki.

Aromaa, S., Helin, K., 2011. Enhancing designers' experience of the final product by using virtual environment. Proceedings of the ACM CHI Conference on Human Factors in Computing Systems (CHI 2011), May 7-12, Vancouver, Canada.

BG Chemie, 2003. Mensch-Sicherheit-Technik. Gestern, Heute, Morgen [Human-Safety-Technology. Yesterday, Today, Tomorrow (ACHEMA 2003 broschure)]. BG Chemie, Heidelberg.

BGG/GUV-G 966, 2010. Ausbildung und Beauftragung der Bediener von Hubarbeitsbühnen (Grundsatz) [Training and assignment of MEWP operators (convention)]. DGUV, Berlin.

BGI 720, 2013. Sicherer Umgang mit fahrbaren Hubarbeitsbühnen [Safe use of mobile elevating work platforms]. BG HM, Mainz.

Chapanis, A., van Cott, H.P., 1972. Human engineering tests and evaluations. In: van Cott, H.P., Kinkade, R.G. (eds.), Human engineering guide to equipment design, pp. 701-728. AIR, Washington.

Cobb, S., Neale, H., Crosier, J., Wilson, J.R., 2002. Development and evaluation of virtual environments for education. In: Stanney, K.M. (ed.), Handbook of virtual environments, pp. 922-936. LEA, Mahwah.

Deuchert, A., 2010. Unfälle mit Hubarbeitsbühnen. Fehlverhalten als häufigste Ursache. VMBG Mitteilungen 4 (Aug/Sept), 23.

EN 280, 2010. Mobile elevating work platforms - Design calculations - Stability criteria - Construction - Safety - Examinations and tests (includes Amendment A2:2009). CEN, Brussels.

EN ISO 6385, 2004. Ergonomic principles in the design of work systems. CEN, Brussels.

EN ISO 9241-11, 1998. Ergonomic requirements for office work with visual display terminals (VDTs) - Part 11: Guidance on usability. CEN, Brussels.

Hart, S.G., Staveland, L.E., 1988. Development of the NASA task load index (TLX). In: Hancock, P.A., Meshkati, N. (eds.), Human mental workload, pp. 139-183. North-Holland, Amsterdam.

Helander, M., 2006. A guide to human factors and ergonomics. CRC Press, Boca Raton.

Helin, K., Evilä, T., Viitaniemi, J., Aromaa, S., Kilpeläinen, P., Rannanjärvi, L., Vähä., Kujala, T., Pakkanen, T., Raisamo, R., Salmenperä, P., Miettinen, J., Patel, H., 2007. HumanICT. New human-centred design method and virtual environments in the design of vehicular working machine interfaces (VTT Working Papers 73). VTT Technical Research Centre of Finland, Tampere.

Huelke, M., Nickel, P., Lungfiel, A., Nischalke-Fehn, G., Schaefer, M., 2010. Cave automatic virtual environments for research into occupational safety and health – practical recommendations and solutions for the construction. Proceedings of the 6th International Conference on Safety of Industrial Automated Systems (SIAS 2010) (Jun 14-15, 2010, Tampere, Finland), F6044, pp. 1-4. Finish Society of Automation, Helsinki.

Jäger, W., 2002. Einsatz von Hubarbeitsbühnen [Use of MEWP]. Die BG 12, 608-612.

Leskinen, T., 2005. Improving safety by interactive design and simulation in immersive virtual work space. Presentation on the Virtsafe Workshop, July 4-6, 2005, CIOP-PIB, Warsaw, Poland.

Määttä, T.J., 2007. Virtual environments in machinery safety analysis and participatory ergonomics. Human Factors and Ergonomics in Manufacturing 17(5), 435-443.

Manzey, D., 1998. Psychophysiologie mentaler Beanspruchung [Psychophysiology of mental workload]. In: Rösler, F. (Hrsg.), Ergebnisse und Anwendungen der Psychophysiologie (Enzyklopädie der Psychologie, C/I/7), pp. 799-864. Hogrefe, Göttingen.

Marc, J., Belkacem, N., Marsot, J., 2007. Virtual reality: A design tool for enhanced consideration of usability 'validation elements'. Safety Science 45, 589-601.

McCann, M., 2002. Areal lift safety in construction. Presentation at the 12th Annual Construction Safety & Health Conference & Exposition, May, 2002, Rosemont.

Miller, C., Nickel, P., Di Nocera, F., Mulder, B., Neerincx, M., Parasuraman, R., Whiteley, I., 2012. Human-machine interface. In: Hockey, G.R.J. (Ed.), THESEUS Cluster 2: Psychology and human-machine systems – Report, pp. 22-38. Indigo, Strasbourg.

Naber, B., Nickel, P., Huelke, M., Lungfiel, A., 2012. An investigation in virtual reality on human factors requirements for human-robot-collaboration. Book of abstracts of the 6th International Working on Safety Conference "Towards Safety through Advanced Solutions" (Sep. 11-14, 2012, Sopot, Poland), pp. 72-73. CIOP-PIB, Warsaw.

Nickel, P., Lungfiel, A., Huelke, M., Pröger, E., Kergel, R., 2012a. Prevention through design in occupational safety and health by risk assessment of virtual river locks. Proceedings of the 7th International Conference on Safety of Industrial Automated Systems (SIAS 2012) (Oct 11-12, 2012, Montréal, Canada), pp. 35-40. Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST), Montréal.

Nickel, P., Lungfiel, A., Naber, B., Hauke, M., Huelke, M., 2012b. Virtual reality in occupational safety and health for product safety and usability. Proceedings of the 7th International Conference on Safety of Industrial Automated Systems (SIAS 2012) (Oct 11-12, 2012, Montréal, Canada), pp. 41-46. Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST), Montréal.

Nickel, P., Lungfiel, A., Huelke, M., Schaefer, M., 2012c. Evaluationsstudien zur Tiefenwahrnehmung in realer und virtueller Roboterzelle [Evaluation studies on depth perception in real and virtual robot cells]. In: Gesellschaft für Arbeitswissenschaft (Hrsg.), Gestaltung nachhaltiger Arbeitssysteme - Wege zur gesunden, effizienten und sicheren Arbeit, pp. 243-247. GfA-Press, Dortmund.

NIOSH, 2007. Current TI research goals and sub goals: Reduce injuries and fatalities due to falls from elevations. In the evidence package provided to the committee to review the NIOSH TI research program. National Institute of Occupational Safety and Health, Washington.

NIOSH, 2009. NIOSH Researchers partner with equipment manufacturers and standards committees to protect workers from falls (DHHS (NIOSH) Publication No. 2010-166). National Institute of Occupational Safety and Health, Washington.

Nischalke-Fehn, G., Bömer, T., 2011. Use of a modified joystick for the avoidance of crushing accidents on elevating work platforms. Focus on IFA's work 0332, 1-2.

NN, 2012. Overhead protection. cranes & access 5(2012), 24-25.

Pan, C.S., Hoskin, A., McCann, M., Lin, M.-L., Fearn, K., Keane, P., 2007. Aerial lift fall injuries: A surveillance and evaluation approach for targeting prevention activities. Journal of Safety Research 38 (6), 617-625.

Pfendler, C., Thun, J., 2001. Der Simulator Sickness Questionnaire von Kennedy et al. (1993) und seine rechnergestützte Version (Technischer Bericht) [Simulator sickness questionnaire by Kennedy et al. (1993) and its software version (Technical Report)]. Forschungsinstitut für Kommunikation, Informationsverarbeitung und Ergonomie, Wachtberg.

Saulewicz, A., Myrcha, K., Skoniecki, A., Kalwasiński, D., 2005. VR fork lift simulator – challenges and limitations. Presentation on the Virtsafe Workshop, July 4-6, 2005, CIOP-PIB, Warsaw, Poland.

Schaefer, M., Lüken, K., 2005. Reasons for the manipulation (tampering) of protective devices. Proceedings of the 4th International Conference on Safety of Industrial Automated Systems (SIAS 2005) (Sep 26-28, 2005, Chicago, USA), S 8, pp. 1-7. Automation Technologies Council (ATC), Ann Arbor.

Schilling, N., 2007. Sicherer Umgang mit Hubarbeitsbühnen [Safe use of MEWP]. Die Brücke 6/01, 15-19.

Simeonov, P.I., Hsiao, H., Dotson, B.W., Ammons, D.E., 2005. Height effects in real and virtual environments. Human Factors 47 (2), 430-438.

Stanney, K.M. (ed.), 2002. Handbook of virtual environments. LEA, Mahwah.

Stanney, K.M., Cohn, J.V., 2012. Virtual environments. In: Salvendy, G. (ed.), Handbook of human factors and ergonomics, pp. 1031-1056. Wiley, Hoboken.

Stanney, K.M., Kennedy, R.S., Drexler, J.M., 1997. Cybersickness is not simulator sickness. Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting, pp. 1138-1142, HFES.

Stickland, D., Hodges, L., North, M., Weghorst, S., 1997. Overcoming phobias by virtual exposure. Journal of Communications of the ACM 40 (8), 34-39.

Stocker, K., Deuchert, A., Zepp, C., 2011. Hubarbeitsbühnen (Sicherheit und Gesundheit) [Elevating work platforms (Safety and Health)]. BGHM-Aktuell 4(2011), 16-20.

Strategic Forum for Construction, 2010. Best practice guidance for MEWPs. Avoiding trapping / crushing injuries to people in the platform. Published for the Strategic Forum for Construction – Plant Safety Group by Construction Plant-hire Association, London.

Wickens, C.D., Lee, J.D., Liu, Y., Gordon Becker, S.E., 2004. An introduction to human factors engineering. Pearson, Upper Saddle River.

Witmer, B.G., Singer, M.J., 1998. Measuring presence in virtual environments: A presence questionnaire. Presence 7(3), 225-240.

Zeier, H., 1979. Concurrent physiological activity of driver and passenger when driving with and without automatic transmission in heavy city traffic. Ergonomics 22(7), 799-810.