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Review

Virtual Reality for Training in Assembly and Disassembly Tasks: A Systematic Literature Review

Valentina Di Pasquale *, Paolo Cutolo, Carmen Esposito, Benedetta Franco, Raffaele Iannone and Salvatore Miranda

Department of Industrial Engineering, University of Salerno, Via Giovanni Paolo II, 132, 84084 Fisciano, SA, Italy; p.cutolo1@studenti.unisa.it (P.C.); caesposito@unisa.it (C.E.); bfranco@unisa.it (B.F.); riannone@unisa.it (R.I.); smiranda@unisa.it (S.M.)
* Correspondence: vdipasquale@unisa.it

Abstract: The evolving landscape of industrial manufacturing is increasingly embracing automation within smart factories. However, the critical role of human operators, particularly in manual assembly and disassembly tasks, remains undiminished. This paper explores the complexities arising from mass customization and remanufacturing, which significantly enhance the intricacy of these manual tasks. Human involvement is essential in these tasks due to their complexity, necessitating a structured learning process to enhance efficiency and mitigate the learning–forgetting cycle. This study focuses on the utilization of virtual reality (VR) as an innovative training tool to address these challenges. By conducting a systematic literature review (SLR) on the impact of VR on training operators for assembly and disassembly tasks, this paper evaluates the current level of VR application, the used technologies, the operator performance, and the VR benefits and limitations. The analysis reveals a limited but promising application of VR in training, highlighting its potential to improve learning outcomes, productivity, and safety while reducing costs. However, the research also identifies gaps in the practical application of VR for training purposes suggesting a future research agenda to explore its full potential.

Keywords: immersive technologies; virtual environments; industrial training; manufacturing industry

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Citation: Di Pasquale, V.; Cutolo, P.; Esposito, C.; Franco, B.; Iannone, R.; Miranda, S. Virtual Reality for Training in Assembly and Disassembly Tasks: A Systematic Literature Review. *Machines* **2024**, *12*, 528. https://doi.org/10.3390/machines12080528

Academic Editor: Kai Cheng

Received: 28 May 2024
Revised: 11 July 2024
Accepted: 25 July 2024
Published: 2 August 2024

1. Background and Motivation

The current industrial landscape, although strongly focused on increasing automation in smart factories, must consider various challenges related to the fundamental presence of operators for the execution of manual activities. Mass customization and remanufacturing are strongly increasing the complexity of manual assembly and disassembly tasks.

Mass customization has emerged as a prevailing trend in contemporary manufacturing companies, representing a strategic departure from traditional mass production methods. The increase in the number of product variants has been driven by customer demand for new product functions and features, leading to a shift from traditional mass-produced products to personalized products [1]. This innovative approach seeks to combine the efficiency of large-scale manufacturing with the flexibility to meet individual customer preferences. In mass customization, products are tailored to accommodate unique customer needs without sacrificing the economies of scale. Manufacturing companies thus face the challenge of managing a huge amount of product variants and build options, which increases overall complexity and risk of quality errors in manual assembly [2]. In this context, the operation of assembly systems becomes much more complex with increased variety and increased production volume, with an impact on cycle times, quality, and cost [3–5].

Remanufacturing is an industrial process aiming to retain the usefulness of both products and components. According to the British Standard 8887-220:2010 [6], "Remanufacturing is the series of steps needed to transform an old product into one that can be considered as new, having at least the same performance and the same warranty of a new product". In June 2021, the European Climate Law was approved by the European Union, with the aim to reach a zero-emission goal by 2050 [7]. This measure is part of the European Green Deal, which aims to promote sustainability principles through the Circular Economy Action Plan (CEAP), which was promoted in early 2020. Remanufacturing (RMfg) strategies appear to be very promising in achieving these goals, reducing the average consumption of natural resources and energy by over 70% and greenhouse gas (GHG) emissions and landfill needs by more than 80% [8], but the RMfg sector is still in the initial stage in Europe, mainly because of technical, economic, and social barriers, which make RMfg-related businesses difficult to access. Among the technical barriers, the process of disassembly represents one of the most important. Often, disassembly cannot be simply considered as the reverse of assembly, and it is affected by the quality of the returned products [9]. Due to its complexity and to the variability in returned products, disassembly is labor-intensive [10] and has low efficiency and high labor costs [11,12]. Robotic disassembly is emerging as an important field of research in recent years and is proposed as an alternative but faces challenges in planning disassembly sequences automatically [10,13].

1.1. Challenges in Assembly and Disassembly Tasks

Several studies have highlighted the challenges faced by humans in performing assembly and disassembly tasks [14,15]:

- Complexity, variability, and uncertainty: The trend toward customized products and on-demand manufacturing increases the complexity of assembly tasks, requiring workers to cope with constantly changing work instructions without impacting production speed [14]. The complexity level of tasks is influenced by factors such as the structure of the task, input factors, process operation factors, and output factors [16]. These factors significantly affect the task complexity in an assembly line and contribute to the overall complexity level of the task [17]. Furthermore, in a mixed-model assembly line, the production process is designed to handle various product configurations, allowing for greater flexibility and efficiency and this entails a strong variability in the tasks that operators must perform. Task complexity also impacts the disassembly process, including interlocked components; the need for optimal disassembly sequences, often inefficient for large or complex products; and the need for parallel disassembly techniques that employ several manipulators (manual and/or automatic) to remove multiple components simultaneously. Disassembly tasks often involve uncertain parameters, such as disassembly time, which can impact the feasibility and cost of operations. The lack of tools to analyze and compare remanufacturing processes is a significant issue [15]. Additionally, uncertainties in product take-back contribute to the complexity of remanufacturing systems [18]. Furthermore, the complexity of assembly and, above all, disassembly tasks impacts on the incessant operators' rotation for tasks in swift alternations between learning and forgetting periods. For this reason, these non-routine and complex tasks require a structured learning process based on employee and workplace assessments [19].
- Cognitive load and motor skills involved: The low-volume/high-production-mix strategy of manufacturing companies increases the cognitive load on manual assembly and disassembly operators, highlighting the need for well-trained operators and efficient training programs [20]. The cognitive load on workers increases with the complexity of manual assembly, leading to more frequent errors and decreased productivity [21]. Assembly tasks primarily comprise cognitive tasks, and the assembly performance depends on the operators' cognition skills [22]. Motor skills in manual assembly and disassembly are necessary to limit short- and long-term fatigue, and for this reason, the workstations must be designed to determine the best ergonomic layout of components for assembly and demonstrate the best assembly sequence to the operator [23].
- Safety: Ensuring the safety of human workers in the disassembly environment is a critical challenge, particularly in collaborative human–robot settings.

To overcome these difficulties, researchers are focusing on three main areas:

- Technologies to support assembly and disassembly tasks: Human–robot collaboration and augmented reality represent the technologies on which the academic and industrial world is focusing to increase the performance of operators and the system. The use of augmented reality technology is proposed to optimize disassembly processes for maintenance purposes, aiming to make it immediate for operators to efficiently carry out the repair process while learning in parallel what they need to do.
- Strategies for managing complexity in task assembly/disassembly involve the development of efficient encoding and decoding strategies for the disassembly process, as well as the application of metaheuristic approaches such as genetic algorithms to solve the asynchronous parallel disassembly planning problem. The application of metaheuristic approaches, such as genetic algorithms, is effective in solving the asynchronous parallel disassembly planning problem and identifying faster disassembly processes, especially for large-scale problems.
- Workforce training and operator learning [19]: Research shows that the architectural complexity of products significantly impacts operator learning, productivity, and quality performance in both assembly and disassembly tasks. Learning repetitions affect manual assembly/disassembly performance, with instructions playing a crucial role in learning and unequal temporal workloads among workers in larger groups, leading to decreased productivity. A planning method for structuring the learning process in manual assembly can improve the performance and support the appropriate human task allocation.

1.2. Training Strategies

The last strategy represents the one of interest for this study. The increasing complexity of manual assembly tasks due to product variants requires a structured training process to qualify employees for their work tasks [19]. In fact, the possibility of intervening in the learning process of operators involved in assembly and disassembly processes through appropriate training sessions represents one of the key elements on which to focus attention.

The learning phenomenon refers to the process through which an individual or a system acquires knowledge or skills through experience, practice, or instruction. This phenomenon involves the ability to absorb, comprehend, and retain information. Learning is a fundamental aspect of human development and the functioning of various systems, ranging from individuals to machines and algorithms. The study of the learning phenomenon spans disciplines such as psychology, neuroscience, artificial intelligence, and systems engineering. Understanding how learning occurs and optimizing knowledge acquisition processes is crucial in various fields, from education to the design of intelligent systems, and even with applications in industries. However, more or less long periods in which the operator does not carry out the learned task trigger the opposite phenomenon of forgetting. Forgetting is the apparent loss or modification of information already encoded and stored in an individual's short- or long-term memory. It is a spontaneous or gradual process in which old memories are unable to be recalled from memory storage.

This means that whenever a worker processes jobs of the same product type repeatedly, he/she gains routine resulting in a decrease in processing times with the increasing number of units processed. During times of interruption, he/she loses some of the previously gained routine leading to an increase in processing times compared to the processing time directly before the interruption. Industrial workers are subject to the effects of learning and forgetting, so the study of these curves, particularly in their application to this field, has received a lot of attention.

1.3. Virtual Reality Technologies for Training

In the last years, virtual training systems have been introduced as efficient alternatives to physical replica training, with experiments classified based on evaluation methods, interaction interface, and product complexity. Virtual reality (VR) means an exclusively digital environment, created by one or more computers, which simulates actual reality and recreates it in a non-tangible way, and which is conveyed to our senses using consoles that allow interaction in time real with everything that is produced within it. This data exchange is enabled by computer devices, mostly visual visors, wired gloves, and earphones, which allow complete immersion in the simulation, created in a three-dimensional and dynamic way, through access to a whole pre-arranged series of contents that are explored to build a truly plausible parallel world. Due to its multi-sensory and immersive nature, VR can fulfill the principles of active learning. Indeed, immersive virtual experiences enhance the sense of presence and embodiment, both key factors that can promote learning.

In recent times, VR has become a promoter of innovative training methods: the use of controlled virtual scenarios has proven to be a valuable tool for training workers in several environments. VR is potentially effective in learning because it guarantees the possibility of immersing users in faithful simulations of real contexts. In fact, if compared to traditional training methods such as lectures, assistance from a senior figure, instructional videos, or text-based procedures, VR offers many advantages in training, as it simulates difficult or dangerous working conditions, allowing skills to be learned safely and avoiding downtime or damage to equipment. VR allows for individual training in the execution of tasks with equipment that does not yet exist or is not available and offers the opportunity to make mistakes during learning without real consequences. VR training has been found to have cognitive benefits, with studies showing that VR platforms generate significantly more enjoyment and higher knowledge retention compared to traditional video platforms [24]. VR-supported training has been found to lead to an increase in learning success compared to traditional training on the job accompanied by a tutor, with small modifications in VR training applications significantly affecting learning outcomes [25].

1.4. Main Contribution and Paper Structure

Although VR is commonly used for training purposes in various fields, such as medical, military, construction, aviation, and industrial training [26–32], an in-depth study has not yet been conducted for assembly and disassembly operations. The industrial sector, and in particular highly complex assembly activities, present peculiarities that can undermine the effectiveness of this tool. As there are currently few studies that aim to assess the effects of VR on operator performance when used as a training tool for personnel in assembly and disassembly operations, the purpose of the paper is to understand the current level of application in this area, to evaluate the VR impact in terms of objective measures (task completion time, number of errors, or time spent on training) and subjective measures (usability, cognitive load, satisfaction level, and comfort level), to identify the benefits and limitations, and to identify possible guidelines for the diffusion of this technology, evaluating what the current open questions are.

This paper is structured as follows: Section 2 provides the materials and method adopted for reaching the goal of the study. Section 3 reports the results of the conducted analysis, and Section 4 presents an in-depth discussion of the results, the conclusions, and the identified research gaps.

2. Materials and Methods

2.1. Systematic Literature Review

In order to identify the impacts of the use of VR on traditional personnel training processes and to assess the actual effectiveness and efficiency of immersive technologies applied to the training of industrial operators, a systematic literature review (SLR) based on the methodology proposed by [33,34] was conducted.

The search was carried out using the relevant scientific databases Scopus and Web of Science in June 2024. It consisted of four consecutive steps: the definition of keywords; the literature database search under constraints; the paper selection according to screening criteria; and the analysis of selected papers and data extraction.

Three groups of keywords related to enabling technologies, training, and task type were defined according to the purpose of the study (Table 1). In particular, the asterisks (*) at the end of certain words are used to indicate all their possible suffixes. The groups were combined with logical operator AND and the keywords of each group with logical operator OR. The search was limited to papers written in English from 2010 onward and whose document type was conference proceedings, articles, or reviews.

Table 1. List of keywords selected for the systematic literature review.

Group A	Group B	Group C
Virtual Reality (VR), VR, Virtual Environment, Immersive Technolog *, GamiFication, Synthetic Reality, Serious Game	Training, Learning	Disassembl *, Assembl *, Remanufactur *

The third step was divided into two screening steps. With the first screening that consisted of reading the titles and abstracts, all papers that were not related to the defined keywords, in which VR was not the main focus or in which only augmented reality (AR) or mixed reality (MR) were used and that did not present case studies, were excluded. Instead, all papers that dealt with workplace training through the application of VR technologies or otherwise related to the performance evaluation of immersive VR training were included. The research was limited in this way with the aim of investigating in depth the use of VR technology for training through application case studies that highlighted the results in terms of the learning of the people involved. The second screening, by reading the full text, enabled the identification of the most relevant papers. All unavailable papers and those which, despite the case study, did not present results according to the metrics predetermined for the analysis were excluded. In addition, papers containing case studies concerning more scholastic or academic topics than industrial applications were excluded as they investigated the potential for teaching and not for training workers.

Once the screening was completed, a set of articles was obtained whose main theme is the training of workers using VR. Through the use of different VR solutions or comparison with traditional methods, performance obtained in assembly or disassembly tasks was evaluated.

To complete the last step of the SLR, a spreadsheet was created to contain all the most relevant information from the obtained papers. The carried-out analysis was focused on

- Main bibliometric characteristics of papers whereby the articles were classified according to information about the authors, the year of publication, and the type of document.
- Content analysis, as better described in the next section.

2.2. Content Analysis

Regarding the content analysis, the following information was reported for each selected study:

- Type of task and research environment: The case studies were classified concerning the assembly or disassembly activities and the type of environment in which they were carried out (laboratory/company plant).
- Technology used: The different technologies for the development of VR used in the selected cases were identified and classified. This was essential to be able to identify the level of immersion reproduced in the case study. Level of immersion is the ability to abstract the user from the real world, using projection screens or helmets. The advancement of information technologies today allows us to navigate photo-realistic environments in real time, interacting with the objects present in them. When talking about VR, it is good to immediately make a distinction between non-immersive VR and immersive VR: in the former, the user simply finds himself in front of a monitor, which acts as a window onto the three-dimensional world with which to interact

through special joysticks. The resulting effect is different from that obtained with an immersive VR, in which the effects that the user perceives are much more engaging and capable of making the user live in a completely new reality.

- Sample experience with technology and tasks: Pre-learning processes were identified for each case study, which aimed to increase participants' confidence in both the technology used for the study and the task to be performed.
- Learning strategy: For each article, the devices used, the methods of comparison, the number of tasks performed, and the number of attempts allowed were defined.
- Operator performance: Results on objective metrics such as training time; task completion time; and number of errors and subjective ones, such as perceived workload, usability, and other qualitative evaluations, were analyzed.

Based on the results identified from the content analysis of the papers, the main benefits and limitations in the use of VR for training in assembly and disassembly tasks were identified. This was evaluated according to the type of task performed and the level of immersion of the technology used. In particular, comparisons between traditional training methods and the use of VR technologies have allowed us to define initial guidelines for the development of successful VR training strategies. A preliminary practical operational approach was formulated.

The analysis of the contents of the selected papers therefore made it possible to identify the current research gaps and the elements for the development of a future research agenda in this area.

3. SLR Results

3.1. Selected Papers

A Scopus and Web of Science database search conducted by abstract, title, and keywords, following the inclusion of the selection criteria relating to time horizon, document type, and language (mentioned above), resulted in the generation of 1098 articles that were reduced to 990 after checking for duplicates. The first screening reduced the set of articles to 128; subsequently, after the second screening, the sample of eligible papers was reduced to 31.

In Appendix A, the full list of selected papers, chronologically ordered, is reported. The identification numbers reported in Appendix A will be used in the subsequent sections to facilitate the discussion.

The bibliometric indicators considered correspond to the type of papers, as well as their year of publication. Regarding the articles' distribution over the years (Figure 1), it is possible to observe, over a 10-year time horizon, a higher concentration (by more than 50%) especially in the last 5 years. This can be explained by considering that the use of VR in workplaces received a significant boost following its adoption as a personnel training method by Walmart. In 2017, Walmart became the first to utilize VR technologies to train managerial skills among its employees, thereby fostering research and opportunities for the application of VR [35].

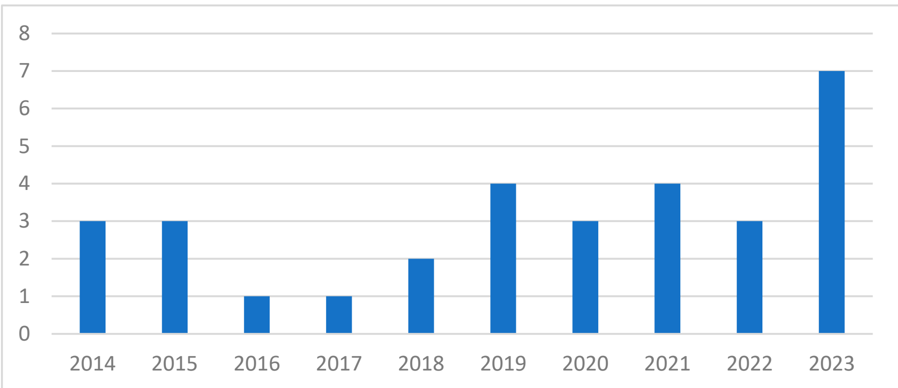

Figure 1. Article distribution over the years.

Furthermore, only articles and conference papers were considered, with a slight prevalence of the former (18) over the latter (13).

3.2. Content Analysis

The goal of the research was to identify the effects of using VR on the performance of assembly and disassembly tasks in industrial environments. Compared with the total number of papers selected, there is a clear prevalence of assembly tasks (90%) (Figure 2) with only two papers also focused on disassembly tasks [36,37]. In fact, it is interesting to observe that assembly arouses more interest among researchers than disassembly, which is never studied independently but always in connection with an assembly task. This aspect represents an important gap in the current literature, as discussed later.

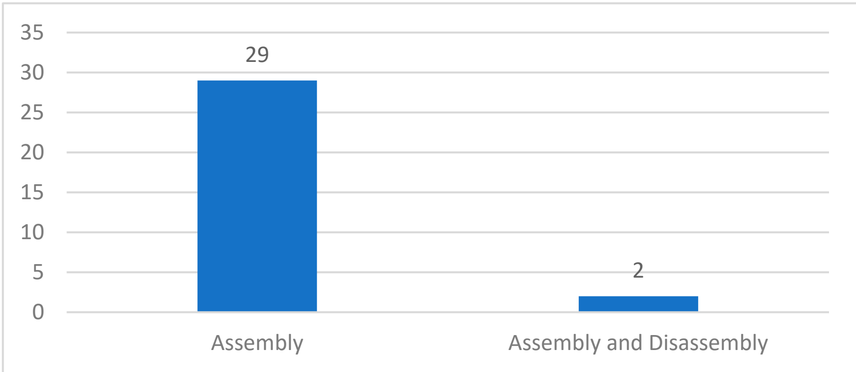

Figure 2. Distribution of application tasks.

3.2.1. Type of Case Study

The case studies analyzed were mainly performed in the laboratory, through carefully designed and tested case studies with samples of different types but mainly characterized by students.

Only two were performed in a company plant [38,39]. Paper [38] analyzed two studies conducted in a plant of an automotive company. The first study investigated the effectiveness of the virtual training system (VTS) on trainees who had no previous knowledge of the chosen assembly task compared to a traditional training method that included paper, video, and expert demonstrations. After completion of the real-world task, performed by both groups one week after training, the results showed an improvement in performance for the VTS-trained groups with a reduction in the average task completion time, as well as a lower average number of errors. The second study, on the other hand, aimed to evaluate the efficiency and acceptance of the chosen VTS system compared to other training methods previously tried by real end users. During this study, three different tasks within the VTS were performed and no time or error measurements were recorded. The aim was to qualitatively evaluate participants' experience to identify the main issues, improving the training quality as much as possible. The results showed a greater acceptance of the system, which was easier to use and better than traditional training for practicing the sequence of the whole assembly process.

Paper [39] aimed to demonstrate how gamification with multiple levels of difficulty affects the efficiency and motivation of participants during VR training in an industrial case. Specifically, the study was conducted on the example of an assembly task in a metallurgical company, in which half of the participants received VR training with gamification and the other half did not. In this way, it was possible to show how learning times in the subjects who received gamified VR training were significantly shorter than in the sample without gamification. Furthermore, assembly times and error rates were also lower in the case with gamification except for the highest level of difficulty, where the error rate was high even in the case with gamification. However, while this result led to a reduction in the participants' sense of competence, it also reduced the probability of errors in the actual assembly. Finally, the group with gamification appeared to be more motivated overall than the group without gamification. In general, therefore, VR training with gamification with multiple levels of difficulty, combined with balanced feedback, is useful both for achieving better results in the application phase of the acquired skills and for supporting and improving the self-assessment of the trained subjects.

3.2.2. Level of Immersion

Each case study, whether it is an experiment in the laboratory or a simulation in a company, aims to understand the effects of using VR technologies on operator learning and task completion performance. In some cases, the VR case is compared with a traditional one; in others, multiple options for applying VR technology are established to understand which method is most effective (Table A1). Traditional training methods include paper-based instruction, video tutorials, audio recordings, or assistance from physical tutors; however, there are various types of VR applications (i.e., with/without gamification, immersive/non-immersive experience, and with/without haptic system, etc.).

The devices used for each VR training session can be classified according to the degree of immersion of the simulation. Based on how closely the virtual scenario corresponds to the real one, three different levels of immersion were distinguished:

- High, characterized by the use of HMDs (Head Mounted Displays), wire gloves, as well as tracking devices for head and eye movements;
- Medium, characterized by the use of stereoscopic viewers and movement-tracking devices;
- Low, characterized by the use of a mouse, keyboard, 2D desktop PC, and headset.

Table 2 shows some of the possible combinations of instruments found in the literature, classified by level of immersion.

Figure 3 presents the classification of the selected papers according to the level of immersion defined by the combination of devices used in each case study. It is clear that most studies present high levels of immersion. This is important as the level of immersion may impact performance and the translation of knowledge and skills to the real world, particularly in tasks combining motor skills with complex decision making.

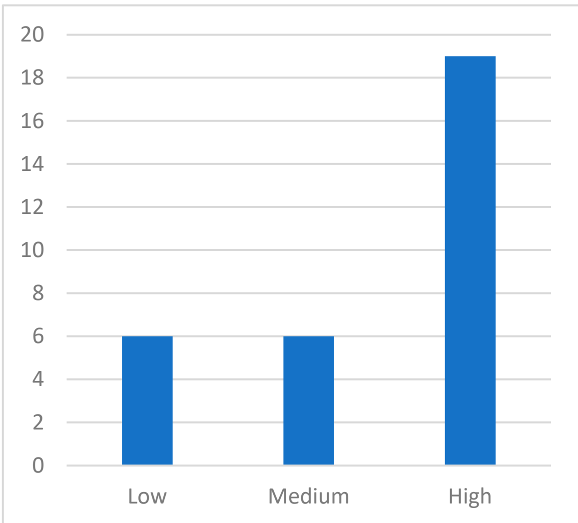

Figure 3. Immersion level assessment.

Table 2. Classification of devices used according to the level of immersion.

Level of Immersion	Devices
LOW [40–45]	PC desktop 2D + Mouse + Keyboard
	PC desktop 2D + Mouse + Keyboard
	PC desktop 2D + Mouse + Keyboard + Leap Motion Controller
	PC desktop 2D + Mouse
	PC desktop 2D + Mouse + Keyboard + Headphones
	Detection Response Task + HMD + Manual controllers
	Mouse + Haptic Phantom OmniVR + Markerless Motion Capture
	Multi-touch table
MEDIUM [36,38,46–49]	HTC VIVE + Manual controllers
	Microsoft Kinect + Controller Nintendo Wii Mote + HMD
	VR Glasses + Joystick
	Laptop + Microsoft Kinect + Wii Mote
	Headphones + HMD + Controllers
	Microsoft Hololens
	HMD + Joystick
HIGH [20,25,37,39,50–64]	HTC VIVE + HTC VIVE headset + HTC VIVE controllers + HTC VIVE base station + VIVE tracker
	HTC VIVE 3 HMD + HTC VIVE controllers
	HTC Vive and accessories + IR camera
	HTC VIVE Pro + Leap Motion Controller
	HTC Vive Pro Head-Mounted Display + 6-DOF Motion Controller
	Keyboard + Mouse + Tactile devices + HTC VIVE
	Oculus Quest (or Oculus Rift) + Controllers
	Oculus Rift + IR camera + Leap Motion Controller
	Optical marker + HMD Oculus Rift DK2 + 3D camera + CAVE system
	HMD + Tactile devices
	3D screen + Tactile devices + Stereoscopic glasses
	3D monitor + Stereoscopic glasses + Wire glove + Hand and head tracking systems

3.2.3. Previous Experience and Pre-Learning

Regarding the sample of workers who participated in the reported case studies, experience information was considered relevant, which was evaluated along two different directions:

- Experience with VR technology, which could influence the time to complete the training because the operator appears to be already comfortable with the new technology;
- Experience with the task, which could result in effects on both the number of errors and task completion time, because experienced operators, while undergoing traditional training processes, could achieve better performance even without the aid of VR technologies.

Overall, cases in which there is no experience with VR technology prevail; those cases in which less than half of the sample had experience with VR were also included in the "no". Similarly, regarding worker experience with the task, excluding the papers that did not collect this information, there is a prevalence of case studies in which the sample has no experience with the assigned task of assembly or disassembly.

Taking into consideration that in most of the case studies analyzed, operators have no experience with either VR technology or tasks, pre-learning strategies are of key importance. Pre-learning is anything that takes place before the operator's actual immersion in the simulation and that can be of help to them either in terms of the training activities for the specific task or familiarization with the VR technologies and platforms to be used during the test. Figure 4 shows the distribution of the types of pre-learning used in the case studies analyzed: cases in which training is performed only to introduce workers to the use of VR and those in which instruction on both the use of VR technologies and task execution are combined prevail ("VR only" and "VR and Task" cases). On the other hand, cases in which no pre-learning is performed at all ("None" cases) are rarer. The pre-learning type specification for each selected paper is given in Table A1.

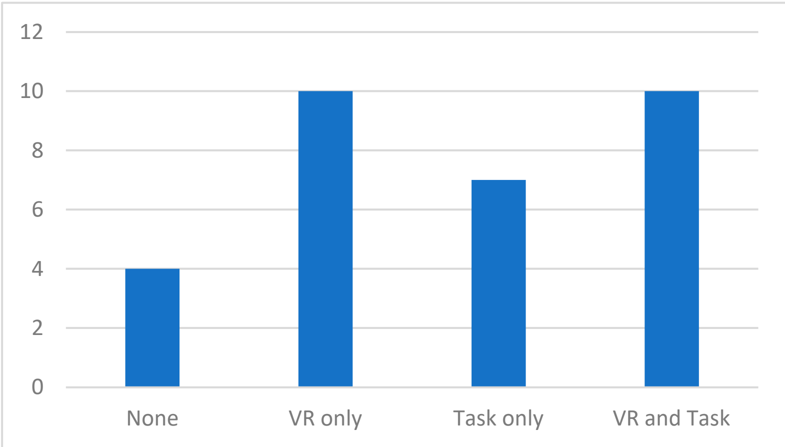

Figure 4. Types of pre-learning.

Regarding pre-learning on the task, very often participants were offered the same task, for which all the steps were explained [40,44,56,59,64]. In other cases, the same task was illustrated but simplified, so that the participants were gradually guided to the actual experiment [36,51,52]. In the case of VR, on the other hand, pre-learning had the function of making the participants familiar with the technology. This is particularly useful if the selected subjects have no previous experience with VR. In this way, the possible lengthening of task completion time due to inexperience with the virtual environment is reduced.

3.2.4. Evaluation of VR Impact

The evaluation of the impact of VR training for assembly and/or disassembly workers was carried out using indicators that can be defined as objective metrics. According to an IEEE definition, a metric is a quantitative measure of the degree to which an attribute is owned by an entity. Those most often found in the analyzed documents are

- time required for training;
- completion time of the assigned task(s);
- number of errors.

Instead, the subjective metrics involve opinions, perceptions, and feedback directly collected by the human operator involved in the task, as

- perceived workload;
- usability;
- qualitative evaluation.

Before proceeding with the explanation of the results deriving from the analysis of the aforementioned metrics, it should be pointed out that the complete list of these metrics does not always appear in each of the analyzed articles. In general, in most of the documents analyzed, it was assessed if VR training compared to traditional training helps improve the above-mentioned indicators. Some of the traditional methods used are

- physical tutors, i.e., people experienced in the specific task [25,54,59];
- paper-printed instructions, i.e., manuals with step-by-step instructions [20,37–39,41,56,62,64];
- video tutorials, depicting the steps needed to assemble/disassemble the object [41,43,47,56,59,61];
- audio recordings, describing the steps needed to assemble/disassemble the object [63];
- conventional guidance, i.e., on-the-job training [36,49].

However, very often, the evaluations also dealt with different alternative methods for performing training using VR. In these cases, the methods proposed differed in the level of immersion [40,43,45,55,57,60], in the technologies used [40–43,47,55,58,61–63], in the levels of task difficulty [46,63], and in the presence or absence of gamification [39,44,48].

Objective metrics were more common than subjective metrics; in fact, most of the articles analyzed did not evaluate the latter. Among the subjective metrics, usability prevailed, followed by perceived workload by the operator and, finally, the qualitative evaluation. By focusing on the case studies that evaluated the subjective metrics, part of these evaluated the usability through the system usability scale (SUS) [38,53,55,61,64] or IBM's Post-Study System Usability Questionnaire (IBM PSSUQ) [63], while others evaluated the perceived workload through the NASA Task Load Index (NASA-TLX) [53,59,64]. The other articles evaluated other qualitative metrics like the satisfaction level [51], subjects' subjective feelings on the virtual assembly system, the Simulator Sickness Questionnaire (SSQ) [55], and the transfer of learning [61].

The analysis of papers comparing the application of VR technologies versus the use of traditional methods did not reveal any significant results in terms of improving task completion performance or reducing training time. On the one hand, a reduction in the number of errors made through the use of VR technologies is much more clearly observed [25,38,39,47,49,56,62]. On the other hand, the analysis of papers that compared different kinds of VR training showed an improvement in all metrics due to gamification. The term "gamification" indicates the application of mechanisms and dynamics borrowed from the world of games to activities that are not directly related to gaming, to boost the user's motivation and active interest in the activity itself. The process of ludicization, applied to a target of performance or training content, can motivate and stimulate participants, thanks to elements of competition and challenge in a production experience or time limits in emergency training simulations. So, thanks to the boost given by reward sounds, progress bar, and score for the task accomplished, the time of completion, training time, and number of errors were significantly reduced [39,48].

In addition, studies focused on the comparison of different VR solutions/devices to evaluate the best solutions in terms of device combination [40,63], level of immersion [39,46], or usability [44] to achieve the best performance by workers.

3.3. Benefits and Limitations

The analysis of the identified case studies showed that VR proves to be an efficient training method, capable of bringing numerous benefits:

- Reducing risks of accidents: VR makes it possible to simulate difficult working conditions, failures, or dangerous/emergency conditions that cannot be reproduced with real equipment, allowing the user to acquire skills and knowledge previously impossible. Through VR, every aspect of the components involved in complex operations can be explored, allowing an infinite number of repetitions. Furthermore, the use of VR can significantly reduce the risks associated with work-related injuries, quality defects, and financial losses [8]. VR-based systems may be more expensive, but they provide risk-free and injury-free environments for teaching and training [45].

- Improved learning and skill retention: Physical exploration of simulated space and time facilitates learning, knowledge, and memorization, while experimental practice helps to understand complex themes, concepts, and theories. According to Edgar Dale, in fact, a person remembers 10 per cent of what he or she learns when reading, 20 per cent when listening, and as much as 90 per cent when performing a determined action [65]. VR provides a platform for 'learning by doing', rather than learning by seeing, hearing, or observing, and this, therefore, explains how VR technologies allow to improve the effectiveness of training and extend knowledge retention time. VR supports active learning and the practice of repeated tasks because it offers the opportunity to examine all the details of the parts involved in a complex operation, and, above all, it offers the opportunity to perform the desired number of repetitions and applications without worrying about the damage that results from any mistakes as these have no consequences in real life. This can only have a positive effect on learning effectiveness, as also underlined in the case study [39].
- Increased staff motivation: As VR is still considered an innovative technology, immersive training is less frustrating and sometimes even more fun than a classic treatment. The possibility offered to the user to immerse and interact with a virtual world and the use of gaming techniques and features (such as the division into levels and the realization of intermediate drill games [39,44,46,48,56]) significantly improves the operator's attention. Again, VR presents an intuitive approach because movement in a virtual environment resembles real-world actions. This makes it possible to enter the training scenario more quickly, keeping the user's attention on the learning content. These aspects, therefore, increase the attention and motivation of the staff and improve the learning process which will be, as mentioned, effective and efficient.
- Enlarged availability: Because it has no physical limits, the virtual environment offers paradoxically unlimited spaces in which many individuals can participate in training activities simultaneously, thus stimulating collaboration and meeting the current needs of increasingly global organizations.
- Easier onboarding: The extended availability thus enables a mass training process at the same time, which in turn speeds up onboarding, i.e., the return on investment on new employees within a company. In addition, for companies that need to train employees who are geographically dispersed or who prefer to work remotely, this mode eliminates the need to organize in-person training.
- Reduced costs: The adoption of VR technologies for personnel training results in cost savings for the company due to several aspects. Firstly, the possibility of interacting with virtual equipment avoids the need to stop the production process to illustrate the structure and operation of the various machines and tools to workers, which represents a significant cost saving. Secondly, again thanks to virtual replicas, real parts are no longer required, avoiding the potential damage not only to expensive equipment due to the inexperience of the trainees, but also to the parts themselves.

Regarding costs, these could be further reduced if training and task completion times could be cut. However, although in many papers an improvement in this aspect is shown, in just as many others, a worsening is recorded. Given the small sample size, we believe that no further conclusions can be drawn regarding the impact of VR on training and task completion times, which will therefore have to be further investigated in future work.

Sources of errors that limit the overall performance of the VR system include several of the following:

- Tracking: It is essential for a quality VR experience to have stable and accurate tracking of the user's body in virtual space. Tracking should be accurate to within 1 mm and without 'jitter'. Common limitations include optical occlusions, limited space, and tracking accuracy.
- Simulation software: This introduces several sources of error in VR interactions, such as usability problems, rendering, scene lighting, and collision detection.

- Visualization: Devices such as HMDs have limitations in the field of view, low latency, and limited frame rate and resolution, which may affect the user experience.
- User factors: The user's level of training and physiological limitations, such as tremor or vision problems, can affect the overall performance of the VR system.

In addition to the aforementioned sources of error, further parameters, this time related to the design of the virtual reality training system (VRTS), impact on the final outcome of the training. In addition to the main objective of a VRTS to facilitate the transfer of knowledge and skills from the virtual environment to the real world, there is sometimes a risk of also transferring inappropriate or incorrect knowledge or skills, due to an incorrect design and validation of the tool. It is therefore evident that there are too many parameters influencing the effectiveness of VR training to be able to control them all. This is one of the main reasons why it is difficult to include this technology in industrial contexts as a personnel training and updating tool. The traditional training mode is no longer able to meet growing social needs due to limitations in training equipment, training time, training location, and training costs. There is less dependence on the physical instructor, as digital instructions can guide the worker [62]. Digital simulations of production processes are the base for optimization activities through novel technologies, fueling time, and cost reductions [58].

4. Discussion and Conclusions

The analysis conducted in this study focused on the VR use for the training of operators involved in assembly and disassembly activities. VR technologies are widely considered in manufacturing industries because they can improve manufacturing operations, leading to efficient and effective learning and training, and can increase productivity, improve quality, eliminate risks, and reduce costs. The articles analyzed highlighted that VR facilitates the training of specific manipulation gestures vital for assembly and disassembly procedures [66]. The experience and skill level of the worker significantly affect the requirements for information presentation in assembly instructions [67].

Furthermore, the possibility of training operators not interrupting production, not entertaining human resources or equipment from production, not producing defective parts because they result from tests carried out by the users being trained, not incurring equipment costs for training, eliminating risks and damages, yields an immediate and obvious economic return.

4.1. Preliminary Guidelines for Defining VR Training Strategies

The effectiveness of VR training may be influenced by factors, such as the level of immersion, cognitive load, and individual characteristics, which need to be carefully considered in VR training design [68,69]. Regarding the design of VR training sessions, it is important to remember the purpose of the training itself, such as the transfer of knowledge from a virtual environment to a real one. To ensure greater effectiveness of the training process, we must first balance the level of guidance provided by the virtual environment. Therefore, when designing a VR training tool, it is important to ensure effective step-by-step guidance through the assigned task, establishing an appropriate level of challenge to promote learning. The large number of suggestions provided in the VR training session can prevent users from reaching the cognitive stage of skill acquisition. It should therefore be considered that not only excessive driving, but also too little, can be harmful. In fact, if the user does not know how to progress in training, he/she could be subject to frustration, capable of reducing his/her willingness to learn. In light of this, it is suggested to structure a VR training session using levels characterized by increasing difficulty or, at most, that are dynamic. Alongside the organization by difficulty levels, one can also ask what is the most advantageous type of driving to adopt. In virtual environments, in fact, the notions could be transferred through textual, auditory, or even audiovisual guides. It is then interesting to underline those studies [70] demonstrating that offering redundant information on multiple sensory channels could be advantageous. An audiovisual guide is therefore suggested, supported by a higher number of details, which can, for example, be structural properties of components in the case of assembly task.

Another extremely important factor to take into consideration when designing a training session is the duration of the training itself. In this regard, it is worth specifying that guidelines on the use of VR provide that the overall duration of VR training is generally limited to 20 min. This is necessary to avoid unpleasant effects such as cyber sickness.

Related to the duration of the training is the number or training sessions. This number should never be less than two to ensure correct consolidation of the concepts learned. It is suggested, however, to guarantee users the possibility of practicing until they reach competence, using, for example, Radio Frequency Identification (RFID) technologies to track each individual operator, memorize their performances, and offer them adequate training depending on the level of competence achieved. Another aspect to take into consideration when designing VR training is represented by the peripherals used. We remind you that a VR environment should provide the user with visual (3D), auditory (stereo), tactile, and olfactory sensory stimulation. While on the one hand the optical viewers on the market are almost similar in terms of performance, tactile rendering, which is especially important for assembly and maintenance tasks (sectors in which the use of VR is consolidated in the training field), is not the same if different devices are used. VR joysticks, for example, do not allow realistic hand movements, which could be obtained through optical sensors, such as the Leap Motion Controller, capable of guaranteeing better training of the object manipulation phases and correct use of the tools in the VR.

Therefore, for procedural training, we recommend tools of this type, capable of making the user simulate the action he would perform in the real environment, for example, rotating the wrist to tighten a screw. Again, the presence of feedback such as force feedback, vibrations, and shocks is important.

Last but not least is the suggestion regarding the possibility for users to familiarize themselves with VR technologies. It is therefore suggested to always include a pre-learning phase, during which the characteristics of the simulation, the purpose, the tools to use, and the dangers the users might encounter are introduced. The pre-learning phase could also include familiarizing users with VR technological devices.

However, it should be noted that these factors, such as level and type of driving, duration of sessions, number of training sessions, and peripherals to be used, may not be of equal importance for learning purposes if different levels of competence are considered.

What was previously said is mostly valid for users with limited experience in terms of training tasks, i.e., novice trainees. For those who only and exclusively need an update of the skills acquired, it is suggested to reduce the information provided during the execution of the simulation.

Moving away from the effectiveness of VR training, another element to pay particular attention to is safety. Although it is less essential in the formation of activities if you are creating VR experiences that contain information fundamental to the activities or the factory or product design, it should be the starting point.

4.2. Research Gaps and Future Research Agenda

From the literature analysis conducted, it emerged that the number of case studies about using VR for training purposes is rather limited, as it is still perceived as a 'new technology'. Furthermore, the selected studies are mainly based on the development of immersive environments (from a technological point of view) and not on their practical application in operator training. This is evident from the numerous studies that aim only to evaluate different VR configurations by measuring, for example, the usability of the devices or the graphics of the simulated environments.

Despite the fact that remanufacturing has seen a significant increase in interest and attention globally, with various countries introducing policies and production concepts aligned with eco-friendly and energy-efficient production [71,72], none of the articles identified address this area of application. In fact, the only papers that address disassembly activities do so in combination with assembly tasks, highlighting how the disassembly techniques and procedures are still in a preliminary phase of development, mainly technological and organizational, and the interest in the human factor is still not evident.

Human factor analysis is evidently poor in almost all the selected articles. Although several articles report information on the level of experience of the subjects involved in the experiments with both the technology and the task, this level of previous knowledge of the task to be performed or familiarity with the devices is not correlated with the objective performances achieved (learning and completion or number of errors). Experience in this area could play a fundamental role and represent a key element for defining appropriate pre-learning and learning strategies and choosing the level of immersion most suited to the type of subject involved.

Furthermore, little or nothing is evaluated on the medium-term/long-term effect of learning (learning and forgetting curves) using VR technologies compared to traditional or different approaches. Instead, the ability to crystallize the skills and competences acquired during the virtual simulation through scheduled training sessions spread over broader time horizons should be explored in greater depth. The forgetting rate should be studied by varying the training method carried out, as well as the pre-learning strategy used and the operator's previous experience with tasks and devices.

Several studies have also highlighted that in human–VR device interaction other attributes of the operator (age, gender, and level of education) or subjective factors (acceptance of technology, trust, and level of usability) also have significant impacts on the operators' performance. These factors should be further investigated. It is therefore imperative to point out that the analysis of such a small sample entails considerable limitations on the statistical value of the results obtained. What probably limits the examination sample is the training string, if not also the sector of application, such as the manufacturing industry. In the future, an extension of the analysis could be considered to sectors such as the chemical or petrochemical industry, in which VR is mainly used for training in the field of risk and emergency management, also obtaining data on the effectiveness of training that does not present a procedural nature.

Finally, a clear correlation between immersion level and operator learning was not identified in the selected articles. Higher levels of immersion do not always improve learning, and the influence of immersion on learning can be complex, as also highlighted in other studies [73,74]. Additionally, the impact of immersion on users may vary based on factors such as gender and the presence of cyber sickness [75,76]. These aspects should be further investigated by focusing on assembly and disassembly tasks that require high cognitive efforts.

Author Contributions: Conceptualization and methodology, V.D.P., R.I. and S.M.; formal analysis, P.C., C.E. and B.F.; writing—original draft preparation, V.D.P., P.C., C.E. and B.F.; writing—review and editing, V.D.P., S.M. and R.I.; project administration, V.D.P.; funding acquisition, V.D.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research work is part of the activities carried out in the context of the RESILIENCE project (Prescriptive digital twins for cognitive-enriched competency development of workforce of the future in smart factories), Code. 2022K2SAFM, CUP H53D23001310001, D53D23003690006, funded by the European Union—NextGenerationEU Plan, component M4C2, investment 1.1, through the Italian Ministry for Universities and Research MUR "Bando PRIN 2022—D.D. 104 del 02-02-2022".

Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | RESILIENCE

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Selected papers.

Ref.	Title	Year	Source Title	Type of Pre-Learning	Experience with VR	Experience with Task	Type of Comparison
[40]	Natural and hybrid bimanual interaction for virtual assembly tasks	2014	*Virtual Reality*	Task	No	Not specified	VR vs. VR
[42]	Virtual training of assembly tasks using virtual reality techniques and haptic systems	2014	*ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)*	VR and Task	Not specified	Not specified	VR vs. traditional and VR vs. VR
[43]	The influence of interaction technology on the learning of assembly tasks using virtual reality	2014	*Journal of Computing and Information Science in Engineering*	VR and Task	No	Not specified	VR vs. traditional and VR vs. VR
[61]	Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks	2015	*Interactive Learning Environments*	VR and Task	No	Yes	VR vs. traditional and VR vs. VR
[37]	Training in VR: A preliminary study on learning assembly/disassembly sequences	2015	*Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*	VR and Task	Not specified	Not specified	VR vs. traditional
[46]	Serious Games and Virtual Simulator for Automotive Manufacturing Education & Training	2015	*Procedia Computer Science*	VR	Yes	No	VR vs. VR
[38]	Establishing the Usability of a Virtual Training System for Assembly Operations within the Automotive Industry	2016	*Human Factors and Ergonomics In Manufacturing*	VR and Task	Not specified	Not specified	VR vs. traditional
[20]	The evaluation of an elementary virtual training system for manual assembly	2017	*International Journal of Production Research*	None	Not specified	Not specified	VR vs. traditional
[56]	A comparison of virtual and physical training transfer of bimanual assembly tasks	2018	*IEEE Transactions on Visualization and Computer Graphics*	Task	Not specified	Yes	VR vs. traditional and VR vs. VR
[57]	Manual assembly training in virtual environments	2018	*Proceedings—IEEE 18th International Conference on Advanced Learning Technologies, ICALT 2018*	None	Not specified	Not specified	VR vs. VR
[48]	Comparison of a gamified and non-gamified virtual reality training assembly task	2019	*2019 11th International Conference on Virtual Worlds and Games for Serious Applications, VS-Games 2019—Proceedings*	VR	No	No	VR vs. VR
[55]	The effects of stereopsis and immersion on bimanual assembly tasks in a virtual reality system	2019	*26th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2019—Proceedings*	VR	Not specified	No	VR vs. VR
[44]	Gamification of assembly planning in virtual environment	2019	*Assembly Automation*	Task	Yes	No	VR vs. VR
[62]	Assessment of virtual reality-based manufacturing assembly training system	2019	*International Journal of Advanced Manufacturing Technology*	VR	Not specified	No	VR vs. traditional and VR vs. VR
[41]	A smart factory in a smart city: Virtual and augmented reality in a smart assembly line	2020	*IEEE Access*	VR and Task	Not specified	Not specified	VR vs. traditional and VR vs. VR
[59]	Effectiveness of Virtual vs. Physical Training: The Case of Assembly Tasks, Trainer's Verbal Assistance and Task Complexity	2020	*IEEE Computer Graphics and Applications*	Task	Not specified	Not specified	VR vs. traditional and VR vs. VR

Table A1. *Cont.*

Ref.	Title	Year	Source Title	Type of Pre-Learning	Experience with VR	Experience with Task	Type of Comparison
[51]	Usability study of auditory feedback and visual feedback in an immersive virtual assembly system	2020	*Proceedings—2020 International Conference on Intelligent Computing, Automation and Systems, ICICAS 2020*	Task	Not specified	Not specified	VR vs. traditional
[49]	Effect of Virtual Reality-Based Training on Complex Industrial Assembly Task Performance	2021	*Arabian Journal for Science and Engineering*	VR	No	No	VR vs. traditional
[47]	Effects of Level of Immersion on Virtual Training Transfer of Bimanual Assembly Tasks	2021	*Frontiers in Virtual Reality*	None	Yes	No	VR vs. traditional and VR vs. VR
[36]	Development of Virtual disassembly and assembly platform for marine air compressor	2021	*Journal of Physics: Conference Series*	Task	No	Not specified	VR vs. traditional
[52]	A System for Collaborative Assembly Simulation and User Performance Analysis	2021	*Proceedings—2021 International Conference on Cyberworlds, CW 2021*	Task	Yes	Not specified	VR vs. VR
[50]	Virtual Reality For Training: A Computer Assembly Application	2022	*ICGI 2022—International Conference on Graphics and Interaction, Proceedings*	None	No	Not specified	Not specified
[39]	Gamification of virtual reality assembly training: Effects of a combined point and level system on motivation and training results	2022	*International Journal of Human Computer Studies*	VR	No	Not specified	VR vs. traditional and VR vs. VR
[63]	Virtual Reality Assembly of Physical Parts: The Impact of Interaction Interface Techniques on Usability and Performance	2022	*Virtual, Augmented and mixed reality: applications in education, aviation and industry, pt II*	VR	Yes	Not specified	VR vs. VR
[25]	Analyzing the potential of virtual reality-supported training for industrial assembly tasks	2023	*Computers in Industry*	VR	No	No	VR vs. traditional and VR vs. VR
[45]	Skill retention after desktop and head-mounted-display virtual reality training	2023	*Experimental Results*	VR	/	No	VR vs. VR
[58]	A Comparison of Two Interaction Paradigms for Training Low Cost Automation Assembly in Virtual Environments	2023	Information (Switzerland)	VR and Task	Yes	/	VR vs. VR
[60]	Low-cost VR system for interactive education of manual assembly procedure	2023	*Interactive Learning Environments*	VR & Task	/	/	VR vs. VR
[53]	Virtual Reality for Industrial Assembly Training: The Impact of Tool Interaction Realism on Learning Outcomes	2023	*Proceedings—2023 IEEE International Symposium on Mixed and Augmented Reality Adjunct, ISMAR-Adjunct 2023*	VR	/	/	VR vs. traditional
[54]	Comparative Evaluation of Virtual Reality and In-Person Onboarding for Assembly Trainings in Manufacturing	2023	*Proceedings—2023 IEEE International Symposium on Mixed and Augmented Reality Adjunct, ISMAR-Adjunct 2023*	VR and Task	No	No	VR vs. traditional
[64]	Assemble it like this!-Is AR- or VR-based training an effective alternative to video-based training in manual assembly?	2023	*Applied Ergonomics*	VR and Task	Yes	No	VR vs. traditional

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