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Virtual training for assembly tasks: a framework for the analysis of the cognitive impact on operators

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Abstract

The importance of training for operators in industrial contexts is widely highlighted in literature. Virtual Reality (VR) technology is considered an efficient solution for training, since it provides immersive, realistic, and interactive simulations environments where the operator can learn-by-doing, far from the risks of the real field. Its efficacy has been demonstrated by several studies, but a proper assessment of the operator's cognitive response in terms of stress and cognitive load, during the use of such technology, is still lacking. This paper proposes a comprehensive methodology for the analysis of user's cognitive states, suitable for each kind of training in the industrial sector and beyond. Preliminary feasibility analysis refers to virtual training for assembly of agricultural vehicles. The proposed protocol analysis allowed understanding the operators' loads to optimize the VR training application, considering the mental demand during the training, and thus avoiding stress, mental overload, improving the user performance.

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Keywords: Virtual Reality; Virtual assembly; Industrial ergonomics; Training Assessment; Cognitive ergonomics.

Introduction

In recent years, industries are shifting towards Industry 4.0, where new intelligent machines, robots, and tools are added to the workforce. In this smarter environment, the role of the human operator (i.e Operator 4.0 [1]) remains fundamental. Thus, the need for adequate training of the operator arises, to guarantee the optimal integration between humans and the innovative advanced technological systems [2].

In the context of Industry 4.0, digitalization is considered one of the most important drivers of innovation, useful not only to save time and cost, but also to optimize data and process management. In particular, digital manufacturing can be applied to different stages of the manufacturing process, such as design, prototyping, and assembly training [3]. Indeed, due to the importance of the assembly step in the manufacturing process, specific training should be provided to the operators, also to cope with the new technologies. In this context, the Operator 4.0 can be supported with different levels of cognitive automation, namely technical solutions helping the operator about how and what to assemble and to control the situation. Virtual Reality (VR) is categorized among these technological supports [4].

VR offers the opportunity of "learning-by-doing" instead of learning by observing or listening [3]. Moreover, VR allows to digitally simulate not only the industrial processes (from the product/system design to the prototyping, assembly, ergonomic analysis, and maintenance) but also the human-machine interaction in a risk-free digital environment. Therefore, VR technology is considered an efficient solution for assembly training, since it provides immersive, realistic, and interactive simulations for helping and training the operator in the smart factory in the execution of complex tasks, far from the risks of the real operational environment [3], [5], [6].

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Indeed, smart interaction between Operator 4.0 and the advanced intelligent machines involves both the physical and cognitive dimensions. Cognitive interactions rely on the worker's cognitive skills and capabilities. VR technology can be used to supply the user with real-time relevant data that may reduce the dependency on the operator memory and decrease human errors. Moreover, wearable devices can be used to monitor workers' conditions under stressful or difficult situations, and proper warnings should be provided when needed [6].

In this context, the development and use of VR training applications can help the creation of the proper skills in a short time, also in delocalized sites. However, virtual training needs to be strongly human-centered in order to be effective and to fully exploit its great potential. As a consequence, human factors (HF) assessment assumes a critical importance in understanding whether and how the virtual training procedure is supporting the operators to leverage their skills effectively. It has been demonstrated that physical and cognitive ergonomics strongly impact manufacturing performance, and, consequently, factory productivity. For this reason, companies should necessarily deal not only with performance objectives (as cost, quality, speed, productivity, flexibility, adaptability) but also with human sustainability, in terms of health and safety, to enhance the operator's wellbeing and improve his/her skills [1], [7], [8]. In addition, psychophysiological stress should be prevented and avoided, safeguarding mental wellbeing. Prolonged sensations of outrageous mental effort and stress may result in the user's burnout, lower performance, and reduced productivity [9]. For these reasons, systems should be designed based on the operators' cognitive and physical needs, to improve the quality of human-machine interaction and, finally, the workers' performances.

Several studies have tried to assess the effectiveness of virtual assembly training. Its utility and feasibility have been proven [3], [9], as the efficacy of giving visible hints [4]. However, a proper assessment of the operator's cognitive response in terms of stress and mental load, during the use of such technology, is still lacking [9].

This paper proposes a comprehensive methodology for the analysis of the users' cognitive states during virtual training sessions. The method is suitable for each kind of training in the industrial sector and beyond, both traditional and virtual. A preliminary feasibility analysis referring to a case study about virtual assembly in the agricultural vehicle sector has been developed to validate the proposed method and understand the prospective for further developments.

1. Research Background

In literature, several works about the effectiveness of VR training in the manufacturing context can be found. Authors used different qualitative and quantitative evaluation criteria, which can be summarized in cognitive skills, levels of trust/acceptance of extended reality tools, motivation in use, participants' attitude, previous experience, cybersickness, physiological reactions, level of presence, and engagement, and technical aspects [10]. Usually, one or a few of these criteria are chosen for the VR training effectiveness assessment. Also, the analysis usually considers the demographic information of participants and performance-related variables such as time of performance for each task of the procedure, number of unsolved and recovered errors, time for error recovery, number of tasks without errors, etc. [10]. Performance measures (in terms of task completion time and error rate), associated with subjective measurement about system usability (through questionnaires), are used in most of the works related to assembly VR training [11], [12], [13], [14]. In some cases, even physical ergonomics has been assessed applying RULA and REBA protocols [15].

However, only a few papers focus on the cognitive and psychophysiological conditions of operators in the smart manufacturing context. Among them, Grandi et al. in [16] analysed the quality of human-machine interaction through the use of sensors for user experience analysis during virtual simulations. However, they did not use a structured protocol centered on the analysis of the cognitive stress. Etzi et al. in [9] used VR to simulate the collaboration between human and robot and evaluated not only the system usability and users' performance but also their mental and physical states. To assess the workers' cognitive conditions and eventual stressful episodes related to the tasks, the physiological parameters of heart rate (HR) and skin conductance level (SCL) have been analysed. The differences between slow and fast tasks sessions were computed: even if the users asserted to have a greater level of stress in the fast session, HR and SCL remained stable in the two different sessions. Nevertheless, only a small sample of users and a short temporal window (2 min) was tested [9]. In addition, Leone et al. [17] proposed a method to analyse the features extracted from the heart rate, electrodermal activity and electrooculography to distinguish between stressful and relaxed conditions during manufacturing activities such as assembly and manual handling.

However, more attention should be paid to the discrimination between stress and mental load that could arise in a smart environment where the traditional human-machine interaction is subject to changes. Indeed, Operator 4.0, interacting with advanced technological systems (such as collaborative robots, extended reality technologies, etc.), needs to develop the proper skills necessary for the management of the intelligent factory. The development of these new skills must be based on the user's cognitive needs and must guarantee low levels of stress and mental effort.

According to the ISO 10075-1, psychological stress is the effect of all conditions with a mental impact on a subject, either cognitive or emotional. It emerges when the perceived demands of the environment exceed a person's ability to cope with these demands [18]. Stress is also defined as a "state of high general arousal and negatively tuned emotion, which appears as a consequence of stressors acting upon individuals" [19]. Commonly recognized stressors include technical complications, time pressure, distractions, interruptions, errors, and increased workload [20].

From a medical point of view, stress is usually described as two general types of response: anxiety or frustration, and the physiological response of the sympathetic nervous system which emerges after a challenge or threat. Concerning this second category, it has been demonstrated that stress causes reactions such as changes in skin conductance (sweating), heart rate (tachycardia), blood pressure (increase), and in the stress hormone cortisol (increase) that spreads to saliva within minutes, during and immediately after performing a stressful task [21].

The multimodal dimension of stress makes the research field very broad; however, according to ISO 10075-3, four main criteria can be distinguished in detecting stress: psychological, physiological, behavioural, and biochemical. The most common analysis typically includes the subjective assessment based on self-reports (e.g., the State-Trait Anxiety Inventory) and the physiological assessment based on electrocardiography (for heart rate monitoring) and skin conductivity (to measure sweat activity). Indeed, the electrodermal activity (EDA), or Galvanic Skin Response (GSR), reflects the surface changes in skin conductance due to the sympathetic nervous system and it is considered "one of the most sensitive psychophysiological indicators of stress" [19]. Even the heart rate variability (HRV) (i.e., the variability of the inter-beat interval (IBI) in ms) is under the control of the autonomous nervous system that commands our capability to react to external stimuli. For this reason, HRV is considered a reliable indirect means to monitor cognitive states. HRV fluctuations can be analysed using time domain, frequency domain, and non-linear domain methods. Four measures in the time domain (RR, SDRR, RMSSD, and pNN50) and one measure in the non-linear domain (D2) result significantly reduced during stressful events. The ratio LF/HF in frequency domain results instead significantly increased, suggesting a sympathetic activation and a parasympathetic withdrawal during acute stress [22]. Moreover, it has been shown that the extent of inter-beat variability decreases with increasing cognitive load [23].

The analysis of Cognitive Load (CL) is one of the most widely studied topics in cognitive ergonomics (CE). CE involves psychological processes and concerns humans interacting with other system components [24]. Some significant items include workload, decision-making, perception, attention, motor response, skill, memory, and learning [25]. It is oriented towards the optimization of human-machine interaction, according to three main criteria: characteristics of human cognitive processes, software science knowledge, and knowledge in diverse work domain technologies. As a logical consequence, the training topic is included in such perspective, since it can contribute to the enhancement of human performances and work conditions [26].

The increase in professional activities that have a mental dimension has therefore encouraged the development of cognitive ergonomics, which thus results fundamental in the design and assessment of training activities. Indeed, its objective is to improve the performance of cognitive tasks in dynamic and technologically advanced environments, through the design of effective support, understanding the fundamental principles of human activities associated with the principles of engineering design and development.

However, although performance measures are strongly used to evaluate the users' skills, the assessment of their cognitive state is more uncommon. This fact is disadvantageous if we consider the introduction of technologies as virtual reality devices, which may help the user during the training and the practice but may also result in a potential risk of information overload. Therefore, the study of cognitive load, related to extended reality applications, merits further in-depth analysis.

Cognitive load "emerges from the interaction between the requirements of a task, the circumstances under which it is performed, and the skills, behaviours, and perceptions of the operator" [27]. Since CL can positively or negatively affect human performances, the principal reason for measuring it is to quantify the mental cost of performing a task to predict the performances [28].

Current studies mainly refer to three assessment methods: performance assessment method, self-assessment method, and physiological measures method (also according to the ISO 10075-3).

The class of task performance measures assumes that CL is relevant only if it affects performance and the most common measurement parameters are response, reaction time, accuracy, error rate, estimation time, objective speed, and signal detection [29]. However, it is demonstrated that performance errors are not necessarily related to a high mental load imposed by the main activity. For this reason, the secondary task method, in which the user is required to perform a secondary activity concurrently with the main activity, is more used.

The class of self-assessment/subjective measures is based on the personal perceived experience about the interaction with the system and is obtained from the direct estimation of task difficulty. The self-assessment provides information on how humans subjectively evaluate various aspects of workload for accomplishing a task, using questionnaires or psychometric scales. The NASA Task Load Index (NASA-TLX) is the most used tool for workload subjective assessment. It consists in a multidimensional questionnaire that rates perceived workload under six different dimensions: mental, physical, and temporal demands, performance, effort, and frustration levels [27].

The class of physiological measures considers physiological responses of the body that are believed to be correlated with the cognitive load. Indeed, changes in psychophysiological parameters, such as HR, HRV, EDA, breathing rate (BR), brain activity (EEG), muscular activity (EMG), eye activity (EOG, pupil diameter, gaze entropy, and velocity), can be indirect indicators of mental workload.

The heart rate variations (i.e., the variations of the number of heartbeats per unit of time, typically expressed as beats per minute (BPM)), are proved to be directly related to the mental load (i.e., HR increases as CL increases) [30].

Even the changes in BR reflect variations in the mental effort. Indeed, for an increase in the mental demand, the respiratory rate increases and the breathing depth decreases [31].

Also, the blinks and eye movements (from electrooculography EOG) have been correlated to cognitive aspects. Researchers demonstrated that blink rate decreases as cognitive load increases [32].

However, these physiological parameters are not selectively optimal indices for measuring mental workload, since they are sensitive to physical activity, strong emotional reactions, environment, and speech. Therefore, it is suggested to use multiple concurrent kinds of measurements to increase the validity of cognitive load assessment [33].

2. Methodology

The optimization of physical and mental workload, comfort, and perceived effort is necessary to prevent disorders and stressful conditions, assuring the best human performances [34]. For this reason, HF must be applied also to the issue of effective training, which includes the effective use of advanced devices.

This work proposes a comprehensive methodology (Figure 1) for the assessment of the mental and psychological conditions of subjects during training sessions or other kinds of activity that involve the cognitive domain.

To perform an overall and structured analysis of subjects' cognitive conditions, the proposed methodology suggests the use of all the three assessment methods: the one related to performance, the one related to self-assessment, and the one related to the measurement of physiological parameters.

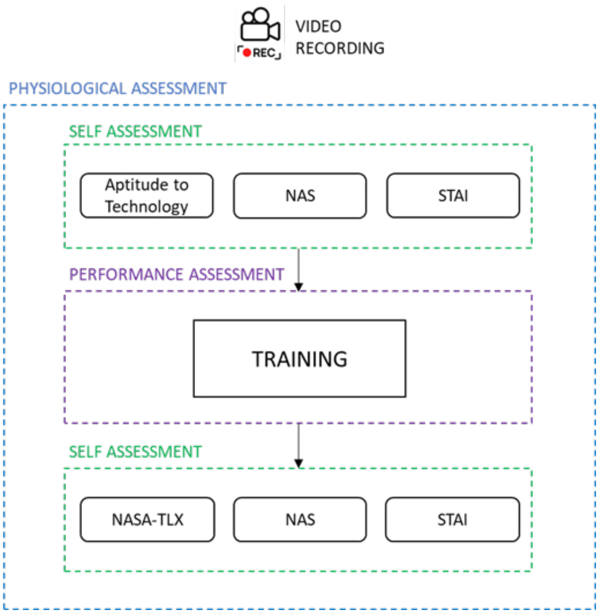

Figure 1: The methodology to assess cognitive conditions during training

Concerning the self-assessment, the defined methodology requires the administration, before the training session, of three different kinds of surveys. The first one refers to the personal aptitude and familiarity that subjects have with the use of technology, defined as the application of IT and telematic devices (i.e., the experience that they have with technological devices from a common smartphone to more sophisticated tools such as head-mounted displays or haptic gloves). The second one is a numerical analogue scale (NAS) for the assessment of the perceived level of stress. It consists of a bar or line divided into ten intervals, numbered from 0 to 10. The subject is asked to select the integer number that best reflects the intensity of his/her stress (0 = no stress, 10 = very strong stress). The NAS has proved to be a valid, effective, and easy-to-implement tool for the rapid assessment of perceived stress [35]. The third questionnaire is the State Trait Anxiety Inventory (STAI), which is one of the most used scales for the assessment of anxiety. It consists of two modules, each one composed of 20 statements: (1) the STAI Y-1 form allows for the assessment of the subject's current state of anxiety, considering feelings of apprehension, tension, worry, and nervousness, (2) the STAI Y-2 form allows for the evaluation of the anxious trait (i.e., the individual tendency to anxiety) to give an index of how a subject generally feels, and it can be used to identify people predisposed to develop anxiety in stressful situations. For each statement, the subject must answer on a 4-points Likert scale [36].

In this way the “baseline” of perceived stress and anxiety levels, before undergoing the activity, can be defined.

After the training session, the same NAS scale must be answered together with the STAI questionnaire. However, in this case, only the STAI Y-1 form should be submitted, since it is necessary and sufficient for the evaluation of the effect that the training has on the subject’s anxiety. Moreover, after the training activity, also the NASA-TLX questionnaire (NASA-Task Load Index) is administered. This questionnaire is used to assess the workload: it is a subjective scale, developed to minimize the variability of assessments between subjects [27], consisting of questions that allow evaluating the importance assigned by the subject to different elements involved in the workload. This questionnaire is included in the proposed methodology because it allows the assessment of the perceived cognitive load (mental demand) needed to perform the activity, as well as the emotional states related to stress such as perceived effort and frustration.

In the case of training sessions with advanced devices (e.g., VR headsets), ad hoc usability surveys could be provided to the users at the end of the activity.

Regarding the physiological measurements, participants must wear the smart devices for the monitoring and collection of the biometric parameters (such as HR, HRV, BR, EDA, …) from the arrival in the training room until the end of the post-training self-assessment. In this way, it is possible to discriminate the parameters’ variations among different stressful, restful, and mentally demanding situations.

The physiological parameters can be collected using non-invasive wearable devices such as smart bands or bracelets, and smart glasses for eye-tracking.

A video camera for the recording of the training session should be provided. During data analysis, it could be useful to stopwatch and track events in relation to physiological variations and times.

With regard to the performance assessment, a specific checklist must be prepared to discriminate among correct, incorrect, and not performed tasks. Furthermore, for each task should be evaluated the completion time, the number of errors, the number of consultations.

The proposed methodology can be adopted in different contexts for assessing cognitive ergonomics and applies to any type of activity that requires mental effort and could generate stressful situations. Therefore, it can be applied in the industrial setting during the operator training and the use of systems for extended reality (not only VR but also Augmented Reality or other types of assistive technology).

3. Case Study

An interesting application of the proposed methodology is related to the training of operators about assembly tasks, by means of virtual reality technology. Indeed, even in Industry 4.0, the manual assembly, done by the operator (and not by robots), is still widespread, especially in the final stages of assembly, in low-batches processes, and for customizations [37]. In order to reduce assembly times and, consequently, to increase the company’s productivity, the training of the operator becomes necessary. Therefore, the effect that the use of technological devices for VR training has on the cognitive conditions of the operator results essential to understand how to avoid cognitive stress and overload, and how to give the most effective learning support.

3.1. *Assessment Protocol*

Figure 2 shows the protocol for the assessment of the operators' cognitive conditions during a virtual training for the assembly of the diesel oxidation catalyst (DOC) component on tractors.

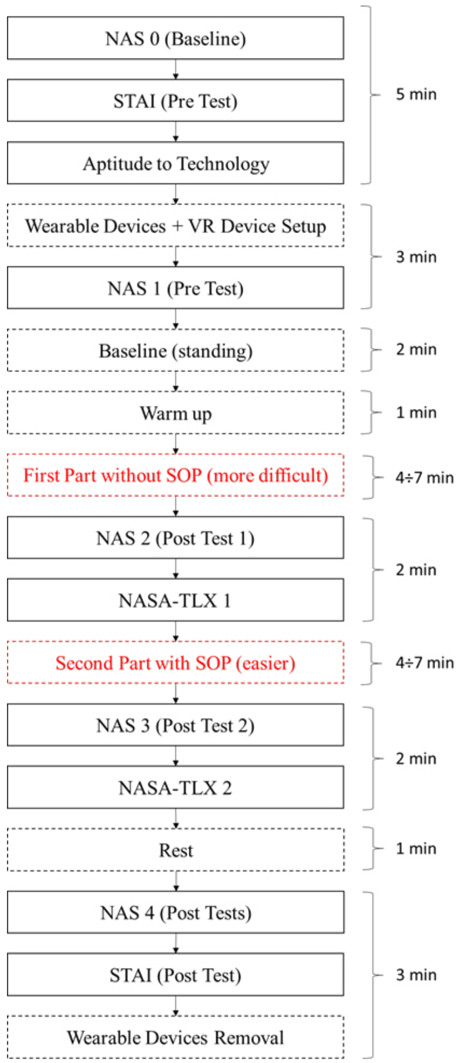

Figure 2: Protocol for the assessment of cognitive conditions during the training for assembly activities with virtual reality

First, the NAS is administered to record the basal level of perceived stress, the STAI survey is necessary to collect the perceived anxiety of the operator before the training, and the questionnaire about the aptitude to technology is useful to understand the familiarity that the subject has with advanced technological devices such as head-mounted displays, or virtual games. Then, the operator has to wear the wearable devices for the physiological monitoring and the HMD for VR. Before the beginning of the training, the NAS questionnaire is administered again, to understand if the use of wearables and VR headset may cause an increment in the perceived stress. At this point, two minutes of baseline should be recorded. This is useful to understand the variation of the biometric parameters between the rest and the training activity. One minute of warm-up should be provided to let the operator become familiar with the use of the VR technology.

The training is divided into two parts: while the first part is provided without showing the standard operating procedure (SOP) in the virtual environment, the second part includes the visualization of a box with the explanation of the tasks to be executed. Following this procedure, it can be supposed that the levels of cognitive load and stress will be higher in the first part, both because the user has to become familiar with the use of VR and because instructions are not supplied. A lowering of CL and stress is therefore expected in the second part, where the operator knows how to use the VR device and is helped by the SOPs.

The NAS and NASA-TLX are administered twice, after the first and the second training parts, to analyse the impact that the two different virtual configurations have on the operator's cognitive conditions.

After a rest period, the NAS and STAI questionnaires are administered again, and then the wearable devices can be removed.

The virtual training is video-recorded, and the performance is assessed in terms of completion time, attempts, and committed errors per tasks unit.

The overall duration of the procedure is about thirty minutes, considering that the time can change based on the subject's performance.

Table 1 summarizes the collected parameters, kinds of data, and tools used in this case study.

Table 1: Collected data

Collected Data	Monitored Parameters	Tools
Subjective	Familiarity with technological devices	Aptitude to Technology survey
	Perceived anxiety	STAI questionnaire
	Perceived stress	NAS scale
	Perceived workload	NASA-TLX questionnaire
Physiological	HR/HRV/IBI/BR	BH3 Zephyr BioHarness chest band
	EDA	Empatica E4 wristband
	PD	Eye Tracker
Performance	Number of Attempts	Reports per tasks unit
	Number of Errors	
	Completion Time	

3.2. *VR Training Application*

The VR immersive training simulation has been developed to be experienced through the HTC Vive, an HMD equipped with 32 infrared sensors for the 360-degree tracking, a gyroscope, an accelerometer, and a laser position sensor, that allow for 6 DOF tracking. The hands tracking is realized by using the Leap Motion, which is a system for human-computer interaction, based on gesture recognition.

The VR assembly application has been divided into two separated parts of different difficulty. The complexity degree of the tasks to be executed is approximately the same in the two different parts. However, the second part is easier because the operator is helped through the visualization of the standard operating procedure.

The first part can be divided into three tasks units as follows:

1. Tasks unit #1:
   - Task1: Pick the clamp hose exhaust and sub-assembly of DOC.
   - Task2: Align the sub-assembly of DOC to the engine exhaust as marked and place over DOC mounting.
   - Task3: Mount the DOC with the help of clamp.
   - Task4: Pick the clamp hose exhaust and sub-assembly of DOC.
   - Task5: Place the clamp assembly over DOC. By aligning the holes of DOC. Mounting. Insert the 4 flange bolts one by one manually up to 3 threads.
   - Task6: Flange bolts with the help of gun-socket.
2. Tasks unit #2:
   - Task7: Pick the shield DOC. and Insulation DOC.
   - Task8: Align the DOC cover with the holes of DOC.
   - Task9: Place the DOC cover over DOC.
   - Task10: Pick the 4 flange bolts and 2 shield expansion tanks.
   - Task11: Place the DOC cover over DOC. shield expansion tank over DOC. Cover and align the flange bolts.
   - Task12: Torque up the bolts with help of gun.
3. Tasks unit #3:
   - Task13: Pick the sensor temp 35 mm.
   - Task14: Mount the sensor to the DOC.
   - Task15: Connect the sensor pig tail to the electrical connector.

The second part consists in four tasks units:

4. Tasks unit #4:
   - Task1: Pick the pipe vertical WA silencer with the help of tackle.
   - Task2: Pick the exhaust hose clamp.
   - Task3: Insert the hose clamp over muffler DOC, do not tighten the clamp now.
   - Task4: Align the silencer to the bkt. Exhaust system & fit the DOC pipe with silencer with the help of clamp. Now tighten the clamp now tighten the clamp.
   - Task5: Pick 1 bolt and 2 nuts.
   - Task6: Insert the bolt to the bkt. Exhaust system and tighten manually up to 3 threads then with socket and gun.
5. Tasks unit #5:
   - Task7: Align both the nut one by one with the mounting studs.
   - Task8: Tighten the nuts manually up to 3 threads and then torque up with the help of socket – gun.
6. Tasks unit #6:
   - Task9: Pick the front hood sub-assembly with the help of front hood tackle.
   - Task10: Pick 2 NY lock nut M6 and 2 washers together.
   - Task11: Align the mounting studs of front hood with the holes of radiator sell and insert the studs to the radiator sell.
   - Task12: Pick each washer with each nut.
   - Task13: Insert the washer-nut over the mounting studs of front hood, tighten the nuts manually up to 3 threads and the with the help of socket-gun.
   - Task14: Lock the front hood with the help of 2 locking latch mounted on both side of front hood as shown. Be ensure the proper fitment of latch lock.
7. Tasks unit #7:
   - Task15: Pick the Centre panel sub-assembly by tackle as shown from the trolley carefully.
   - Task16: Place the centre panel over tractor move panel towards the indicating direction and pick 2 bolts, 2washer together by inserting washer over bolt.
   - Task17: Insert 2 bolts to the marked position with washer, tighten the bolts manually up to 3 threads then by socket-gun.
   - Task18: Pick 1 bolt, 1 washer, 1 spacer and 1 nut. Hold the spacer with nut to the inside of panel with spanner and insert the bolt with washer to the marked position and tighten the bolt by socket-gun.
   - Task19: Pick 1 bolt, 1 washer, 1 spacer and 1 nut. Hold the spacer with nut to the inside of panel with spanner and insert the bolt with washer to the marked position and tighten the bolt by socket-gun.

3.3. *Preliminary test*

A preliminary laboratory test has been accomplished to verify the feasibility of the protocol setup, for the assessment of cognitive conditions during a training session for assembly.

Figure 3: Frames of the first (left) and second (right) parts of the VR training for DOC assembly

Figure 4: External view of the preliminary trial

Figure 3 shows a few frames of the VR application. A couple of frames on the left show tasks 1-3 of the first part. The element that must be assembled is suggested in cyan, and when the operator is in the correct position, it turns yellow.
On the right, an example of a box with the tasks' descriptions, visualized, in the second training part, to help the operator.

Figure 4 shows the laboratory protocol setup, with the user wearing the smart devices for biometric monitoring.
The user was not expert in the assembly tasks described in section 3.2. The trial lasted twenty-eight minutes. The user highlighted the usefulness of the warm-up session to become familiar with the VR technology. She did not experience nausea or headache using HTC Vive for almost half an hour. Subjective questionnaires were easily collected, physiological parameters were correctly recorded, and the assessment of performance was simple to accomplish.

4. Perspectives and Future Work

The preliminary laboratory test has confirmed the feasibility of the proposed protocol for the analysis of operators' cognitive conditions during training activities with VR technology.

With this structured assessment methodology, it is possible to analyse the cognitive states of learners during training activities, in terms of anxiety, stress, and cognitive load from the subject's perception and from his/her physiological signals monitoring, which can be considered a more objective measure. These measurements are related to the performance evaluation to identify eventual mutual correlations between the worsening of performance and the increment in negative cognitive states (such as excessive stress, frustration, and/or mental effort). The partition of the test into two separate parts of different difficulty, linked with the three kinds of assessment measures (self-assessment, physiological monitoring, and performance evaluation), allows accomplishing a twofold aim:

- To verify if it is useful, in terms of performance, to supply the operator with virtual SOP in addition to the help furnished through the color-coded elements to be assembled in VR. Therefore, it will be possible to understand if this extra-aid allows a reduction of committed errors, attempts, and tasks execution time.
- To verify if giving an extra-aid allows reducing performance anxiety, stress, and avoiding cognitive overload.

It is expected that VR training shortens the learning period and permits the trainers to save time. This will be positively reflected on the productivity of the company, which will save money and resources. In this context, the effectiveness of the VR training must be guaranteed, and the cognitive ergonomics of the operator must be safeguarded.
For this reason, future works will consist in the validation of the developed VR training application through the proposed protocol, with a larger sample of inexpert operators. A comparative randomized study will give the opportunity to also compare virtual training procedures and traditional training practices, performed through the use of documents and videos, analysing the differences between the standard training and, hopefully, the benefits of VR mode. Specific metrics will be defined to compare the procedures, e.g., time to complete the entire procedure, committed errors, and cognitive conditions. A specific usability survey will be administered to analyse the operators' acceptance and opinions about the use of HMD and VR application in the training context.
Finally, this study will allow the optimization of the VR application. Indeed, after this analysis, it will be possible to re-design the VR training application, considering the requested mental demand, and thus avoiding stress, mental overload, and improving the performance.

Conclusions

The importance of the training for Operator 4.0 is widely highlighted in the literature. The great increase in the use of advanced technologies in the manufacturing context arises the necessity to switch from a traditional training approach, based on paper and video instructions, to a more engaging and effective model.
VR applications are becoming always more employed in the educational field. On one side, they provide a more immersive and safer environment but, on the other side, if not properly designed, they could distract or overload the user, making the tasks more difficult. For this reason, VR applications must be designed considering human capabilities, limitations, perceptions, and cognitive responses. Indeed, the use of HMDs requires an additional mental and physical burden, demanding different skills and experience.
In this context, the adoption of a human-centered approach is compulsory for the creation of successful training paths. For this reason, this paper proposed a structured protocol for the assessment of performance and cognitive conditions of operators during assembly training with VR applications. Experimental results will allow optimizing the VR training app from a human-centered perspective, permitting a consequent improvement in the operators' knowledge and skills.

Credit Author Statement

Agnese Brunzini: Conceptualization, Methodology, Writing - Original Draft.
Fabio Grandi: Software.
Margherita Peruzzini: Conceptualization, Writing - Review & Editing.
Marcello Pellicciari: Visualization, Supervision.

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