Virtual reality training platform for a computer numerically controlled grinding machine tool

Journal Article

Author(s):
Hirt, Christian; Spahni, Martina; Kompis, Yves; Jetter, Dominic; Kunz, Andreas

Publication date:
2021

Permanent link:
https://doi.org/10.3929/ethz-b-000488893

Originally published in:
International Journal of Mechatronics and Manufacturing Systems 14(1), https://doi.org/10.1504/ijmms.2021.115460

Virtual reality training platform for a computer numerically controlled grinding machine tool

Christian Hirt*, Martina Spahni, Yves Kompis, Dominic Jetter and Andreas Kunz

Innovation Center Virtual Reality,
ETH Zurich,
Leonhardstrasse 21, CH-8092, Zurich, Switzerland
Email: hirtc@iwf.mavt.ethz.ch
Email: spahni@iwf.mavt.ethz.ch
Email: ykompis@student.ethz.ch
Email: djetter@student.ethz.ch
Email: kunz@iwf.mavt.ethz.ch
*Corresponding author

Abstract: In-depth training of machine tool (MT) operators is crucial to avoid machine damage due to faulty operation. However, machine-hours are costly and during the training, the MT is unavailable for regular production purposes. Here, virtual real-size models offer a solution by providing basic operation principles to future operators. In this context, it is yet unknown whether a virtual teaching enhanced by real walking is similar to a real teaching scenario regarding the learning efficiency and long-term memory retention. This paper describes a study comparing the learning efficiency of a virtual training session with traditional instructions on a real MT. The learning success of both training groups is objectively and subjectively assessed on a real MT a week later. In this assessment, the task completion time and the number of errors are recorded. We observed that the virtually taught group slightly outperformed trainees taught in reality regarding both objective measurements.

Keywords: virtual reality training; digital twin; digital manufacturing; machine tool; virtual reality; learning transfer; machine tool training; virtual reality application; industrial application for virtual reality; real walking in virtual reality; immersive virtual reality.

Reference to this paper should be made as follows: Hirt, C., Spahni, M., Kompis, Y., Jetter, D. and Kunz, A. (2021) 'Virtual reality training platform for a computer numerically controlled grinding machine tool', *Int. J. Mechatronics and Manufacturing Systems*, Vol. 14, No. 1, pp.1–17.

Biographical notes: Christian Hirt is a PhD student at ETH Zurich, Switzerland. He earned his MSc in Mechanical Engineering at ETH Zurich in 2017 with a focus on robotics and mechatronics. Since August 2017, he has worked on virtual reality applications in the scope of his dissertation.

Martina Spahni is a PhD student at ETH Zurich, Switzerland. She achieved her MSc's degree in Mechanical Engineering at ETH Zurich in 2016 with specialisation in manufacturing and machine tools. Starting October 2016, her research focus lies on process cooling.

Yves Kompis is a Master student in Mechanical Engineering at ETH Zurich.

Dominic Jetter is a Master student in Mechanical Engineering at ETH Zurich.

Andreas Kunz is a Professor at ETH Zurich, Switzerland. He obtained his degree in Electrical Engineering at the Technical University in Darmstadt in 1989 and finished his PhD in Mechanical Engineering at ETH Zurich in 1998. Since July 2006, he is also an Adjunct Professor at BTH.

This paper is a revised and expanded version of a paper entitled 'Alles rund um die Maschine – Begehbare virtuelle Schulung an Werkzeugmaschinen' presented at *VAR2 – Realität erweitern*, Chemnitz, Deutschland, 4–5 December, 2019.

1 Introduction

Simple visualisation of complex geometries and accessibility for new users are the most relevant achievements of virtual reality (VR). Initially, the absence of sufficient computational power and easy-to-access, affordable VR infrastructure limited the use of VR for industrial purposes. Additionally, cumbersome output devices further impaired a seamless integration into existing work processes. Consequently, such an integration of VR systems caused additional expenses both in a financial as well as in a procedural perspective due to time-consuming data refinement and the employees' adaption to newly incorporated hardware.

Not only the VR equipment caused issues, but also its complex operation required specifically trained personnel to enable users to passively experience a virtual environment. A classic example is the so-called cave automatic virtual environment (CAVE) from Cruz-Neira et al. (1992), which required a large space, expensive equipment, as well as trained personnel to operate and maintain. Due to these limitations, it was not possible for a long time to allow exploratory behaviour, which affected the so-called sense of presence as defined by Slater (2003). Later, technical development allowed navigation by teleportation (i.e., point and jump) to a certain extent. Certainly, this did not completely satisfy an industrial user's expectation because of the abrupt, unnatural feeling. Accordingly, the user acceptance was rather low and useful applications could not profitably be employed in industrial environments.

More recently, technical advancements result in less expensive and easier-to-use VR equipment. In industry, especially the use for training purposes becomes more popular due to its simple integration into business processes and equipment handling. These recent advances not only drastically improve the quality of the visual representation by using a head-mounted display (HMD), but also allow a more natural and direct interaction with the virtual environment. Therefore, a paradigm shift from passive user behaviour, mostly being used for showing images, to an active user behaviour, in which a user becomes a part of the virtual environment, is observed.

This active user behaviour promotes the use of VR for educational purposes, for which active participation of the learner is essential for long-term learning success. By using modern VR equipment, more complex operations from real life can be mapped into a virtual training environment (VTE), for example the operation of a machine tool (MT). Compared to a traditional training in a real life scenario, a virtual training offers crucial advantages. For instance, the hourly cost that is accumulating whenever an MT is used for training instead of production can be omitted. In VR, no additional costs arise from tool wear or material consumption. Another valuable advantage of VR is safety. Dangerous or faulty manipulations of the real MT could result in injuries of the trainee or machine damages, which are completely avoided when using a VTE as stated by Dalgarno and Lee (2010). Unlike in a real training environment, the exact same training sequences could be repeated multiple times, with consistent boundary and starting conditions. Further, the training can be interrupted and continued again at any time. A more advanced VTE allows triggering malfunctions of the MT by the click of a button, which is convenient for the training of future operators as well as of service technicians.

In this paper, we address the question whether enhancing a VTE with the immersive feature ‘real walking’ allows trainees to perform similarly or better compared to traditional teaching. If we add real walking as an immersive feature, will the trainees be able to transfer the virtually gained knowledge to the real world? To tackle this question, a user study was designed and implemented to verify the capabilities of a VTE compared to a traditional training. In the user study, objective and subjective measures were recorded to ensure the capture of training effectiveness and users’ task load.

In Section 2, we discuss aspects of general industrial acceptance and present some related work. In Section 3, we introduce the design of the user study and guide through its implementation and conduction. In Section 4, we highlight the most relevant results of the user study, and discuss them together with their limitations in Section 5. Finally, we conclude in Section 6 and dare a brief glimpse into the close future of learning and teaching in VR.

2 Literature review

The idea that acquiring new skills requires a fixed schedule and the presence of a teacher was valid for a long time. This gave rise to a mostly passive learning experience for trainees. But in recent years, it became clear that the efficacy of the learning process benefits from an active learning experience. This allows a trainee to adjust the learning speed based on their personal experience and learning rate. However, out of habit, trainees are often still taught by instructors. But the increasing capability and availability of computers lead to numerous studies investigating the advantages of VTEs, e.g., by Garnier et al. (2014), Langley et al. (2016), Mehrfard et al. (2020), Ostrander et al. (2020), Gisler et al. (2020), or Osti et al. (2020). These virtual learning environments provide a personal learning experience for each trainee, while making a personal instructor obsolete. There is a multitude of possibilities to include virtual environments in the learning process. Depending on the interpretation, the first steps toward teaching in VR were already made by explanatory videos and 3D-animations. Even though videos allow an insight in environments that are not accessible in reality, for example the inside of a pressure tank or an oven, this kind of VR is not interactive at all and therefore similar to passive teaching by an instructor. In other VR applications, the user actively engages with the exclusively virtual content, where they can push virtual buttons, move virtual parts, use virtual handles, etc.

The key distinction between different VR applications is the level of immersion. Non-immersive training environments mostly rely on desktop applications, visualised on a simple computer screen. The user interacts with the application by a mouse or similar. In contrast, highly immersive VTEs allow a user to dive into the virtual world for example by using an HMD with spatial sound.

According to Slater (2003), immersion and presence should be treated differently. Immersion objectively describes the hardware capabilities whereas presence is the human reaction to immersion. The findings of studies on non-immersive and highly immersive VTE so far suggest that learning and training is improved by increased immersion and thus increased sense of presence, as stated by Langley et al. (2016) and Sowndararajan et al. (2008). Ragan et al. (2010) for example used a CAVE system and reduced the field of view as well as the field of regard to test this correlation. They found that performance in procedure memorisation was significantly reduced with lower levels of immersion.

VR systems are particularly suitable to train sequential procedures such as assembly tasks as described by Brough et al. (2007), Gavish et al. (2015), or Hirt et al. (2019). The required motoric skills are easily integrated in an interactive VTE as was shown by Jensen and Konradsen (2018). It was shown by Sowndararajan et al. (2008) in multiple studies that VTEs not only allow fast knowledge acquisition, but also an increased memorisation was demonstrated in Babu et al. (2018), Passig et al. (2016) and Sportillo et al. (2018).

The VR studies presented above did not take into account the influence of real locomotion since they all used unnatural locomotion techniques such as teleporting. However, presence is increased when real walking is used (Usoh et al., 1999). Furthermore, participants using real walking performed better in virtual exploration tasks than those using joystick interfaces regarding navigation and way-finding (Grant and Lochlan, 1998). The real-walking-group travelled shorter distances to find specific targets in the real environment compared to the joystick-group. Spatial information combined with visual inputs also seems to support the memorisation process, following Maguire et al. (2003) and Nyberg et al. (2003).

So far, it has not been shown yet that the operation of a machine tool can be trained by using a VTE only, and that the gained knowledge can be transferred to a real world operation of such a machine. Thus, the study presented in this paper allows large-scale real walking around an entire MT and aims to compare the learning outcome of this VTE to a traditional teaching carried out by an instructor.

3 Materials and methods

In this section, we describe the hardware components employed for the user study and a general overview of the study design.

Technical setup

The system utilised for the user study consists of an extended HTC Vive Pro system, which includes an HMD, two controllers, and four connected lighthouses for tracking, allowing a tracking space of 6×8 m. Thus, it is possible to naturally walk around the virtual MT instead of employing locomotion metaphors such as teleporting. The user wears a backpack-mounted XMG U507 laptop with an integrated NVIDIA GeForce GTX 1070 graphics card, an i7-6700 processor (@3.4GHz) and 16GB RAM. The computer drives the HTC Vive Pro system and renders the complete VTE. For the realistic rendering of the MT, 3D sounds are replayed via the HMD's headphones.

The MT used for the user study is a five-axis grinding machine 'GrindSmart 528XW' from Rollomatic. Such machines are used for manufacturing rotating cutting tools such as milling cutters or drill bits. Due to the high complexity of the cutting tools, also the handling of the MT's interface is quite advanced. This MT thus offers a wide spectrum of possible training tasks with varying complexity.

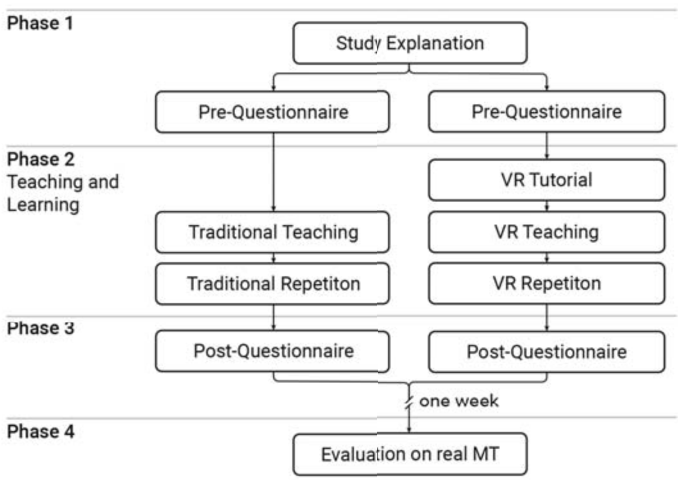
3.1 Study design

The presented study aims to answer the question whether trainees who received their training in VR are able to perform equally well as trainees who were trained in a traditional way. Unlike previously highlighted examples and their outcomes, our technical setup and virtual environment require the trainees to really walk to change their virtual location. Since this is still a rather uncommon kind of locomotion in VR, specifically in larger spaces than the HTC Vive's inherent tracking area (i.e., >16 m^2), it remains questionable whether the same conclusions about learning effectiveness can still be drawn as for other unrealistic locomotion metaphors.

This study also investigates potential differences in the learning outcome regarding the long-term memory. In order to do this, a learning task on an MT is developed and carried out in the scope of a user study. For this, the subjects are divided into two groups. The first group ("traditional group") receives a traditional training from an instructor on the real MT. The second group ("VR group") is taught the same operations in a VTE. Right after the teaching, the trainees are asked to repeat the tasks they were shown during their teaching session in their respective environment. One week after the training, the trainees from both groups are asked to redo the task on the real MT. During this evaluation, the completion time is measured and the number of errors is counted by a supervisor.

Figure 1 shows the structure of the study consisting of four phases. After a brief explanation of the study, trainees have to fill out pre-questionnaires in phase one. The second phase is dedicated to the training of the individual groups and consists of two (respectively three) components. Afterwards, trainees are asked to answer post-questionnaires in phase three. The post questionnaires conclude the first day of the study and trainees are invited to return one week later to complete the fourth phase: the evaluation on the real MT. The individual phases are elaborated in more detail in Section 3.3.

Figure 1 Structure of the study



3.2 Data acquisition

As suggested in literature by Langley et al. (2016), it is essential to simultaneously show evidence for effectiveness and efficiency to prove the usefulness and industrial applicability of a VTE. Accordingly, we conduct subjective and objective measurements to verify these core requirements. For the subjective measurements, we employ relevant and state-of-the-art questionnaires, while we use a mixture of manual and automated objective measurements.

The subjective questionnaires used in phase one contain a custom demographic questionnaire (i.e., age, gender, VR and MT affinity) and a simulator sickness questionnaire (SSQ) for the VR group. The SSQ is a powerful tool which allows to test participants for symptoms regarding simulator sickness (Kennedy et al., 1993). Each of the different symptoms (e.g., nausea) is rated on a 4-point scale from 'none' to 'severe'. In case a study participant shows a weighted accumulation of such symptoms, the participant is most likely biased by these sensations and is excluded from further evaluation processes. The SSQs are answered before and after VR exposure and using the difference of these ratings, the participant's well-being is verified. Accordingly, the SSQ is filled out again in phase three along with the NASA task load index (NASA TLX) (Hart and Staveland, 1998) and the slater-Usoh-steed (SUS) Presence (Slater et al., 1994) questionnaire. The NASA TLX is an established questionnaire which is used to identify a person's workload or cognitive demand (e.g., mental demand, level of frustration). Each of the TLX's questions is rated on a scale from 1 to 100. Finally, the SUS Presence questionnaire is a state-of-the-art questionnaire focusing on the degree of presence a person can sense during VR exposure and is filled right afterwards. If a study participant feels truly immersed, they temporarily accept the virtual environment as part of their current being and thus effectively experience the training. The SUS Presence questionnaire consists of seven questions, each of them is answered on a 7-point Likert scale.

Addressing the objective measurements, we record the completion time and the total number of errors in phase four. We utilise these two measures to assess the performance of the single trainees and to directly compare the two groups.

3.3 Teaching and learning

In this section, we present the four tasks the trainees are asked to master and apply.

3.3.1 VR tutorial

To reduce trainees' bias originating from no or only little experience in VR, each trainee of the VR group completes a tutorial to get used to a generic virtual environment. In this tutorial, they are first introduced to the VR equipment and then taught how to perform simple interactions in VR such as pressing a button, interacting with a touch screen, and moving a sliding door.

3.3.2 Teaching

The focus of our study lies on the comparison of teaching trainees either virtually or on the real MT various tasks concerning machine handling and operation. However, we aim to avoid evaluating a specific application and focus on the influence of adding immersive features on the learning effect and long-term memory retention. Therefore, we chose simple operational tasks that are required to follow in a sequential order such as opening a valve or pressing a pushbutton. This allows a fast implementation of the required functionalities, while the focus of the VTE is on learning the correct sequence.

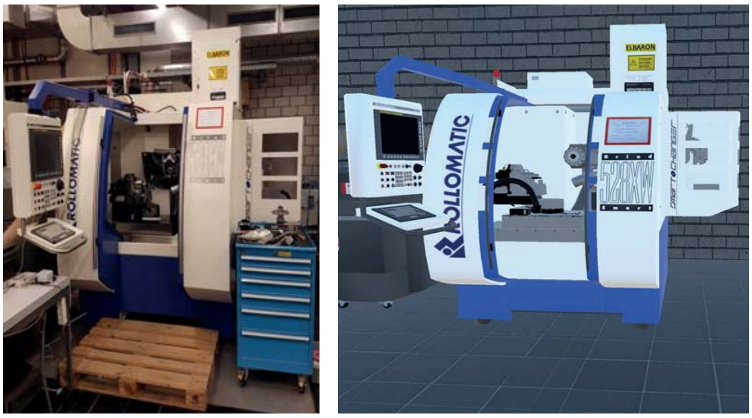
Both kinds of teaching (real and virtual) are kept as similar as possible to ensure that the trainees gain the same knowledge in both conditions. Therefore, the VTE intentionally abstains from classical benefits of VR (e.g., highlighting of important parts) and provides the same amount of information as the real teaching scenario. In the real teaching part, the trainee is guided through the tasks step-by-step by an instructor. Both groups are not allowed to interact with the MT during the teaching sequence.

Taking the aforementioned constraints into account, the following core tasks are selected for our study, which should be learnable in a short period of time:

- powering up the MT
- initiating a reference run of the MT
- using the tool changer to switch to a different grinding wheel
- switching off the MT

These basic tasks are taught to both groups, either on the real or the virtual MT (see Figure 2).

Figure 2 Real MT and the virtual twin (see online version for colours)



Instructions on the virtual MT are generally shown to the trainees using the principle of the so-called 'floating hands", which will demonstrate every task (see Figure 3).

The visualisation employing the floating hands is further supplemented by a detailed, verbal explanation. This phase can also be seen as an interactive video which introduces the trainee to the topic using animations without requiring any input from them. In the following, the training tasks are described in more detail.

Task 1: Powering up the MT

In this task, the compressed air supply for the MT is activated first to allow motion of the MT's axes. The valve for the compressed air supply is located on the wall behind the MT (see Figure 4). The instruction shows and tells the user to slowly open the valve to avoid pressure shocks in the MT's piping.

Figure 3 Explanations at the virtual MT using floating hands (see online version for colours)

Figure 4 Real valve for the compressed air and the virtual twin (see online version for colours)

After activating the compressed air supply, the MT has to be electrically powered up. The main switch for the power supply is located at the back side of the MT (see Figure 5).

Once the air supply is secured and the main switch activated, the initialisation process of the MT is continued at the control panel in the front. Here, the MT's computer is powered up first with the main switch located at the bottom of the vertical control panel (see Figure 6).

The trainee now waits until the boot process of the computer has finished. Then, the user is instructed to start the MT by pressing the green 'O' pushbutton (see Figure 7). The successful start of the MT control is indicated by lighting up the pushbutton and by illuminating the interior of the MT.

Lastly, the control GUI is started by double-clicking the respective icon on the touch-screen on the control panel (see Figure 8). This finalises the boot sequence and the trainee is ready to proceed.

Figure 5 Real main switch for the power supply and the virtual twin (see online version for colours)

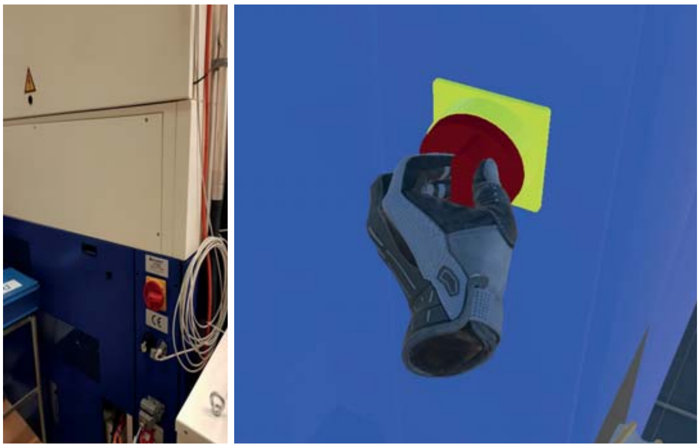


Figure 6 Real start-up button for the computer and the virtual twin (see online version for colours)

Figure 7 Real main button for the machine control and the virtual twin (see online version for colours)

Task 2: initiating a reference run of the MT

After each complete restart, a reference run is initiated for the self-calibration of the MT. This is typically done while the doors of the MT are open. Thus, for safety reasons, it has to be guaranteed that none of the operator's hands can reach the moving axes. Accordingly, the trainee needs to hold the handle of the control panel to avoid injuries. This is done by pressing a pushbutton on the handle bar with one hand, and by simultaneously pressing a yellow pushbutton on the control panel with the other hand (see Figure 9).

Figure 8 Starting the control GUI (see online version for colours)

Figure 9 Initiating a reference run (see online version for colours)

Task 3: Exchanging a Grinding Wheel

The exchange of the grinding wheel is done by using the automatic tool changer while the doors are closed. Thus, the virtual instruction first demonstrates how the doors are closed (see Figure 10).

Figure 10 Instruction how to close the machine doors (see online version for colours)

Next, the instruction explains the locking mechanism of the doors: By turning the key on the control panel into the position 'LOCKED' (see Figure 11), the locking mechanism of the machine doors is activated. With the doors locked, a simple GUI guides the trainee through the routine of the tool changer by interacting with the touchscreen of the control panel. Once the grinding wheel is exchanged, the doors can be unlocked again by turning the key into the position 'UNLOCKED".

Figure 11 Locking the doors on the real control panel and the virtual twin (see online version for colours)

Task 4: Switching off the MT

Switching off the MT is done in reverse order compared to the startup process. Thus, the virtual instructions are also presented in the reverse order.

3.3.3 Repetition

Right after the instruction, both groups are given the possibility to train the newly learned knowledge. Accordingly, the trainees are asked to go through the same sequence of tasks in the right order, but this time on their own without an expert's instruction or any other additional help. The individual repetition is conducted in the same environment as the training, i.e., trainees experiencing the VTE also repeat the sequence virtually, and vice versa for the other group.

3.4 Evaluation

One week after the training session, the trainees were asked to reproduce the gained knowledge. The evaluation for both groups was conducted on the real MT to further identify the transfer of virtually taught information to reality. Accordingly, each trainee performed the four previously taught tasks by interacting with the real MT. The instructor was always present during this evaluation and only intervened if there was any danger to the MT or the trainee. Furthermore, due to general safety concerns, the trainees were asked to announce interaction with the MT to the instructor prior to its execution. In case the instructor needed to intervene, both spontaneously or regarding announcements, the intervention was counted as an error. Otherwise, the trainee was only allowed to interact with the instructor if they were unaware of the continuation of the sequence. Since the trainees knew that interacting with the instructor would count as an error, they avoided interaction in most cases.

4 Results

During the user study, in total 19 participants (age 28±5, 18 male) were trained: ten in the VTE, and nine using the real MT. None of the participants had worked with this particular MT before, however general MT experience was balanced between the groups. For the VR group, half of the participants did have some experience in VR before. For both conditions, the training (i.e., teaching and repetition) duration was limited to prevent a bias due to a longer training exposure. The subjective measures from questionnaires filled in the first and third phase are shown in Tables 1 and 2.

Table 1 NASA TLX questionnaire results (rated from 1 to 100)

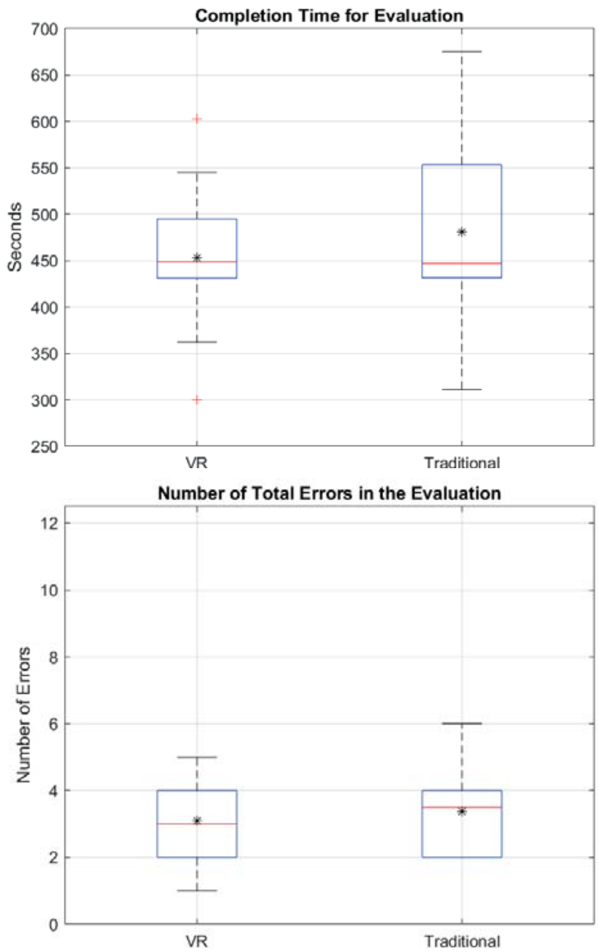
NASA TLX	*Mental demand*	*Physical demand*	*Frustration*
VR	49.6	13.6	16.3
Traditional	37.1	18.8	27.1

Table 2 Presence (7-point Likert scale) and SSQ results (evaluated according to Kennedy et al. (1993))

Presence		$\Delta SSQ = \lvert SSQ_{\text{Pre}} - SSQ_{\text{Post}} \rvert$
Mean	*STD*	*Mean*
5.13	1.05	6.36

The objective results for completion time and total number of errors for the evaluation phase are given in Figure 12.

Figure 12 Objective results of the evaluation: completion time (top) and number of errors (bottom). Boxplots are given with the median in red, bottom and top edges of the box indicate the 25th resp. 75th percentile, outliers are marked with '+' and the average using a star mark (see online version for colours)



5 Discussion

Considering the results of the SSQ (see Table 2), none of the participants were excluded due to simulator sickness. Furthermore, the realistic and detailed model of the MT, authentic sounds, and also the possibility to walk around the virtual MT, e.g., for opening or closing the valve for compressed air, led to a high acceptance of the VTE. This was not only received as a qualitative feedback after the study, but is also shown in the results from the presence questionnaire (see Table 2). With an average value of 5.13 (out of 7), a very good presence score was achieved. A further subjective measure, the TLX, is presented in Table 1. Whereas the mental demand was perceived to be higher for the VR group, the physical demand and level of frustration both indicate the opposite. Specifically, the comparative results of the mental and physical demands seem reasonable, since the VR group is mainly exposed to digital content and the only physical task is walking whereas the other group also needs to fully interact with the real MT. The lower level of frustration of the VR group is presumably caused by VR still being seen as a new and exciting technology, especially for trainees with little to no VR experience.

Even though the difference is small, it is still remarkable that the VR group made less errors than the traditionally trained group in the evaluation one week after the training. This shows that VR is not only capable of addressing a trainee's memory retention, but also that virtually taught information can be transferred to a real application. Furthermore, the completion time in the evaluation also seems to be very similar, with a slight favour for the VR group. Both of these observations may additionally be influenced by the fact that the VR group was exposed to fewer external distractions than in the traditional case. For example, the virtual MT was isolated from the rest of the shop floor and thus no other visual distractions exist during the training (e.g., from a neighbouring MT). Further, the instructions were visible more clearly since the instructor would not block the view. Eventually, also the different perspective may have given the VR group a slight advantage. Instead of watching the instructor presenting the sequence and interactions from a third person perspective, VR trainees often acted as if the floating hands belonged to them and accordingly changed to a first person view. This observation has already been shown to have minor positive effects on knowledge retention (Makransky et al., 2017)).

6 Conclusion

This paper presented a novel way to introduce trainees without prior knowledge to simple MT operations of a grinding machine by providing them with the possibility of real walking in a virtual environment. The training was designed in such a way that a single trainee masters four basic operational tasks, i.e.,

- powering up the MT
- initiating a reference run of the MT
- exchanging a grinding wheel
- switching off the MT.

The core of the training, teaching and learning, was divided into two parts. In the first part, the trainees were mainly taught how the four operations work by demonstrating and verbally explaining the tasks, whereas in the second part, the trainees were asked to repeat the operations by themselves. To assess the virtual training, we conducted a user study with two groups. One group experienced the training in a fully immersive VR using an HMD, while the other group was instructed utilising a real MT. The user study was divided into four phases, namely pre-questionnaires, teaching and learning, post-questionnaires, and one week later, an evaluation. This evaluation was performed on the real MT regardless of the trainee's earlier group allocation. Besides common state-of-the-art questionnaires for VR exposure, we assessed the performance of the trainees regarding task completion time and number of errors. Both groups performed very similarly, with slight advantages for the VR group. These results show that adding the immersive feature of real walking VR allows a basic training of simple operations for MTs with a reasonable effort. Besides an improved knowledge retrieval due to the individualised character of VR, it is also possible to save costs for the machine hours required for training in the traditional way, as well as for the instructor. The real MT and the instructor could then be used for more complex training tasks that cannot be represented in VR with the same quality yet, due to the current limitations related to the controllers which do support full haptic feedback and gestures only to a limited extent.

Future work will research on the effect of immersion, i.e., on the required technical effort to generate an efficient VTE. In the presented paper, we used a highly-immersive system, but the training content could probably also be taught with a less immersive system, e.g., by using a smartphone. On the contrary, it is also still possible to increase the immersion by allowing a more realistic representation of the trainee's hands in the VTE. This could be investigated by employing additional hardware which allows finger tracking. This would render the standard controllers of the HTC Vive obsolete and would support a more intuitive manual interaction (e.g., with the touch screen of the MT). Furthermore, on top of improved hand tracking, providing realistic haptic feedback most likely establishes the next major step in VTEs. So far, the MT tutorial is aimed at trainees without or very little prior experience in operating an MT. Thus, the target group (the trainees) is a younger generation, represented in our study by mainly inviting students to the training. A generalised age group cannot simply be assumed, could however potentially be investigated in further studies by additionally evaluating a personal innovativeness questionnaire for the participants. In this way, there may be some correlation between the age of participants and the reception of the virtual training.

Acknowledgement

We would like to thank all of our trainees who have participated in the user study. We are particularly grateful to the company Rollomatic SA, Le Landeron, for providing the real 'GrindSmart 528XW'.

Christian Hirt and Martina Spahni contributed equally to the paper.

References

Babu, S., Krishna, S., Unnikrishnan, R., Bhavani, R. (2018) 'Virtual reality learning environments for vocational education: a comparison study with conventional instructional media on knowledge retention', *18th IEEE International Conference on Advanced Learning Technologies (ICALT)*, IIT Bombay, Mumbai, India, pp.385–389.

Brough, J., Schwartz, M., Gupta, S., Anand, D., Kavetsky, R., Pettersen, R. (2007) 'Towards the development of a virtual environment-based training system for mechanical assembly operations', *Virtual Reality*, Vol. 11, No. 4, pp.189–206.

Cruz-Neira, C., Sandin, D., DeFanti, T., Kenyon, R. and Hart, J. (1992) 'The CAVE: audio visual experience automatic virtual environment', *Communications of ACM*, Vol. 35, No. 6, pp.64–72.

Dalgarno, B. and Lee, M. (2010) 'What are the learning affordances of 3-D virtual environments?', *British Journal of Educational Technology*, Vol. 41, pp.10–32.

Garnier, F., Horaeau, C. and Tisseau, J. (2014) 'Evaluation of procedural learning transfer from a virtual environment to a real situation: A case study on tank maintenance training', *Ergonomics*, Vol. 57, No. 6, pp.828–843.

Gavish, N., Gutiérrez, T., Webel, S., Rodríguez, J., Peveri, M., Bockholt, U. and Tecchia, F. (2015) 'Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks', *Interactive Learning Environments*, Vol. 23, No. 6, pp.778–798.

Gisler, J., Hirt, C., Holzwarth, V. and Kunz, A. (2020) 'Designing virtual training environments: Does immersion increase task performance?', *International Conference on Cyberworlds*, Caen, France, pp.125–128.

Grant, S.C. and Lochlan, E.M. (1998) 'Contributions of proprioception to navigation in virtual environments', *Human Factors*, Vol. 40, No. 3, pp.489–497.

Hart, S. and Staveland, L. (1993) 'Development of NASA-TLX (task load index): results of empirical and theoretical research', *Advances in Psychology*, Vol. 52, pp.139–183.

Hirt, C., Holzwarth, V., Gisler, J., Schneider, J. and Kunz, A. (2019) 'Virtual learning environment for an industrial assembly task', *International Conference on Consumer Electronics*, Berlin, Germany, pp.337–342.

Jensen, L. and Konradsen, F. (2018) 'A review of the use of virtual reality head-mounted displays in education and training', *Journal of Education and Information Technologies*, Vol. 23, No. 4, pp.1515–1529.

Kennedy, R., Lane, N., Berbaum, K. and Lilienthal, M. (1993) 'Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness', *The International Journal of Aviation Psychology*, Vol. 3, No. 3, pp.203–220.

Langley, A., Lawson, G., Hermawati, S., D'cruz, M., Apold, J., Arlt, F. and Mura, K. (2016) 'Establishing the usability of a virtual training system for assembly operations within the automotive industry', *Human Factors and Ergonomics in Manufacturing and Service Industries*, Vol. 26, No. 6, pp.667–679.

Maguire, E.A., Valentine, E.R., Wilding, J.M. and Kapur, N. (2003) 'Routes to remembering: The brains behind superior memory', *Nature Neuroscience*, Vol. 6, No. 1, pp.90–95.

Makransky, G., Terkildsen, T. and Mayer, R. (2017) 'Adding immersive virtual reality to a science lab simulation causes more presence but less learning', *Learning and Instruction*, Vol. 60, pp.225–236.

Mehrfard, A., Fotouhi, J., Forster, T., Taylor, G., Fer, D., Nagle, D., Navab, N. and Fuerst, B. (2020) *On the Effectiveness of Virtual Reality-based Training for Robotic Setup*, arXiv preprint, 01540.

Nyberg, L., Sandblom, J., Jones, S., Neely, A.S., Petersson, K.M., Ingvar, M. and Bäckman, L. (2003) 'Neural correlates of training-related memory improvement in adulthood and aging', *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 100, No. 23, pp.13728–13733.

Osti, F., de Amicis, R., Sanchez, C. A., and Tilt, A. B., Prather, E. and Liverani, A. (2020) 'A VR training system for learning and skills development for construction workers', *Virtual Reality*, Vol. 24, Nos. 3–4, pp.1–16.

Ostrander, J.K., Tucker, C.S., Simpson, T.W., Meisel, N.A. (2020) 'Evaluating the use of virtual reality to teach introductory concepts of additive Manufacturing', *ASME. J. Mech*, Vol. 142, No. 5, p.051702.

Passig, D., Tzuriel, D. and Eshel-Kedmi G. (2016) 'Improving children's cognitive modifiability by dynamic assessment in 3D immersive virtual reality environments', *Computers and Education*, Vol. 95 pp.296–308.

Ragan, E., Sowndararajan, A., Kopper, R., Bowman, D. (2010) 'The effects of higher levels of immersion on procedure memorization performance and implications for educational virtual environments', *Presence*, Vol. 19, No. 6, pp.527–543.

Slater, M., Usoh, M., Steed, A. (1994) 'Depth of presence in virtual environments', *Presence: Teleoperators and Virtual Environments*, Vol. 3, No. 2, pp.130–144.

Slater, M. (2003) 'A note on presence terminology', *Presence Connect*, Vol. 3, No. 3, pp.1–5.

Sowndararajan, A., Wang, R. and Bowman, D. (2008) ‘Quantifying the benefits of immersion for procedural training’, *Proceedings of the 2008 Workshop on Immersive Projection Technologies/Emerging Display Technologies*, Los Angeles, California, USA, pp.2.1–2.4.

Sportillo, D., Avveduto, G., Tecchia, F. and Carrozzino, M. (2018) ‘Training in VR: a preliminary study on learning assembly/disassembly sequences’, *International Conference on Augmented and Virtual Reality*, Otranto, Italiy, pp.332–343.

Usoh, M., Arthur, K., Whitton, M. C., Bastos, R., Steed, A., Slater, M. *et al.* (1999) ‘Walking> walking-in-place> flying, in virtual environments’, *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques*, Los Angeles, California, USA, pp.359–364.

Abbreviations

CAVE	Cave automatic virtual environment
GUI	Graphical user interface
HMD	Head-mounted display
MT	Machine tool
NASA TLX	NASA task load index
SSQ	Simulator sickness questionnaire
SUS presence	Slater Usoh steed presence
VR	Virtual reality
VTE	Virtual training environment