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Original Article

Use of virtual reality technology in chainsaw operations, education and training

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Abstract

Wood harvesting operations represent one of the industrial sectors with the highest risk of accidents at work. In semi-mechanized logging operations, the great majority of accidents generally occur using chainsaws during tree felling. Unfortunately, these situations frequently cause serious injuries and even the deaths of workers. In numerous cases, the accidents occurred to people who were badly trained and inexperienced, with a short employment history. One solution to reduce these harmful events is to support workers employed in this sector with training applications. This paper presents a description of a research and training programme for operating with chainsaws in tree felling operations using a Virtual Reality (VR) application called ForestVRoom. This innovative education method was compared with the traditional theoretical lesson based on a slide show. The results of the training were verified through a statistical analysis of questionnaires administered to a sample of 45 students in undergraduate and master's degree programmes at the School of Agriculture and Forestry at the University of Florence. We have shown that the combination of traditional didactics and symmetrical collaborative VR leads to an increase in knowledge and especially in the ability to understand situations in a real forest site. VR is a useful teaching tool that can complement conventional training methods because of its potential to provide an immersive and attractive experience that facilitates learning and recognition of situations in forest sites.

Introduction

One of the most common pieces of equipment used for tree pruning, felling and processing is the chainsaw (Picchio *et al.*, 2010; Albizu-Urionabarrenetxea *et al.*, 2013), as it is extremely versatile and implies low investments (Russell & Mortimer, 2005; Liepiņš *et al.*, 2015). This tool is used in forestry, although it is also used in households and gardens, agriculture, arboriculture, construction and rescue (Cividino *et al.*, 2012; Hammig & Jones, 2015). However, the use of a chainsaw is connected to numerous hazards and one of the highest accident rates both in professional and non-professional work (Klun & Medved, 2007; Tsioras *et al.*, 2014; Laschi *et al.*, 2016). Many accidents are due to lack of knowledge and training concerning health and safety recommendations (Ferreira *et al.*, 2022; Häggström & Edlund, 2022).

Despite the technological improvements introduced on this machine, the inadequate training of workers in the use of the chainsaw continues to be one of the main problems (Albizu-Urionabarrenetxea *et al.*, 2013; Melemez, 2015; Cheţa *et al.*, 2018). The most dangerous activity for operators is felling and processing trees. In detail, the three most common types of fatality are due to being hit by a tree or branch, slipping and being cut by the chainsaw (Robb & Cocking, 2014; Laschi *et al.*, 2016). The workers involved in motor manual tree felling and processing are the most exposed to the risks in the forestry sector (Spinelli *et al.*, 2016). These aspects reveal that tree harvesting-related work is very dangerous (Peters, 1991; Bell, 2002; Lefort *et al.*, 2003; Albizu-Urionabarrenetxea *et al.*, 2013; Robb & Cocking, 2014).

Numerous studies have examined the risk factors related to the use of chainsaw (Table 1) and the knowledge created in this study is crucial to develop specific training programmes that are a key element to reduce accidents (Allman *et al.*, 2017; Damalas *et al.*, 2019).

Nowadays, new training programmes for operators are being developed in all working sectors. In the field of forestry, these are always based on a theoretical part and on a practical one focused on working techniques (Albizu-Urionabarrenetxea *et al.*, 2013). Sometimes, it can be difficult, due to the seasonality of the work, the availability of forests or the weather conditions, to carry out all the practical tests scheduled by the training programme. In this context, complementing theoretical lessons with practical experiences through Virtual Reality (VR) could be very useful.

VR has become very popular in recent years and it is successfully used in training and education in many industries, such as medicine, military, entertainment, marketing and architecture. VR is based on a virtual environment (VE) that gives the user the experience of being somewhere other than his or her actual location (Xie, 2010). It simulates the real world, current or past, to allow the user to view and experience an environment that is not the present reality. This advanced form of communication has the goal to create as real of an experience for the user as possible (Riva *et al.*, 2004). VR has for example been recognized as a powerful tool for investigating issues related to the health and safety of forest machine operators (Dickey *et al.*, 2013; Müller *et al.*, 2019). VR-based training should simulate as closely as possible

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Table 1. Previous studies related to risk factors analysis in chainsaw operations.

Authors	Examined factor	Key findings
Wang *et al.*, 2003, Lefort *et al.*, 2003, Bentley *et al.*, 2002, Shaffer and Milburn, 1999	Experience	Injuries occurred to workers with <1 year of employment.
Neely and Wilhelmson, 2006, Wilhelmson *et al.*, 2005, Thelin, 2002, Salminen *et al.*, 1999	Operator's age	Logging injuries occurred most frequently to workers under 35 years old.
Picchio *et al.*, 2010, Montorselli *et al.*, 2010, Wang *et al.*, 2003	Seasonality and type of company	Most injuries occurred November through March. Crews from public companies showed a significantly lower frequency of risk-taking behaviour.
Cividino *et al.*, 2015, Blombäck *et al.*, 2003, Häggström and Edlund, 2022, Ferreira *et al.*, 2022	Training activities	The best safety performance is achieved when there is a regular usage of the chainsaw and when a formal safety training is administered.
Albizu-Urionabarrenetxea *et al.*, 2013, Lilley *et al.*, 2002	Frequency of use	Near-miss injury events are more common amongst those reporting a high level of fatigue and length of working time.
Albizu-Urionabarrenetxea *et al.*, 2013	Use of personal protective equipment	The 50% of workers injured or involved in an accident reported that they were not fully using their safety gear.
Thelin, 2002, Salminen *et al.*, 1999, Peters, 1991	Working technique	The major causes of felling fatalities are a hang up fell (26%), poor felling technique (15%), butt rebound (11%), broken limbs or tops (11%), working too close (11%), a snag fell (8%). Firewood production was shown to be a key factor behind the large number of accidents for self-employed.
Tamboreno *et al.*, 2015, Robb and Cocking, 2014, Tamboreno, 1989	Working site features (work at height)	Lack of training detected on rescue techniques.

the actual machine system, equipment and environment in which the trainee is to operate (Brunnström *et al.*, 2018; Brunnström *et al.*, 2019). If this can be achieved, VR can be used as an aid in training to recreate conditions that would otherwise be logistically impossible to create during real-life trainings due to high costs or hazard risk.

A previous study (Wodzyński, 2020) focused on the development of a training platform for operating portable chainsaws using VR technology. Wodzyński (2020) simulates phenomena occurring whilst working with a chainsaw, such as falling tree parts, the occurrence of chips and characteristic sound effects. The application allows controlling a virtual chainsaw using a real-life device tracked by a system for mapping objects in space. The system was verified by comparing the results obtained from a sample of people during a practical test based on the users' ability to complete the work phases performed, respectively, with a controller and a dummy chainsaw. The task completion time and efficiency were measured and results revealed that, despite the much longer time to complete a single task in the dummy chainsaw mode, the average efficiency was 61 per cent higher than in the controller mode. Furthermore the surveyed testers, highly appreciated the dummy chainsaw control mode for its versatility and accuracy. Other studies (Brunnström *et al.*, 2018; Brunnström *et al.*, 2019) investigated the use of simulators in wood harvesting training with highly mechanized machines, such as harvesters and forwarders. Simulators and VR can be particularly useful when harvesting processes involve multiple operations and require an additional need for coordination, such as in the case of cable land clearing or combined mechanized and manual felling operations (Müller *et al.*, 2019). With the introduction of VR training, professional trainers have been able to record precisely their movements in real-time as well as monitor the evolution of trainees' performance during their training sessions (Dickey *et al.*, 2013; Westerberg & Shiriaev, 2013; Zahabi & Razak, 2020).

Lapointe and Robert (2000), who conducted several hands-on VR trainings, found that an additional 25 h of VR training led to harvested volume increases by 23 per cent. The authors also stated that with the supplementary VR training, repair and maintenance costs were reduced by 26 per cent during the first month of operation in the field (Lapointe & Robert, 2000). VR-based training resulted in a 10 per cent increase in productivity compared with the traditional classes (Lapointe & Robert, 2000).

In summary, only a few studies have analyzed the use of VR for training people on manual chainsaw operations (Wodzyński, 2020). However, the potential seems high given the constraints often observed with respect to organizing practical and theoretical lectures in a limited amount of time. Whilst VR has been generally found to be a valuable educative approach (Renganayagalu *et al.*, 2021; Saredakis *et al.*, 2020), one main limitations of VR for educative purposes is the isolation of the user in the virtual experience (Vergara *et al.*, 2022). The paired use of traditional lectures and VR lectures has hardly been examined and whilst many studies have evaluated the effect of the VR approach on the learning performance (Pirker & Dengel, 2021; Zahabi & Razak, 2020), the perceived quality of the virtual experience has rarely been studied (Brunnström *et al.*, 2019). In this study, we address these points with the following research question (RQ) and hypothesis:

RQ. Is it possible to create a VR app with educationally effective storytelling for chainsaw forestry operator training, improving collaboration between teachers and students?

The RQ will be tested through the following sub-questions (SQ):

SQ1: Does the combination of traditional lessons and VR experiences enhance learning?

SQ2: Do students positively evaluate the quality of a VR experience compared with a traditional lesson?

To answer these questions, we evaluate a new VR application, called ForestVRoom, which was developed for chainsaw operations training. This innovative training method was compared with a traditional theoretical lecture based on a slide show. The training results have been verified through statistical analysis of questionnaires administered to a sample of 45 students enrolled to a forestry degree.

Methods

VR system features and storytelling

Features

VR systems are divided into two categories (Bashabsheh *et al.*, 2019; Whyte & Whyte, 2007): (1) non-immersive VR (IVR) when the user views the recreated VE on a screen and can explore it through input peripherals, usually referred to as Desktop-based VR; (2) IVR, when the VE surrounds users and does so through specific hardware. Modern hardware that enables IVR systems are Head Mounted Displays (HMD), which are often combined with headphones that, thanks to the audio, increase users' immersiveness in the simulated world and can easily produce the visceral feeling of being in the real world. IVR also offers the possibility of creating low-cost, high-quality educational laboratories that replicate dangerous sites (Drey *et al.*, 2020).

IVR can be achieved through two technologies: a 360° immersive video and a three-dimensional (3D) modelling of a real-world scene. The 360° videos are made by video cameras with two or more fisheye lenses. They allow for very realistic VEs with low production costs. In 3D models, the VE is realized by a combination of geometric solids in a 3D space. They reproduce the real environment more artificially but allow for more efficient and extensive interaction between the VE and the user.

The application of the Collaborative Learning (CL) method to VR has made it possible to create IVR learning experiences that can be used in today's classrooms. CL between two categories of people (in our case the teacher and the class of students) is one approach, independent of VR, to increase learning outcomes (Slavin, 1980). Collaborative Virtual Reality (CVR) is a host-based virtual space in which participating users have different roles and privileges over educational interactions in the environment with the possibility of implementing multiple learning scenarios (Konstantinidis *et al.*, 2009). CVR is symmetrical if all users use the same device type, e.g. two VR headsets (HMDs) (Drey *et al.*, 2022), whilst it is asymmetrical if users use different device types, e.g. a VR HMD and a laptop (Grandi *et al.*, 2019) to access the VE. In the study by Drey *et al.* (2022), symmetrical collaborative VR provided statistically significantly greater presence, immersion, player experience and lower intrinsic cognitive load, all of which are important factors for learning.

ForestVRoom is a symmetric immersive CVR system that combines 360° videos and 3D environment models into one system. This system aims to merge the advantages of the two individual approaches and thereby minimize the limitations described above.

Storyboard and storytelling

ForestVroom's narrative is immersive and consists of visiting 15 virtual scenes. The initial setting serves to immerse students in the scene, a 360° image of the exterior of the Forestry Institute 'Il Paradisino,' the summer home of the University of Florence's forestry degree programmes. This scene is designed to familiarize participants with the new way of interacting in the VE. Immersed in this forestry setting, users receive textual information about the history of the forestry institute and, after reading the information, users can connect to the server and choose the role of a teacher or a student.

They then enter the main classroom where the virtual collaborative experience begins. Considering that the results of Drey *et al.* (2022) show that communication between participants in a symmetrical CVR is easier and more engaging if an avatar is present as a point of attention, we designed ForestVRoom so that participants can see themselves as a simplified avatar (represented by head and hand position) and recognize the teacher's avatar, which has a different appearance (wearing a customized high-visibility vest). The narrative requires the lecturer to begin by explaining protective equipment because it is a necessary condition for entering the woods. The teacher then enters a workshop modelled in 3D; the workshop contains all the personal protective equipment and tools needed by the forestry worker. The teacher has the freedom to set up his or her lesson by choosing for himself or herself how and which objects to present to the students. We chose this setting to be 3D because it is necessary to interact and visualize with the protective equipment and tools in 3D to fully capture all aspects. With each completed teaching step in the workshop room, prizes will be given to students as positive reinforcement. The prizes can be used to dress individual avatars in forestry worker safety clothing to continue to emphasize the importance of personal protective equipment.

Back in the main classroom, the teacher is free to choose amongst the 12 360° immersive videos to explain certain work safety aspects to the students. The list of videos is arranged within a whiteboard presented in the classroom and has been divided into three types of technical forestry operations: direction cut (two videos), main felling cuts (eight videos) and cross-cutting (two videos). Also within the videos, participants see themselves as avatars and can interact with each other collaboratively. The teacher has a dashboard for playing the video stream (pause, fast forward, fast reverse, etc.) and a laser with which to indicate points of interest. The 360° video was chosen to explain felling techniques because it was necessary to faithfully reproduce reality (Figure 1).

Study areas and immersive video shootings

The 360° immersive videos were shot in three forested areas located in the Tuscan-Emilian Apennines:

- Area A: 'Cutigliano' E:10.7569692; N:44.1058759;
- Area B: 'Teso Forest' E: 10.850808; N: 44.068433;
- Area C: 'Pian del Voglio' E:11.2314618; N:44.1677737

The forest areas are located at an elevation of ~1000–1300 m above sea level and host pure and even-aged stands of silver fir (*Abies alba* Mill.) with diameters between 30 and over 100 cm and heights between 20 and 30 m. In areas A and C, a silver fir clearcut was carried out on a small surface. Area C was characterized by larger tree diameters, all >60 cm at the cutting height, whereas in area A trees with diameters between 30 and 50 cm were cut. In area B, a thinning was carried out in a 50 year old stand of silver fir and cutting techniques related to small and medium-sized trees were adopted. In this area, the correct technique for taking down a hung-up tree safely and ergonomically was also performed and a corresponding video recorded. The chainsaws used were chosen amongst the professional models available on the market and the power and the length of the guide bar were identified in relation to the diametric dimensions of the trees to be cut.

Tree felling operations were carried out by qualified trainers of forestry operators from the University of Florence and the Tuscany Region. The following cutting techniques were performed:

1. Sink cut in trees with a diameter smaller than the guide bar length
2. Sink cut in trees greater than twice the guide bar length
3. Basic felling technique
4. Split level felling cut
5. 'Saved corner' felling cut

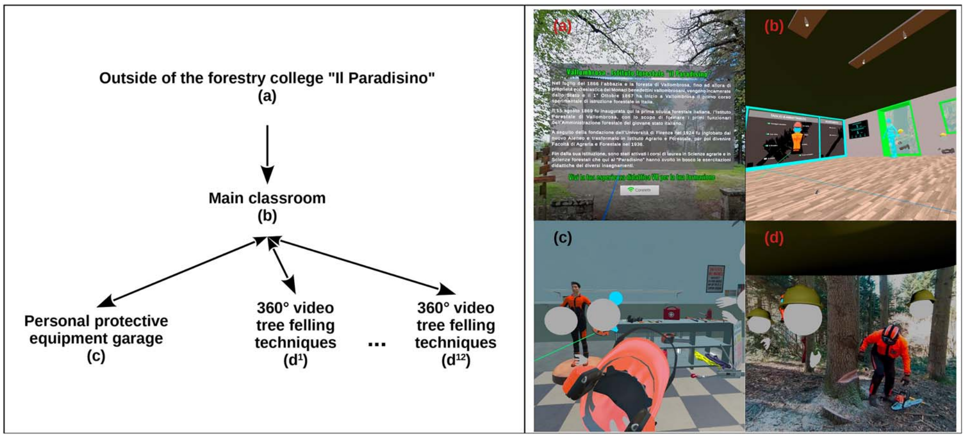

Figure 1. Storyboards and screenshots of the ForestVRoom application.

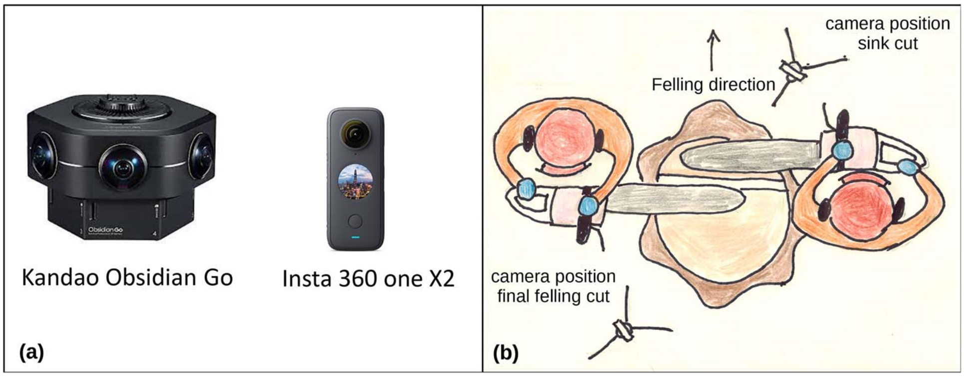

Figure 2. Video shooting.

6. Safe cut of a hung-up tree (hinge reduction and tree rotation)
7. Felling tree with hydraulic jack
8. Forward leaning tree cut with boring technique
9. Backward leaning tree cut using wedges
10. Felling trees greater than twice the guide bar length
11. Cross-cutting under compressive forces
12. Delimbling

Two video cameras were used for video shooting (Figure 2). The Kandao Obsidian Go is a professional six-lens video camera that can make 3D videos at 4K resolution; this camera due to its greater weight and bulk was used in easier localizations. The Insta360 one X2, on the other hand, is a two lens 5.7K resolution action camera and was used in the more complicated terrain or stand situation.

The shooting technique of the culls involved the use of two different camera points for the directional notch cutting and final culling operations (Figure 2). The cameras were placed ∼2 m from the operator; this position allows for views that students could not have during the actual felling for safety reasons.

Programming of the symmetric immersive collaborative VR system

The application was developed with Unity Engine 2020.3.24f1 software. Unity XR Plugin Management and XR interaction Toolkit packages were used for development in VR, and Unity Photon Pun, Photon Realtime and Photon Voice packages were used for multiplayer development. The application was developed and tested on Meta Quest2 visors. The total number of users who could simultaneously connect to the software was set to 10 (nine students and one teacher) to meet the data limits available in the free version of the Photon packages.

Each player's movements are synchronized with reality and being in multiplayer mode, avatar movements are synchronized over the network and visible to all users in real-time. This is done using the Remote Procedure Call (RPC) of the Photon package; each command in the dashboard invokes an RPC method that sends a signal over the network and allows synchronized playback of the video.

Each player can move freely in space autonomously through the use of the Teleport function associated with the controllers. This function was necessary to avoid overlap between avatars in the VE and to allow all users to have an optimal view of the digital lesson. The visit in the VE is guided by the teacher who chooses the order of the scenes to be visited. The teacher and students automatically move to the scene chosen by the teacher.

The initial classroom was modelled to meet the requirements of a VE spacious enough and clear of objects to allow the 10 users a comfortable digital presence. Inside the classroom, only the teacher can interact with the elements present, such as the 3D model of the lumberjack that allows entry into the garage and the blackboard on which the 12 buttons connected to the 360° videos are arranged.

The 3D workshop was downloaded from https://sketchfab.com/ and has been modified to suit our needs. Inside the workshop is a 3D character wearing only a cut-resistant suit like the one used by forestry workers at the University of Florence. Next to the forestry worker is a table with all the necessary personal protective equipment and forestry tools. At the moment the teacher picks up one of the objects on the table, a textual description appears above the table and the same object appears in the students' hands so that they can observe it closely. When the teacher releases the object, it is attached to the forester's uniform or his toolbox.

In the 360° videos, the dashboard is modelled in 3D according to the controls we found most useful in the video stream (play, pause, stop, forward 10 sec, forward 1 min, audio, mute) and is visible and can be interacted with only in the teacher's role. The dashboard allows the teacher to synchronize video playback for all users.

Students survey

The effectiveness of the ForestVroom application in supporting the chainsaw training operation was evaluated through an experiment with students. The objectives of the experiment were twofold: (1) to evaluate the learning outcomes of a class that was exposed only to traditional lectures and then to compare the increase in learning outcomes of the same class after it used ForestVRoom; (2) to evaluate the qualitative user experience of ForestVRoom.

The experimental protocol included a traditional lecture via slides on the 12 felling techniques given by the university professor of forestry and logging operation. The traditional lecture was given in the morning from 9 to 10:30 a.m. At the end of the lecture, the first set of two questionnaires was administered to the students to assess their acquired knowledge and the quality of the lesson.

Afterward, students participated in a collaborative lecture via ForestVRoom given by the same lecturer; the lecture was given in symmetric mode, i.e. students and the lecturer used HMDs. The CVR lesson was held in the afternoon of the same day as the theory lesson and was divided into three parts of ∼30 min each, with two breaks of ∼15 min to avoid the stress of using the device. Following the CVR experience, the second of the two questionnaires was administered to the students.

Questionnaires

We used two different questionnaires. The first questionnaire focuses on acquired knowledge (Knowledge Questionnaire, KQ) and the second type assesses the quality of the user-perceived learning experiences (Quality of Experience Questionnaire, EQQ). The KQ consists of two sections. The first section (KQ1) consists of 10 text-only multiple-choice questions with three choices for each question and only one correct answer. The second section (KQ2) is based on recognizing situations in forestry sites using pictures; this section also has 10 multiple-choice questions, but with four choices. In both questionnaires, the questions are related to the topics covered in both the traditional lecture and the lecture through forestVRoom. The questionnaires administered after the traditional lecture and after the lecture using the CVR system had the same difficulty.

The EQQ were based on a five-value Likert scale: Strongly Disagree (1), Disagree (2), Neither Agree nor Disagree (3), Agree (4) and Strongly Agree (5). The questionnaire distributed after the theoretical lecture consisted of eight questions, whereas the one after the lecture with ForestVRoom had 16 questions. The questions of the two questionnaires are shown in Table 2. The full questionnaire is available in the Supplementary Material.

Statistical analysis

We used the paired student *t* test for the learning questionnaire analysis and a Likert data visualization technique and reliability analysis for the qualitative user experience questionnaire. Statistical software R 4.3.0 was used for data visualization and data analysis.

KQ analysis

The comparison of learning outcomes with only the traditional lesson and the additional CVR lesson input represents a typical case of paired data. In fact, paired data are when the same variable is measured on the same experimental units under different conditions; in our case, the variable was the score achieved in the learning questionnaire and the two conditions were before and after the VR experience with ForestVroom. We first verified that the response variables follow a normal distribution:

$$VR_i \sim N\left(\mu_{VR}\sigma^2_{VR}\right), Tr_i \sim N\left(\mu_{Tr}\sigma^2_{Tr}\right), \tag{1}$$

with VR_i score achieved by student *i* after the lesson with CVR and Tr_i score achieved by the same student with only the traditional lesson. The normality of the distributions was checked with a Q–Q plot. The Q–Q Plot is the graphical representation of the quantiles of a distribution. It compares the cumulative distribution of the observed variable with the cumulative distribution of the normal. If the observed variable has a normal distribution, the points of this joint distribution thicken on the diagonal running from bottom to top and from left to right. Since these are responses given by the same student, it is normal to assume that their differential follows a normal distribution:

$$\mathrm{D_i} = (\mathrm{VR_i} - \mathrm{Tr_i}) \sim \mathrm{N}\left(\mu_{\mathrm{VR-Tr}}\sigma^2_{\mathrm{VR-Tr}}\right) \tag{2}$$

The hypotheses to be tested are:

$$H_0 : \mu_{VR-Tr} = 0 \tag{3}$$

$$H_1 : \mu_{VR-Tr} \neq 0. \tag{4}$$

If H_0 is true, the VR lesson did not lead to an increase in knowledge; if H_1 is true, on the other hand, the student's skills increased. Student's *t* test value is calculated as the ratio of the observed mean difference to its standard deviation multiplied by the square root of the number of pairs examined, i.e.

$$\mu_D = \frac{\sum_i D_i}{n}, \tag{5}$$

$$\sigma_D = \frac{\sum_i \left(D_i - \overline{D}\right)^2}{n-1}, \tag{6}$$

$$\mathrm{t} = \frac{\overline{\mathrm{D}} - \mu_{\mathrm{D}}}{\frac{\sigma_{\mathrm{D}}}{\sqrt{\mathrm{n}}}} \tag{7}$$

Qualitative user experience questionnaires analysis

Data from the five-value Likert scale qualitative user experience questionnaire were displayed using divergent stacked bar graphs. This is a variation of the horizontal stacked bar graph. The origin of the x-axis is placed in the neutral value of the Likert scale, 'Neither Agree nor Disagree' (3); favourable or positive levels are usually shown to the right of the origin, whereas segments representing unfavourable or negative results are placed to the left of the centre line. The graph shows the percentage of values

Table 2. Items in the qualitative user experience questionnaire.

Item	Dimension
Q01 – I felt disoriented, whilst using the system	VR Experience
Q02 – I experienced motion sickness using VR	
Q03 – I feel that the felling techniques were represented by VR more realistically than the theoretical lecture	
Q04 – The VR system was successful in representing real-life situations during the lecture	
Q05 – I felt focused during the VR experience	
Q06 – The VR system allowed me to see more clearly the differences between different culling techniques	
Q07 – Learning through VR was an enjoyable experience	
Q08 – All in all, I evaluate the learning experience with VR positively	
Q09 – The VR system is better than the traditional lecture for understanding the techniques of safe felling of forest plants	
Q10 – I found the VR experience to be positive overall	
Q11 – I found the system easy to use	
Q12 – I feel that a higher resolution of the videos is needed	
Q13 – VR will help me remember concepts learned in the long run (over a year)	
Q14 – I would recommend a similar VR experience to my friends	
Q15 – I am willing to have similar VR experiences in the future on other topics	
Q16 – I would like to have a VR educational system to use at home	
Q01 I believe the felling techniques were represented realistically	Traditional lecture
Q02 The lesson was successful in representing real situations on forestry sites	
Q03 The lecture will help me remember concepts learned in the long run (over a year)	
Q04 I felt focused during the lecture	
Q05 The learning was enjoyable	
Q06 I would recommend a similar lesson to my friends	
Q07 I would like to take a similar lesson in the future on other subjects	
Q08 Overall, the TR lesson was an enjoyable learning experience	

in agreement on the right and the percentage of values in disagreement on the left. The divergent bar graphs were made using the R library 'likert' (Bai *et al.*, 2009).

According to Classical Test Theory, any measurement made by testing consists of a true component and an error component. To evaluate this error component objectively, reliability measures are used. In fact, evaluating the reliability (also called trustworthiness) of a test or questionnaire means measuring how accurate the scores obtained are. In other words, reliability indices allow you to objectively assess how well a group of items can be grouped together in the same dimension. If, in fact, a group of items purports to measure a particular concept, then you would expect the scores of these items to be like each other. In our case, the two conceptual dimensions analyzed are the quality of the traditional lesson and the quality of the lesson through the CVR system.

Cronbach's alpha coefficient (Cronbach, 1951) is the most widely used statistical index to assess the reliability of the dimensions of a test or questionnaire (Brown, 2002). Cronbach's alpha coefficient is defined as follows:

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum_{i=1}^{k} \sigma_{Y_i}^2}{\sigma_X^2}\right), \tag{8}$$

where k is the number of items, ${\sigma_X}^2$ is the variance of the total score and σ_X^2 is the variance of item i for the sample of individuals under consideration. Generally, high reliability values are to be considered for those ranging from 0.70 and up (Gliem and Gliem, 2003). In our reliability analyses, we also calculated the value of Cronbach's Alpha when an item is eliminated from the dimension under consideration. This is because if the value of Cronbach's alpha increases when a specific item is removed, it is possible to consider whether to keep this item or remove it as inconsistent with the others in representing the dimension under consideration. In fact, its removal will result in better reliability of the dimension being analyzed.

The omega coefficient (ω) is also a measure of internal consistency reliability. ω represents an estimate of the overall factor saturation of a test, proposed by McDonald. (Zinbarg *et al.*, 2005) compare McDonald's omega with Cronbach's α and conclude that omega is the best estimate (Zinbarg *et al.*, 2006). Omega coefficient is defined as follows:

$$\omega = \frac{\left(\sum_{k=1}^{k} \lambda_i\right)^2}{\left(\sum_{k=1}^{k} \lambda_i\right)^2 + \sum_{k=1}^{k} \delta_{ii}} \tag{9}$$

where, λ_i is standardized factor loading and δ_{ii} is standardized error variance (i.e. $\delta_{ii} = 1 - \lambda_{i2}$). As a general guideline, threshold values $(\alpha, \omega) \geq 0.70$ are adequate for research purposes.

Results

The results of the training were verified through statistical analysis of questionnaires distributed to a sample of 45 students in the bachelor's and master's degree programmes of the School of Agriculture and Forestry at the University of Florence. In total, 20 females (44.4 per cent) and 25 males (55.6 per cent) aged 20–25 with an average age of 23.6 years participated in the survey.

Results of learning questionnaires

We first examined the score variation obtained by pairing the traditional lesson with the lesson with ForestVroom by calculating six scores for each student:

- number of total correct responses after the lesson and after the lesson with ForestVroom;
- number of correct responses to text-only items (questions) after the lecture and after the lecture with ForestVroom;

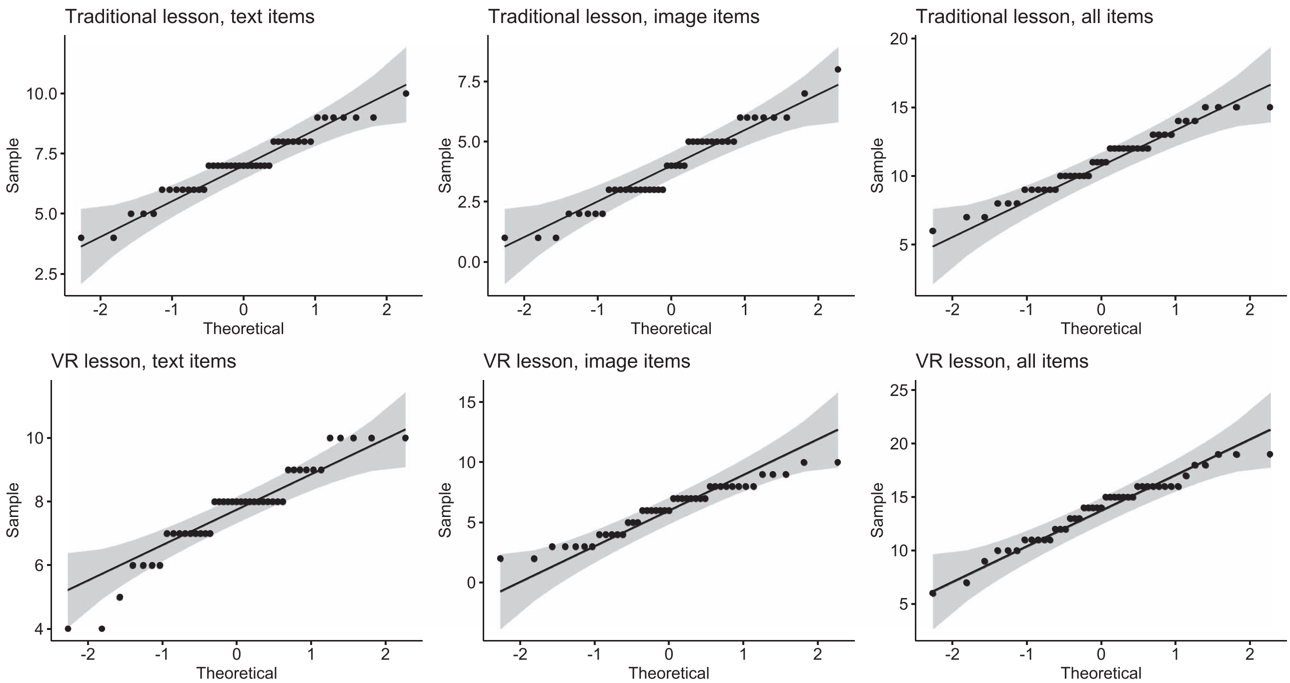

Figure 3. Q–Q Plot of the scores. The area shaded in grey indicates the 95% confidence interval under the null.

Table 3. Parameters of the frequency distributions of the scores.

	Mean	Standard deviation (SD)	Median	Min	Max	Skewness	Kurtosis
Number of correct answers after the traditional lesson	7.07	1.37	7.00	4	10	−0.18	−0.32
Number of correct answers for questions with pictures after the traditional lesson	3.95	1.68	4.00	1	8	0.16	−0.69
Number of correct answers after the lesson with VR	7.72	1.45	8.00	4	10	−0.57	0.27
Number of correct answers for questions with pictures after the lesson with VR	6.12	2.17	6.00	2	10	−0.21	−1.00
Total score of the traditional lesson	11.02	2.35	11.00	6	15	−0.05	−0.83
Total score of the lesson with VR	13.84	3.09	14.00	6	19	−0.43	−0.30

- number of correct answers to items with pictures after the lecture and after the lecture with ForestVroom.

We then checked the normality of the six distributions obtained. According to Figure 3, the six scores fall within the confidence intervals of the Q–Q Plot and, therefore, the distributions can be considered normal; normality is also confirmed by the low skewness and kurtosis values reported in Table 3.

Analysis of the difference in scores showed how the inclusion of CVR in teaching related to vocational training for chainsaw use led to an increase in the scores obtained by students answering the questionnaire questions. On average, students with only the theoretical lesson answered ∼11 out of 20 question correctly with a minimum value of six and a maximum of 15 (Table 3 and Figure 4). With the inclusion of the VR experience, the average number of correctly answered questions increased to ∼14, with a minimum of six and a maximum of 19. According to the t-Student test, this difference is significant with a probability of >99 per cent (Figure 4).

The greatest improvement was found for questions where students had to analyze forest site situations through pictures. For these 10 questions, the correct answers went from an average of four with a minimum of one and a maximum of eight to an average of six with a range of 2–10 (Table 3). For these items, the Student *t* test indicates a significant difference with a probability >99 per cent, which answers SQ1 and proofs that the inclusion of ForestVroom increased students' knowledge (Figure 4).

The students also performed better with respect to the text-only questions but to a lesser degree with the median of correctly answered questions increasing from seven to eight. This difference is still significant, but with lower reliability (90 per cent).

Results of qualitative user experience questionnaires

The results of the ForestVRoom qualitative user experience evaluation questionnaire are shown in Table 4 and Figures 5 and 6.

The questions related to the qualitative user experience of the traditional lesson had all items with a median of four or higher and questions ' Q07 – Would you like to have a similar lesson in the future on other subjects?' and ' Q08 – Overall, was the class an enjoyable learning experience?' have a median of five with five being the highest positive value achievable.

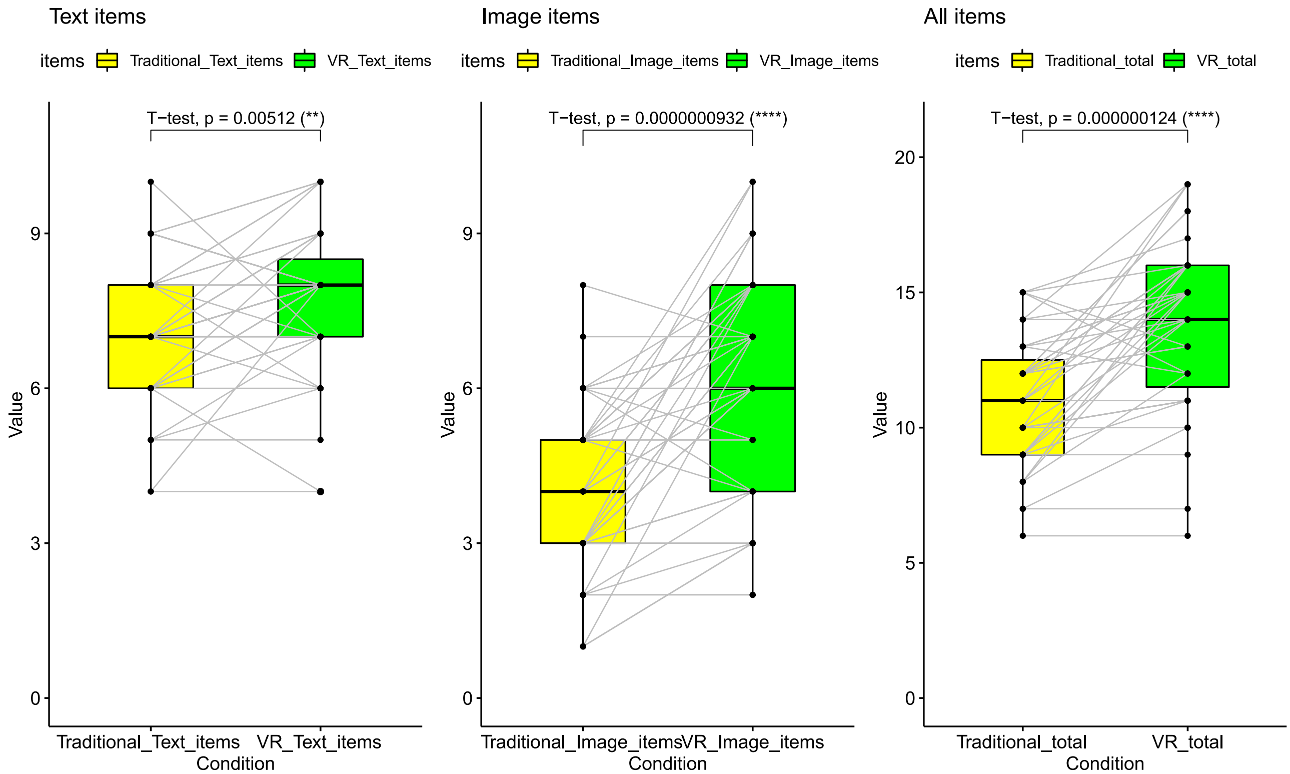

Figure 4. Frequency distribution of learning questionnaire results.

Table 4. Descriptive statistics of learning questionnaire results.

	Items	Mean	SD	Median	Min	Max	Skew	Kurtosis
Traditional	Q01	4.000	0.873	4	1	5	−1.049	1.647
	Q02	3.814	0.794	4	2	5	−0.228	−0.503
	Q03	3.837	0.898	4	2	5	−0.266	−0.846
	Q04	4.163	0.814	4	2	5	−0.809	0.212
	Q05	4.163	0.721	4	3	5	−0.239	−1.111
	Q06	4.140	0.889	4	2	5	−0.464	−1.138
	Q07	4.233	0.922	5	2	5	−0.637	−1.123
	Q08	4.372	0.725	5	3	5	−0.662	−0.892
VR	Q01	3.419	1.180	3	1	5	−0.320	−0.780
	Q02	3.814	1.139	4	1	5	−0.587	−0.779
	Q03	4.628	0.757	5	1	5	−2.842	9.941
	Q04	4.419	0.626	4	3	5	−0.552	−0.710
	Q05	4.186	0.880	4	2	5	−0.971	0.274
	Q06	4.674	0.566	5	3	5	−1.463	1.118
	Q07	4.512	0.668	5	3	5	−0.977	−0.285
	Q08	4.558	0.666	5	2	5	−1.627	3.057
	Q09	4.209	0.861	4	2	5	−0.836	−0.121
	Q10	4.605	0.541	5	3	5	−0.850	−0.471
	Q11	4.372	0.926	5	1	5	−1.651	2.659
	Q12	4.163	0.924	4	2	5	−0.669	−0.765
	Q13	4.116	0.586	4	3	5	−0.011	−0.264
	Q14	4.721	0.591	5	3	5	−1.896	2.378
	Q15	4.605	0.728	5	2	5	−1.801	2.599
	Q16	4.070	1.242	5	1	5	−1.148	0.220

For questions concerning the CVR experience, the range of ratings varies from a minimum median of three related to the question ‘Q01 – Were you disoriented when using the system?’ to a maximum of five related to the questions: ‘Q06 – Did the VR system allow you to see more clearly the differences between different felling techniques?’, ‘Q07 – To what extent was learning through VR an immersive experience?’, ‘Q10 – Was the VR experience overall positive?’, ‘Q11 – Did you find the system easy to use?’, ‘Q14 – Would you recommend a similar VR experience to your friends?’, ‘Q15 – Would you have similar VR experiences in the future on other subjects?’, ‘Q16 – Would you like to have a VR educational system that you could use at home?’.

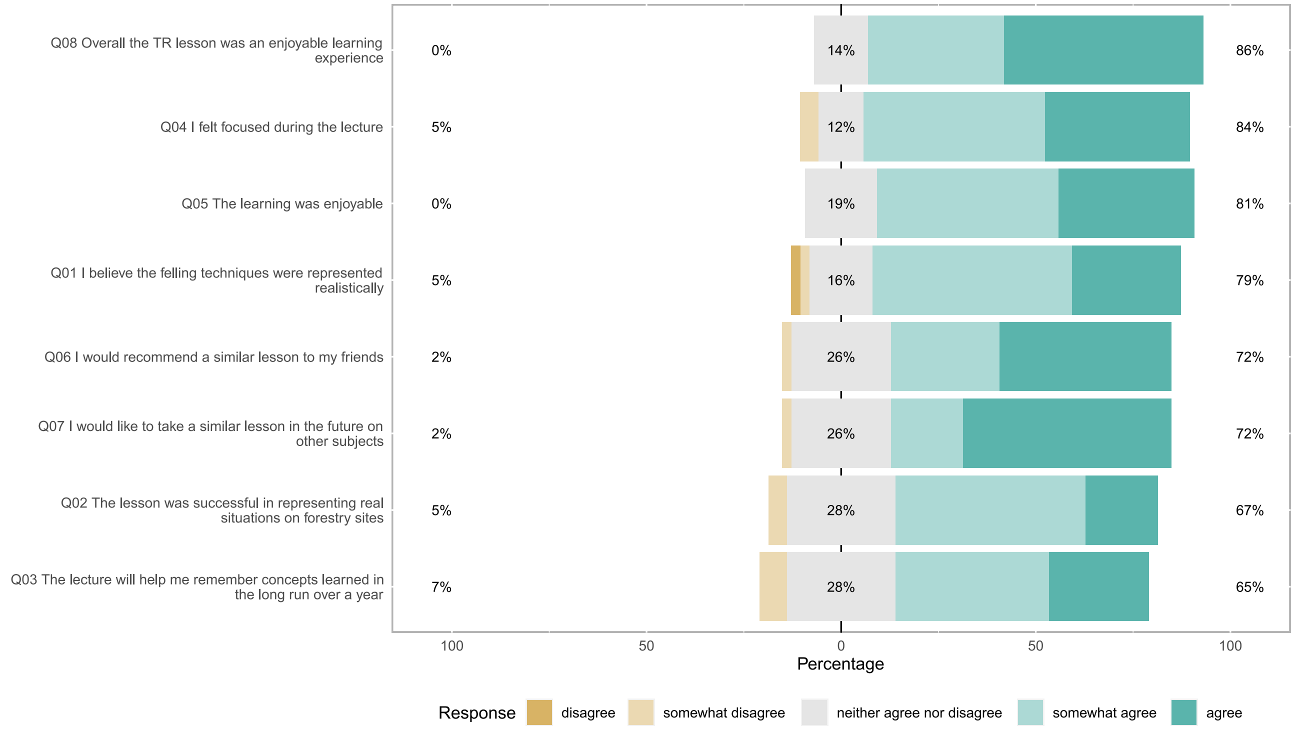

Figure 5. Bipolar plot of Traditional lecture items. The values on the left of the barplot are the percentage of disagreement ratings (sum of somewhat disagree and disagree ratings), whereas those on the right are the percentages of agreement ratings (sum of somewhat agree and agree ratings).

The bipolar graph of the traditional lesson shows that the items with the highest positive percentage agreement (considering the sum of somewhat agree and agree ratings) are 'Q08 Overall, the TR lesson was an enjoyable learning experience ' and 'Q04 I felt focused during the lecture' and 'Q05 The learning was enjoyable' with percentages above 80 per cent. There is very little disagreement (considering the sum of somewhat disagree and disagree ratings): 'Q5' and 'Q8' have no negative ratings and the items with the highest percentage agreement are ' Q02 The lesson was successful in representing real situations on forestry sites' and ' Q03 The lecture will help me remember concepts learned in the long run (over a year)' with 5 per cent and 7 per cent, respectively.

As for VR, the most positive item evaluations (considering the sum of somewhat agree and agree ratings) were 'Q10 – I found the VR experience to be positive overall' and 'Q08 – All in all, I evaluate the learning experience with VR positively' with a consensus rate of >95 per cent.

For VR, however, there are also problematic items: for question 'Q01' 48 per cent agreed or somewhat agreed in having experienced a feeling of disorientation. For question 'Q02' 65 per cent agreed or somewhat agreed in having experienced motion sickness; 'Q16 – Would you like to have a VR educational system that you could use at home?' was negatively evaluated by 10 per cent of participants.

To better understand the reason for the negative ratings, items Q1 and Q2 of the CVR dimension were analyzed by gender. From Figure 7, it can be seen that women are more sensitive to the negative consequences of their experience with ForestVRoom. In fact, regarding questions 'Q01' 35 per cent of females felt disoriented whilst using the system, compared with 57 per cent of males. For question 'Q02' 50 per cent of females experienced motion sickness using VR *vs* 75 per cent of males.

Figure 8 shows the average ratings and QQ-Plots of the dimensions 'Traditional lecture' and 'VR experience'. The QQ-plots (Figure 8a) shows the normality of the two frequency distributions. The average Likert rating value of the VR experience is higher than that of the traditional lecture (Figure 8b), with values of 4.44 and 4.25, respectively, with a very similar third quartile value: 4.5 *vs* 4.6. More sensitive is the difference in the first quartile: 3.45 for the traditional lecture and 4.19 for the VR experience. Overall, according to the pairwise t-Student statistic the VR Experience dimension has a higher mean rating than the theoretical lecture with a 95 per cent probability.

Finally, the values of Cronbach's alpha and McDonald's omega are satisfactory (α and $\omega > 0.7$) for both dimensions and for the whole survey even considering the lower and upper confidence limits for a probability $P > 95$ per cent. The detailed results of the analysis of Cronbach's alpha McDonald's omega indices are available as Supplementary Material.

Discussion

Responses to the RQ and SQ

Regarding our general RQ1, ' Is it possible to make a VR app with educationally effective storytelling for chainsaw forestry operator training, improving collaboration between teachers and students?', the use of CVR through ForestVRoom, which combines 360° videos and a 3D environmental models, demonstrated significant strengths. The use of VR allows for an immersive experience in which in just a few square metres the student can actually perceive the spatial organization and real dimensions of the virtualized environment. Students have no distractions and can simultaneously observe the same phase of the work having the opportunity to see details that they might miss when being in the forest. Virtualization of scenes allows students to visit a plurality of situations that in the field would require time and resources that are not always available; in fact, in our study, it was possible to accurately show and describe 12 cutting techniques in

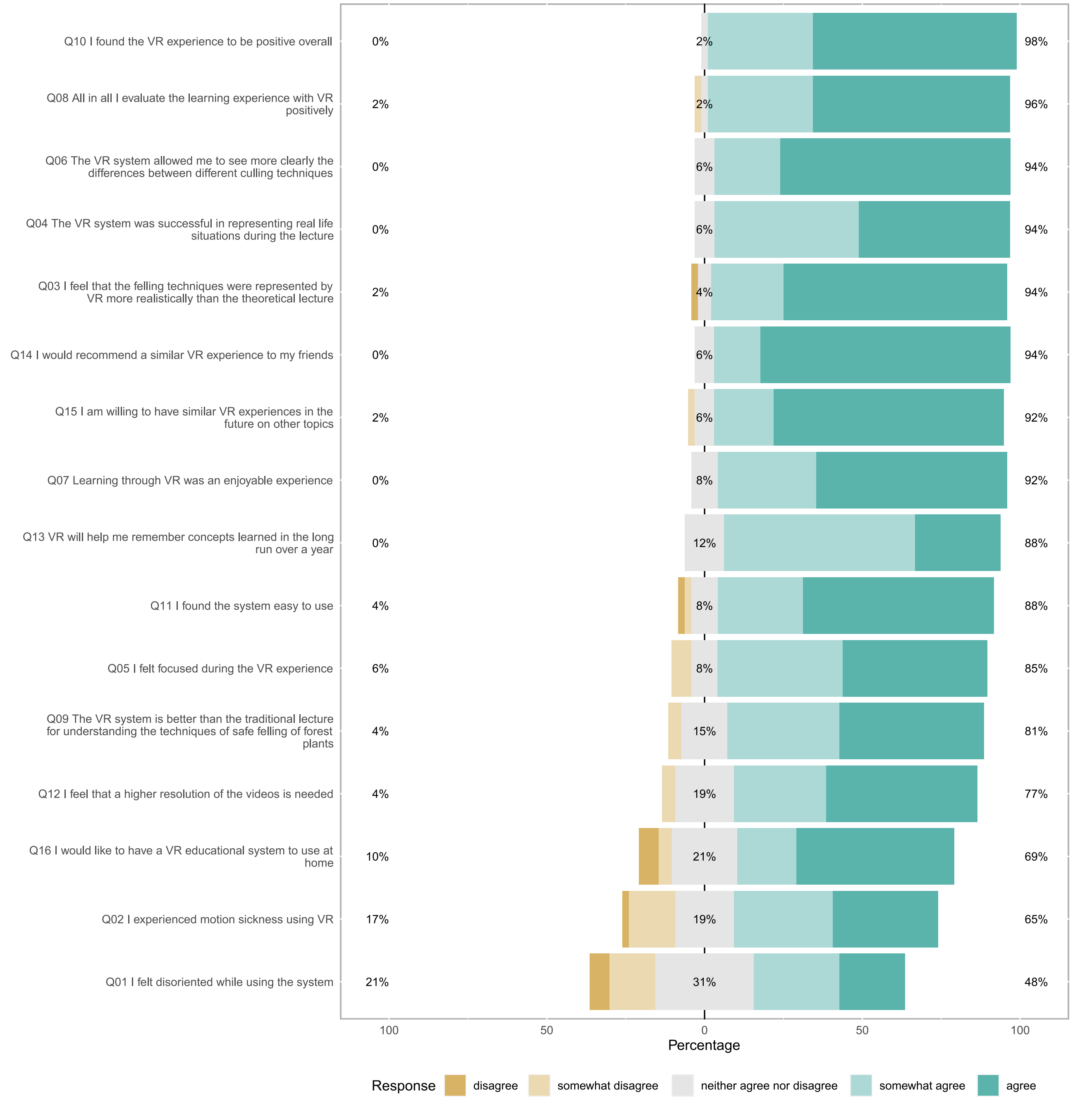

Figure 6. Bipolar plot of CVR lesson items. The values on the left of the barplot are the percentage of disagreement ratings (sum of somewhat disagree and disagree ratings), whereas those on the right are the percentages of agreement ratings (sum of somewhat agree and agree ratings).

2 h. During forestry training courses this would require at least 6 h just for cutting and description and several days to find the right trees in terms of diameter and leaning conditions.

In addition, the absence of hazards allows students to see the various stages of tree cutting and processing up-close; for example, raising the head allows them to appreciate the movements of the canopy, the operation of the hinge, the closing of the sink during the felling phase and the correct postures of the operator. Finally, the student’s position is very close to the cut, which allows them to understand the importance of moving away before the tree finally falls as a safe behaviour for the operator. Knowledge of all these factors is critical to understanding the dynamics of many forestry accidents that occur during tree felling and processing operations.

Through the CVR teacher and students access the platform simultaneously seeing themselves as avatars. The teacher explains ‘live’ by acting on hotspot buttons, starting and stopping 3D videos and moving the class from one scene to another and students can interact by asking questions. In addition, the teacher can choose the order of the scenes to be described; he or she can stop and quickly move back in the video projection to answer any questions or to finish describing technical details.

In this context, a very important role is played by the organization of the training project with particular reference to the choice of the forest site, the type of trees to be felled and the sequence of operations that the teacher wants to show in the virtual lesson. The time spent in the forest for the preparation of the videos results in the possibility of showing and

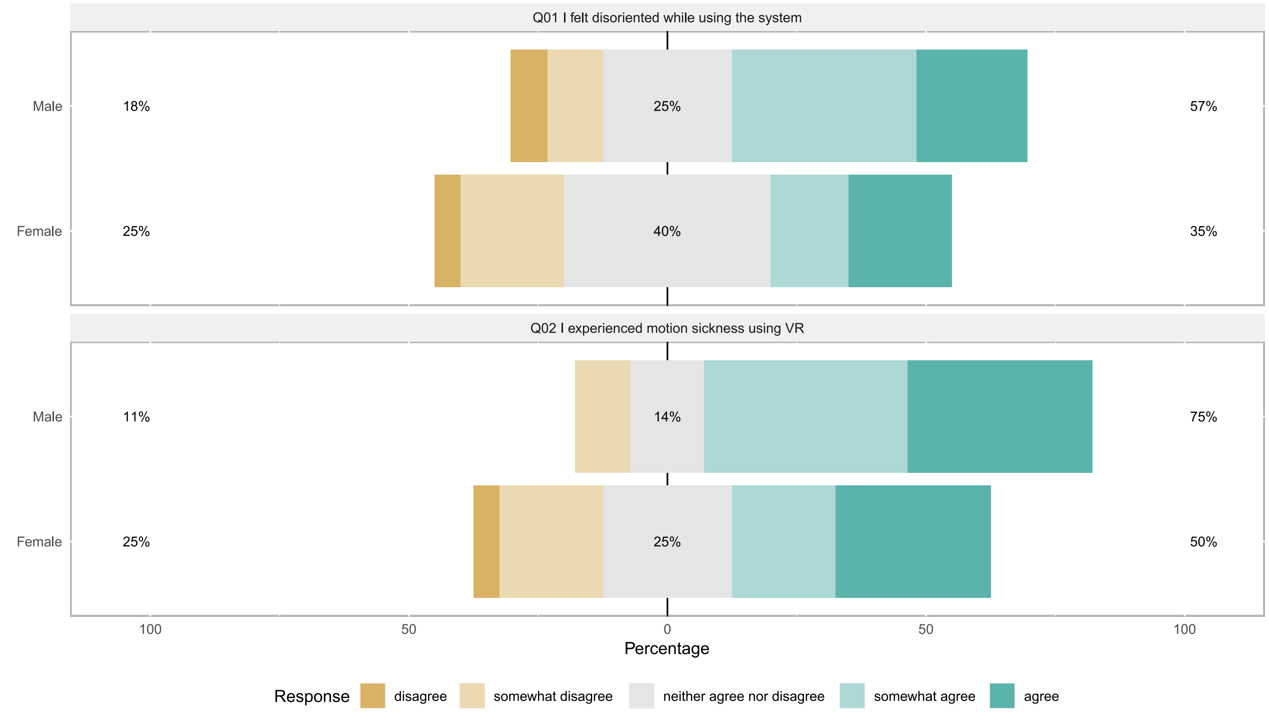

Figure 7. Bipolar plot of Q1 and Q2 items.

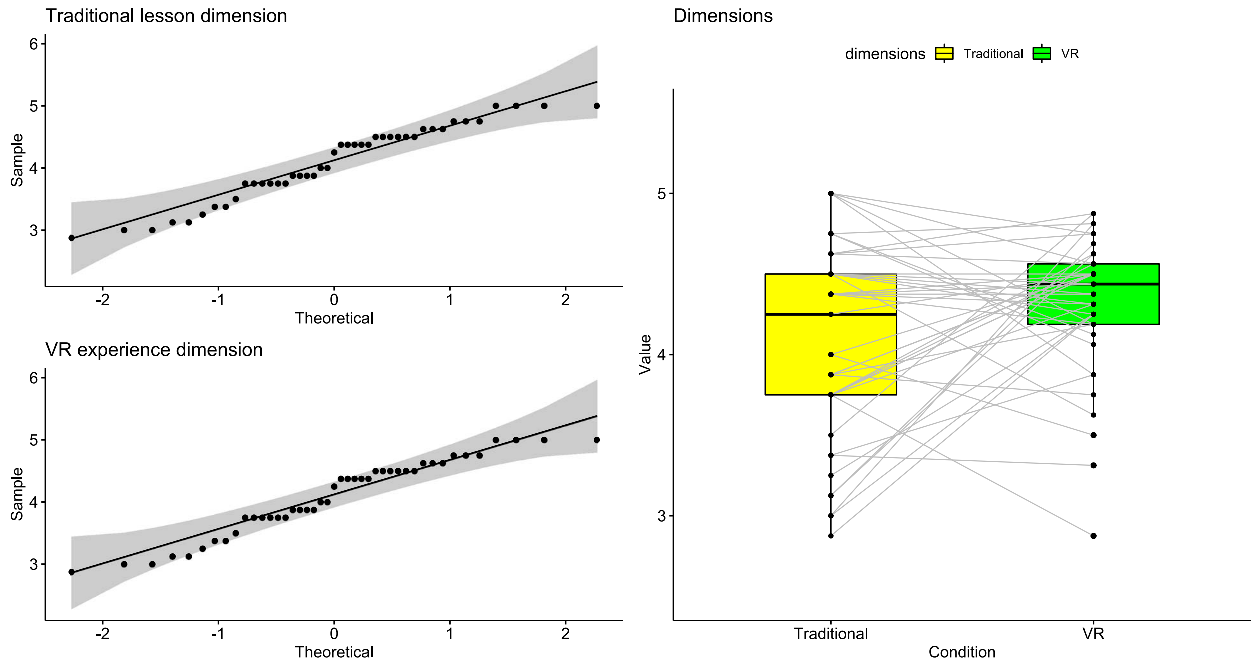

Figure 8. QQ-Plot (a) and Boxplot (b) of Traditional and VR lectures. The area shaded in grey indicates the 95% confidence interval under the null.

describing successfully a plurality of situations in a very short time.

For SQ1: 'Does the combination of traditional lessons and VR experiences enhance learning?', the results showed that CVR led to an increase in correct answers, especially in the second section of the questionnaire, in which the students were asked to recognize the most appropriate forest work techniques based on photographs, whilst the improvement in results was smaller for text-only multiple-choice questions. Therefore, the VR lesson seems to complete the theoretical lesson with practical knowledge that otherwise cannot be acquired in a lecture room.

Finally, for SQ2: ' Do students positively evaluate the quality of a VR experience compared to a traditional lesson?', the results were positive for both teaching modes, which are thus perceived by students as complementary rather than alternatives. However, the VR experience is rated slightly better overall, with a statistically significant difference. This is confirmed by the fact that 94 per cent of respondents agree or substantially agree to item 'Q03 – Did you feel that the felling techniques were represented by VR more realistically than in the theoretical lecture?'.

The importance of 360° videos in understanding forest work situations is confirmed by the high percentage of respondents agreeing with the item ' Q06 – Did the VR system allow you to see more clearly the differences between different felling techniques?' (96 per cent) and ' Q04 – To what extent did you feel that the VR system succeeded in representing real-life situations in the lecture?' (94 per cent). The high percentage of agreement obtained for these questions assessing immersivity confirms the part played by CVR in increasing the score of questions based on recognition of construction site situations through photos.

The reliability and consistency of both questionnaires were validated by alpha and omega statistics. The high values of the two statistics (well above the threshold of 0.7) indicate that both dimensions capture the concepts under consideration well.

Comparison with previous research

The effect of increased learning outcomes due to the inclusion of VR in our research is in line with the results of previous research (Sacks *et al.*, 2013; Xu and Zheng 2020; Nykänen *et al.*, 2020). Our results also confirm Feng *et al.* (2020) who found that students appreciate a VR system as a learning tool. Feng *et al.* (2020) successfully used VR technology to communicate the links between wood structure and properties, although they also stated that a priori knowledge of the material is desirable for students prior to the use of VR. The feeling of disorientation and motion sickness captured by questions Q1 and Q2 of the VR Experience section in the questionnaire is well documented in the literature. In a meta-analysis on the literature from motion sickness in HMD use, Saredakis *et al.* (2020) found the highest simulator sickness questionnaire scores in studies that used 360° videos. To mitigate this problem, a gradual and progressive introduction of HMDs into the teaching activities of college students is needed (Saredakis *et al.*, 2020). Regarding the greater propensity of females to HMD-induced motion sickness, previous research has yielded inconclusive results. Saredakis *et al.* (2020) found no significant differences, whilst Lawson *et al.* (2004) found, in agreement with our results, that female students less frequently report experiencing motion sickness.

Innovative results, weaknesses and future research development

Our research has demonstrated the possibility of complementing traditional didactics with VR experiences, resulting in improved learning outcomes. ForestVRoom has also been validated with a specific qualitative user experience questionnaire with an internal consistency and reliability evaluation.

The use of VR in training and teaching also faces some critical issues. In the literature, university professors of Science, Technology, Engineering and Mathematics subjects have noted some negative aspects of VR lectures (Wells & Miller, 2020; Yildirim *et al.*, 2020): the isolation of students in the VE, the cost of equipment and the lack of specific professional training on the part of professors (Vergara *et al.*, 2022). For these reasons, it is currently not recommended to completely replace traditional lectures with educational experiences in VR. However, it is likely that a long period of pairing traditional lectures with VR experiences lays ahead in the near future.

Most previous simulated environments with symmetric immersive collaboration were limited to the co-presence of a teacher and a student (Chheang *et al.*, 2019; Dey *et al.*, 2017; Drey *et al.*, 2022). ForestVRoom is one of the few applications offering immersive videos with CL in a rather large virtual classroom and the only one, to the authors' knowledge, in the field of forest operation workplace safety and training. Finally, ForestVRoom is to the authors' knowledge the only mixed application that combines immersive video with interactive 3D environments in forest operator training.

An apparent limitation of our sample design is that the improvement in learning outcomes could be due to the repetition of the topics covered first in the traditional lesson and then once again in the one via VR. However, this hypothesis is unlikely since the greatest improvement occurred in the questions related to pictures rather than in the text questions. Thus, the VR lecture seems to have filled gaps that prevailed after the traditional lecture.

The potential main limitation of the research is that it only answers the question, 'Is there an increase in knowledge by combining theoretical lectures with VR experiences?' However, other important questions remain to be investigated, e.g. 'What is the difference between learning with a traditional lecture alone, a traditional lecture coupled with a VR experience, and VR experience alone?' 'What is the optimal number of participants in an educational experience with symmetrical collaborative VR?' These questions were not investigated because they require a split sampling protocol instead of the paired sampling protocol used in this study and will be the subject of future research.

Other limitations include the small number of Likert scale items adopted, which led to smearing in the frequency distributions, and the relatively small sample, although, as reported by Pirker & Dengel, 2021, 43 respondents is close to the median value in research with 360° videos involving college students.

ForestVRoom is a collaborative symmetric VR application that bases mostly on 360° videos as content. Compared with a 3D environment, 360° videos are passive contents in that they have no depth compared with 3D models, that is, the user cannot move within the 360° video and cannot interact with any elements. To overcome this limitation, it is planned to develop an application that has only 3D content to simulate the felling of a tree. The student and teacher will be able to enter a forest together and stand in front of one of the previous felling cases seen and implement it as if they were in reality. To make the forestry training as realistic as possible we will implement a mixed reality function. The student can activate the mixed reality and superimpose the real chainsaw with the virtual one so that they can really feel the weight of the chainsaw; at the same time, the teacher can control the posture that the student is holding during the cutting in the mixed reality environment.

Conclusion

We showed that a pairing of traditional didactics and symmetrical CVR leads to an increase in knowledge and especially the ability to understand situations in a real forestry worksite.

Our results show that VR systems hold potential as a learning tool and this is consistent with the findings from other research (Dickinson *et al.*, 2011; Sacks *et al.*, 2013; Zuluaga *et al.*, 2016), highlighting that VR is a useful educational tool that can integrate conventional training methods due to its potential for providing an immersive experience associated with extensible and flexible interactions. Our study amplifies the existing IVR technology and proposes a multi-user platform to improve the interaction between participants.

The logical interactions delivered by the immersive environment were perceived as attractive by the participants in the experiment. The concept of developing different levels to familiarize users with the virtual world has proven effective. The improvements in simulation techniques have provided a great opportunity for educational purposes. Training through virtual experience allows new entrants to memorize critical points of the lecture with less effort securely, and the idea of virtual training should be amplified to produce more efficient methods for saving educational costs and incidental costs.

The absence of risks allows students and users, in general, to observe up-close the typical steps of manual tree felling and processing. This helps to understand the safety procedures that must characterize the activity of the chainsaw operator as safe behaviours to reduce the incidence of forest accidents.

Based on our results, we believe that the study of the dynamics of accidents in the forestry sector can be completed with the introduction of training courses based on VR that we have seen to be effective in proposing multiple case studies in a short time and above all in a safe environment independent of weather conditions that always affect all forestry activities, from real work to training activities.

This study is the first of its kind in the field of forestry utilization, as far as we know. We hope it will encourage further exploration of symmetrical CVR as a means of enhancing learning by forestry and wood science academics.

Supplementary data

Supplementary data are available at *Forestry* online.

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Conflict of interest statement

None declared.

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Authors' contribution statement

Irene Capecchi developed the software and contributed to the original text. Francesco Neri carried out the experiments, collected the data and contributed to the original text. Tommaso Borghini developed the 3D models and performed the video shooting. Iacopo Bernetti conceptualized the work, processed the data and contributed to the original text. All authors read and approved the published version of the manuscript.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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