Teaching Styles of Virtual Training Systems for Industrial Applications – A Review of the Literature

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Abstract. The demand for individualized and efficient production yields more capable but also more complex manufacturing environments. Virtual training systems were proposed to train the operators who control and maintain industrial machines. This article reviews such training systems with a focus on their teaching styles and identifies new research directions in the field of adaptive training systems. The review applies a classification scheme that describes the instructions, the presentation of the instructions, and the interaction possibilities of a virtual training system. Another aspect of the classification scheme are the capabilities to adapt a training system to the characteristics of the trainee. The review indicates that existing training systems apply similar teaching styles and provide limited adaptive capabilities. The development of training systems that adapt their teaching style to the disposition and the qualification of individual trainees is proposed, to address the increasingly diverse workforce.

Keywords: Virtual training systems, Teaching styles, Adaptive systems, Industrial procedures.

1 Introduction

Increasing globalization is forcing the German manufacturing industry to pursue continuous improvements in efficiency. At the same time, an increasingly individualized product portfolio has to be offered at competitive costs [14]. Different approaches that are subsumed under the term “Industry 4.0” address these requirements. This concept describes the digitization and connection of all resources in a factory to create smart, autonomous, and flexible production systems [60].

Efficient training is vital for a successful implementation of Industry 4.0, since it allows humans to adapt to the new and changing technological environment [31]. In particular, virtual training systems that provide a flexible and attractive training environment are of interest for research [22] and applied in industry, for instance to practice engine maintenance procedures [2, 54]. The need for effective training systems is reinforced by the complexity of modern production equipment that must be controlled by a workforce that is increasingly diverse. The demographic change leads to a considerable aging of the workforce [70]. Aging is connected to sensory and cognitive decline [18] that has to be accommodated by training systems. Training systems need to adapt to user characteristics, for instance by changing the way information is presented or by offering different interaction modalities. These variations in conveying a lesson are called teaching styles.

To the best of our knowledge, a comprehensive and recent review of virtual training systems for industrial applications based on the applied teaching styles is missing and will be provided by this paper. We conclude that existing training systems are similar in their teaching styles. Furthermore, they cannot adapt their teaching styles to the characteristics of the user. This article suggests that the consideration of adaptivity yields training systems that address the increasingly diverse workforce of future manufacturing environments. Developing such training systems supports the inclusion of additional user groups into the workforce and increases their productivity and satisfaction.

2 Virtual Training Systems

Virtual training is defined as training within a virtual environment using virtual or augmented reality technologies [43]. A typical domain is flight simulation, where they allow training without exposure to the dangers or incurring costs of actual flying. Virtual training systems are applied in further fields from sports training [36] to psychotherapy [27]. They are particularly prevalent in the field of complex industrial manufacturing and assembly tasks [22, 30]. This review targets virtual training systems for industrial applications. These training systems will be understood as virtual training systems that train interactions with industrial machines or assembly procedures. The development of such systems started in the 1990s. Waller and Miller [74] and Abe et al. [1] conducted early research that investigated virtual training for assembly procedures. Matsas et al. [51] or Loch and Vogel-Heuser [48] provide recent research for assembly and machine operation.

Several aspects motivate the application of virtual training systems. First, virtual training systems are more attractive than traditional teaching methods (e.g., paper-based manuals). An increased attractiveness is connected to improvements in intrinsic motivation that enhance the effectiveness of the training system [20, 59]. A virtual environment should induce the feeling of presence and yield a training result that is similar to the one that could be achieved in the real environment [50]. Furthermore, virtual training saves on trainers and material that real training would consume and reduces potential damage to equipment. This is relevant when improper handling could damage expensive machinery, for instance in lathing machine operation [45]. Virtual training also provides a safe environment to practice potentially dangerous procedures, such as power line maintenance [29]. As Mechlih [53] puts it, virtual training systems forgive mistakes.

3 Classification of Teaching Styles

The following section develops the classification scheme for virtual training systems. The classification scheme describes the teaching styles that the virtual training systems apply and serves as the foundation for the literature review that is conducted in Section 4. Section 3.1 provides the basic terminology about learning and training. Section 3.2 and Section 3.3 apply this terminology to develop of the components of the classification scheme.

3.1 Definitions

The acquisition of new or the modification of existing knowledge, behaviors, skills, or preferences which may lead to a change in synthesizing information, depth of knowledge or behavior is called *learning* [32]. *Teaching* describes activities that facilitate learning [34].

Knowledge is distinguished into *procedural knowledge* and *declarative knowledge*. Procedural knowledge is goal-oriented and comprises rules or actions that are applied during the performance of a task or a problem-solving activity [19]. An example is the proper handling of a tool to dismount a component of a machine. Declarative knowledge describes factual knowledge that can be thought and spoken about explicitly [8], such as the steps that comprise a maintenance procedure. The training systems considered in this review teach procedural and declarative knowledge. Gutiérrez et al. describe the knowledge that is taught by virtual training systems as “the operator's ability to obtain a good representation of how to perform each step of a task and its correct order“ [33].

The key component of a training system is how it provides the lessons. Teaching methods and teaching styles describe this aspect. A teaching *method* describes a way of teaching, such as demonstration or individual work [42]. A training system may demonstrate how components must be assembled but might also allow a user to explore the assembly procedure independently. Teaching methods can be infused with teaching *styles* that describe the teaching procedure, for instance whether the trainee is active or passive during the lesson, in a context-independent way.

The interaction between a learner and a virtual training system can be compared to the one between a student and a teacher. Even if aspects such as hierarchy or the ways of interaction differ, a virtual training system can use different teaching styles, just as its users can have different learning styles. A key requirement for successful training is the correspondence between the styles of the teacher and the student.

3.2 Teaching and Learning Styles

A teaching system has different characteristics. They describe whether the teacher (i.e. a virtual training system) focusses on concrete or abstract content or to what extent they leave decisions about the course of the lesson up to the learners. These characteristics are called teaching styles and are largely content-independent [26].

Table 1. Learning and teaching styles described by Felder and Silverman [25].

Learning Style	Corresponding Teaching Style
Perception Sensory vs. Intuitive	*Content* Concrete vs. Abstract
Input Visual vs. Auditory	*Presentation* Visual vs. Verbal
Organization Inductive vs. Deductive	*Organization* Inductive vs. Deductive
Processing Active vs. Reflective	*Student Participation* Active vs. Passive
Understanding Sequential vs. Global	*Perspective* Sequential vs. Global

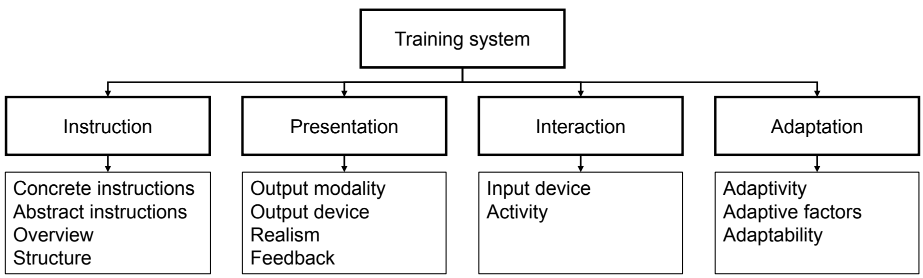
There are also different learning styles. Since every person has different psychological and cognitive characteristics, learners (i.e. users of a training system) differ in terms of perception and mental processing, which results in different learning preferences. Felder and Silverman [25] provide a well-established scheme for learning and teaching styles in engineering education. They propose five learning styles that classify learners and five corresponding teaching styles (see Table 1).

3.3 Development of a Classification Scheme

This section introduces a classification scheme for the teaching styles of virtual training systems for industrial applications. The aim is to provide a content-independent classification of virtual training systems that the literature review applies.

The first component of the classification scheme (*Instruction*) describes the characteristics and the structure of the instructions, for instance whether they target concrete cases or abstract principles. *Presentation* describes the communication between the training system and the trainee. This concerns aspects such as output devices. *Interaction* describes the interaction possibilities of the training system (e.g., the input device). *Adaptation* describes whether the system can be adapted to the characteristics of the trainee or the situation automatically or manually. Figure 1 visualizes the classification scheme.

Figure 1: Components and subcomponents of the classification scheme for virtual training systems.



The component **Instruction** describes the instructions that the training system provides. *Concrete instructions* target specific applications, scenarios, or procedures and do not relate the content to other applications. An example are procedures or safety mechanisms that are specific to a procedure at a certain machine of a specific vendor. Instructions can also be *abstract* and focus on knowledge that is relevant in multiple occasions, for instance the handling of a tool or general interaction mechanisms of the user interface of the machine.

Table 2. Subcomponents of *Instruction*.

Component	Description
Concrete instructions	Describes whether the instructions relate to a concrete procedure in a specific context.
Abstract instructions	Describes whether the instructions go beyond a specific example and relate to other applications.
Overview	Describes whether and when an overview of the procedure is provided (during training, before, after).
Structure	Describes the structure of the instructions (e.g. linear, tree) and whether the trainee can leave that structure.

While some training systems focus on the visualization of the current step, some also provide an *overview* of the complete procedure. The latter can support the user in obtaining a correct mental model. Such an overview can be beneficial if the steps of the procedure are interrelated. Furthermore, the instructions can follow different *structures* (e.g., a linear sequence or a tree). Table 2 provides the subcomponents of this component.

Presentation describes how the training system presents information. An important characteristic is the *output modality*. Visual presentation uses graphics or diagrams to describe a subject. Visual indications of worksteps use animated, three-dimensional representations of the tool or arrows that indicate the location of the workstep. Verbal presentation relies on textual explanations of the workstep and are often used in addition to visual output. A third form is haptic presentation, where content is transported via the sense of touch. Providing different ways of presentation allows addressing learners who prefer specific senses. A training system can combine different output modalities.

The training system can present the information on various *output devices*. Typical output devices are visual (e.g., head-mounted displays), auditory (e.g., headphones), or haptic output devices.

The virtual environment can be characterized with regards to *realism*. A training system may provide a very realistic representation of both machine and environment. Other training systems may be less realistic and remove details of the environment to provide a more abstract or less-distracting training environment.

The presence or absence of *feedback* also characterizes the presentation. Feedback can vary within the modalities mentioned above – a training system could flash a light (visual), make a sound (auditory), or vibrate (haptic) to confirm that it has received input and transport whether it was correct. The *feedback type* may be immediate or delayed. Table 3 provides the subcomponents of this component.

Table 3. Subcomponents of *Presentation*.

Component	Description
Output modality	Describes the modality of the presented information (visual, verbal, and haptic).
Output device	The output device that is used to present information.
Realism	Describes the realism of the virtual environment.
Feedback	Describes whether feedback about the execution of the operations is provided and which modality is used (visual, auditory, and haptic).
Feedback type	Describes the type of the feedback (delayed or immediate).

Interaction describes how the user interacts with the training system. Training systems can be more reflective, when the procedures are demonstrated and observed by the trainee, or more active, when the trainee is actively involved in carrying out the procedure. *Input devices* are pivotal for interaction. Static input devices, for instance mouse and keyboard, support a more reflective teaching while dynamic devices that support gesture-based interaction put the trainee in a more active position.

Training systems require different *activities* from the trainee. Some training systems provide the possibility to observe the content without user input. In more active training systems, the trainee can manipulate components or navigate through the training environment. Table 4 provides the subcomponents of this component.

Table 4. Subcomponents of *Interaction*.

Component	Description
Input device	Describes the supported input devices (e.g., mouse and keyboard, motion capturing or speech).
Activity	Describes the required interaction by the user (e.g., navigation within the training system, completion of operations).

Adaptation describes the extent to which the training system can be adapted. The aim of adaptation is to change the configuration to address users with different dispositions (e.g., age) and qualifications (e.g., work experience). There is a distinction between adaptivity and adaptability. *Adaptivity* is initiated by the system to change its characteristics to meet the requirements of the user and the situation; *adaptability* refers to the possibility of user-initiated changes to the system [24].

Adaptivity can be triggered by different *adaptive factors*. Some factors are related to the characteristics of the worker, such as constitution disposition, qualification and competence, or adaptive attributes [65]. Such adaptations could concern the reduction of complexity or the modification of the presentation to compensate for perceptive limitations. Further adaptive factors relate to the context, which denotes any information that can be used to describe the situation of an entity [23]. *Adaptability* describes adaptations of the training system that can be triggered by the user. Table 5 provides the subcomponents of this component.

Table 5. Subcomponents of *Adaptation*.

Component	Description
Adaptivity	Describes the components of the teaching style that can be adapted automatically.
Adaptive factors	Describes the factors that trigger adaptivity.
Adaptability	Describes the components of the teaching style that the user can adapt.

4 Review of the State of the Art

This section reviews the state of the art of virtual training systems for industrial applications. The review uses the classification scheme of the previous section. The discussion addresses two types of training systems. One type addresses the training of industrial *procedures*, for instance maintenance or assembly procedures. These systems train the sequence of steps of a procedure and how to perform each step correctly (Section 4.2). Another type teaches industrial *skills*, for instance welding or spray painting. The focus of these systems is not to teach a specific routine, but to provide an environment for experimentation with the use of a tool, including different settings and ways to apply the skill (Section 4.3). Section 4.1 introduces the method that was applied to collect the reviewed articles.

4.1 Method

The reviewed articles were collected using a search in scientific databases (i.e. “Science Direct”, “IEEE Xplore”, “Springer Link”) with the search string “Virtual training AND (manufacturing OR maintenance OR assembly)”. Relevant articles that describe the training of industrial skills and procedures using virtual training systems were included based on a screening of the abstract. We excluded articles that were not in English or not accessible in full text. The review is not exhaustive and aims at providing an overview of the current approaches in virtual training to identify future research directions. **Errore. L'origine riferimento non è stata trovata.** in the appendix provides a full list of the reviewed articles (*n = 48*) and their classification.

4.2 Training Systems for Industrial Procedures

Industrial procedures are standardized sequences of worksteps. The aim of training systems for such procedures is to teach the sequence of the steps and how each step has to be carried out [33]. Typical procedures that are trained with these systems are assembly (e.g., assembly of car components [68]) or maintenance [11]. Training systems provide different modes to practice the worksteps of a procedure. The systems use various input and output modalities, such as head-mounted displays (e.g., Bhatti et al. [10]) or VR-walls. Recent systems introduce advanced interaction devices for haptic interaction (e.g., [63]). The following sections describe the teaching methods of the training systems according to the classification scheme.

Instruction. The training systems use concrete instructions that apply to a specific procedure. The systems developed by Peninche et al. [58] and Ordaz et al. [57] describe the next step in an assembly procedure with a graphical indication and a verbal description. Such instructions can also cover the complete procedure, as it is done in the videos in the system proposed by Brough et al. [15] or virtual assembly instructions by Boud et al. [13]. However, the provided instructions only describe the current operation and procedure and do not relate it to other procedures.

Few systems provide abstract instructions that are applicable to multiple cases. An example of this is the system described by Galvan-Bobadilla et al. [29]. Their system for training maintenance procedures conveys information about tools and components in a “Virtual Catalog”. Familiarizing the user with the tools should save time in the subsequent training. Antonietti et al. pursue a similar approach with their training system for lathing machine operation [6]. Their system allows the user to obtain information about the functioning of the machine prior to training.

Few training systems provide an overview about the procedure during training such as an indication of the next step or an overview of the structure of the procedure. The benefits of the provision of such an overview for the formation of a mental map of the procedure are suggested by Vélaz et al. [72], who propose a system that shows a comprehensive description of the current task by request of the trainees. Hoedt et al. [35] provide an exploded view of the assembly task.

The trainees cannot leave the linear structure of the surveyed training systems. This is motivated by the standardized structure of the procedures. The training system presented by Galvan-Bobadilla et al. [29] offers the possibility to explore the tools and components that are needed in the maintenance procedures. Abe et al. [1] suggest that trainees could lose their learning motivation if the structure is too strict and, thus, allow them to try out different (dis)assembly sequences.

Presentation. Most training systems use a combination of visual and verbal instructions. Jia et al. use graphical indications that show the orientation of the component that should be integrated into the assembly [37]. Rodriguez et al. use a Lego assembly task in their training system and indicate the brick that has to be used next and the position where it needs to be assembled [62]. Systems often supplement visual with verbal instructions that describe the worksteps (e.g., Peninche et al. [58] and Olive et al. [56]).

Most training systems represent the assembly components in a neutral three-dimensional environment with low realism (e.g., Brough et al. [15]). Matsas et al. [51] use a more immersive presentation technique. They provide a first-person view of the assembly that can be manipulated using motion capturing. Stork et al. introduce the surroundings of a factory in their training system [68]. According to Hoedt et al. [35], a more realistic presentation provides a better interface, but often results in larger cost for both training system and scenario creation. In one experiment, they use a 3D-view via stereoscopic glasses to make visual information more realistic.

Several training systems introduce special output devices to convey the haptic components of worksteps. Examples are the systems of Jia et al. [37], Gutiérrez et al. [33], and Bhatti et al. [10], which use haptic devices to convey the feeling of manipulating the components of an assembly process. Recent work has investigated haptic interaction for assembly training. Adams et al. [3] focus on the benefits of force feedback – they evaluated the effectiveness of a haptic device for teaching a Lego assembly task and concluded that such haptic training is superior to other training approaches. Sagardia et al. [63] apply a combination of constrained- and penalty-based haptic rendering methods, while Neges et al. describe the integration of real components in a virtual environment for training [55].

Typical output devices are head-mounted displays (e.g., [10, 51, 63]) and different stereoscopic displays (e.g., [48, 58]). Haptic devices are either custom made [3] or devices available on the market [33].

Interaction. The input modalities depend on the trained task. Loch and Vogel-Heuser developed a system that simulates the operation of a machine user interface and therefore uses touchscreen input [48]. Bluemel et al. use a mouse-based interface to control the training system and navigate the environment [11]. Input modalities that introduce physical movements are suitable for teaching assembly procedures realistically. Stork et al. introduce a system for assembly training that uses motion tracking systems and allows placing components with hand movements [68]. Haptic devices allow physical interaction with the training environment and can increase the training success [3, 33]. Recent approaches use bimanual haptic interaction to simulate complex assembly procedures and the collisions between the components [33, 63]. Brough et al. [15] and Besbes et al. [9] offer handheld wands to control the training system.

Adaptation. None of the surveyed training systems provides system-initiated adaptivity. Capabilities for adaptability are discussed below.

Training systems can gradually reduce the amount of instructions to increase the difficulty. This should support the transformation to the real environment and reduce the dependency of the trainee on the training system [83]. These capabilities allow the adaptation to the knowledge level. Bhatti et al. increase the level of user activity while decreasing the feedback from the training system [10]. Bluemel et al. gradually increase the level of interactivity and decrease the level of instructions [11]. Gutiérrez et al. [33] and Loch and Vogel-Heuser [48] propose similar approaches. These adaptations put the students from a reflective to a gradually more active mode, where the student must remember the procedure. The most important contextual factor is the assumed knowledge state. Funk et al. [28] propose a shared virtual platform in which a trainer is involved and adapts the system. The trainer can individually support the trainee by activating or deactivating feedback and visual cues.

4.3 Training Systems for Industrial Skills

Industrial skills, such as welding or spray painting, are distinct from industrial procedures. The success is distinguished by the correct handling of a tool. Welding requires the correct handling of the torch regarding speed of movement, distance, and orientation. Jo et al. [38] present a welding simulator that provides feedback to allow the trainees to improve their welding skills. Spray painting is another application. Virtual training allows reducing the paint consumption and training costs caused by improper paint jobs of novices. Konieczny et al. [41] present a simulator for spray painting that provides feedback about the quality of the painting. The following sections describe the teaching methods of the training systems according to the classification scheme.

Instruction. These systems provide abstract instructions, since the covered skills are applicable in various tasks. Crison et al. [21] propose a system for milling machine operation using a haptic device. The acquired skills are transferrable to other procedures that require the use of milling machines.

The training systems do not imply a rigid structure and encourage exploration and experimentation, since the user can perform a trial, inspect the feedback, and improve gradually. Konieczny et al. [41] and Jo et al. [38] provide feedback about the quality of the painting or welding procedures, such as the thickness of the applied paint or the form of the weld bead. The systems provide few explicit instructions, since they do not target standardized procedures but provide an environment for the iterative refinement of a skill.

Presentation. The training systems use different output modalities. Most training systems rely on visual presentation of feedback. Applied output devices are stereoscopic [82] or head-mounted displays [41]. Some systems introduce haptic and auditory output, such as the welding simulator introduced by Kim et al. that provides haptic feedback about the orientation of the welding torch [40].

Immediate and delayed feedback is a key component of these training systems, since it provides hints how the trainee can improve. Jo et al. [38] propose a welding simulator that provides detailed graphical and numerical feedback. A graphical visualization of the weld bead provides visual feedback. Konieczny et al. [41] use graphical visualizations of the thickness and quality of the painting that was done by the user by means of two output modes: a photorealistic simulation as well as a cold-hot color visualization scheme. Kim et al. [40] introduce haptic feedback. All surveyed systems use realistic simulations. According to Kim et al. [40], realistic modeling is a key factor for effective skill training.

Interaction. Most training systems use motion capturing. The systems track the movement and position of realistic replications of real tools to provide a realistic training system and a high level of immersion. The user has the option to parametrize the training systems and experiment with different ways to use a tool. The systems allow a high degree of freedom.

Adaptation. None of the surveyed training systems provides system-initiated adaptivity. Solely Liang et al. [45] indicate capabilities for adaptability – their proposed system lowers the stiffness of a slender cutting tool gradually, so novice operators do not break it too easily.

5 Discussion

This section proposes directions for future work. The aim of the proposed research directions is the development of training systems that are flexible and adaptable to the requirements of diverse user groups. These groups are characterized by different characteristics regarding constitution, qualification, and competence. Such an approach would be in line with the idea of universal design [69] that promotes the development of systems that are accessible for users with different capabilities.

5.1 Instruction

Future work could investigate the effect of different teaching strategies (e.g., top-down, bottom-up). Implementing a top-down structure could support users in building a correct mental model of the procedure. Research suggests that the provision of information about the goals that are achieved by lower-level steps can support the formation of a correct mental model and enhance knowledge acquisition [72]. Empirical studies could address the validity of this hypothesis for users with different characteristics regarding constitution (e.g., targeting elderly users) and qualification (e.g., targeting users with low work experience).

The communication with the surveyed virtual training systems is unidirectional and directed from the system to the trainee. However, experienced users possess tacit knowledge that could be valuable for novice users. Alm et al. [5] propose ontology-based annotations to integrate tacit knowledge of the operators with the knowledge base of an assistance system. Unstructured annotations allow experts to provide tacit knowledge and its relation to a specific work situation. Future work could address the benefits of the integration of expert knowledge into the knowledge base of virtual training systems. This could improve the training of novice workers by providing tacit expert knowledge to facilitate conducting the trained procedures efficiently.

5.2 Presentation

The surveyed training systems rely on visual output devices. Auditory presentation (e.g., spoken instructions or acoustic feedback) is almost absent. The application of the auditory modality for the presentation of instructions and feedback could improve a training system since it is typically unoccupied during virtual training. Auditory cues can be processed in parallel to visual cues according to the model of Wickens and could increase the perceivable information bandwidth [78]. Future work could evaluate the inclusion of auditory output in virtual training systems.

5.3 Interaction

Mouse and keyboard and motion capturing are the primary interaction devices of virtual training systems. Speech-based interaction is not applied. However, speech input could provide interaction possibilities that do not distract the visual modality by having to allocate attention to an additional input device. This modality is also suitable to address users with low qualification, such as illiterate users. Future work could investigate the integration of speech-based interaction for the control of training systems and its potentials for different user groups.

Haptic interaction devices have been applied in virtual training systems to provide a more realistic simulation of the worksteps (e.g. Gutiérrez et al. [33], Bhatti et al.

[10]). However, haptic devices cannot convey the physical properties of a tool and require the user to focus on a visual output device during interaction. The introduction of physical artifacts to virtual training systems could increase training efficiency. Such training systems could be realized using augmented reality projections as proposed by research such as Loch et al. [49] or Stoessel et al. [67]. Evaluations could assess the benefits of the integration of physical artifacts for training efficiency.

5.4 Adaptation

The domain of adaptive system is an important research field in human computer interaction. It proposes the adaptation of the system to factors such as user interests, user traits, behavior of the user, and environment [16, 24]. Brusilovsky provides a taxonomy for adaptive hypermedia technologies that summarizes techniques to adapt a system, for instance affecting the presentation of providing adaptive navigational support [16]. However, adaptive interfaces always bear inherent complexities since users may not behave predictable at all times and could perceive automatic changes of the interface as disruptive [66].

The literature survey indicates that only a small fraction of virtual training systems for industrial applications considers adaptivity. One direction for future work could therefore address the implementation of adaptivity in virtual training systems. Several approaches for adaptive assistance for manual assembly were presented (e.g., [5, 67, 71]). These approaches propose the provision of context-sensitive instructions based on the current state and the knowledge of the employee. Their transferability to the domain of virtual training systems is discussed below.

Adaptation to constitution. The demographic change impacts the composition of the workforce [70]. Aging is associated with sensory decline (e.g., lower visual acuity, lower peripheral vision) and a general cognitive slowing [18]. The presentation of training systems should compensate these aspects. Such adaptations could add auditory output of the instructions or reduce the realism of the environment to reduce distractions. Future work could evaluate different approaches to compensate perceptive limitations by the adaptation of the presentation using subjective (e.g., usability) and objective measurements (e.g., training time or learning success). A possible negative effect of reduced realism on measurements such as immersion must be evaluated as well.

Adaptation to qualification. The presentation of the training system could be adapted based on the qualification. Novice workers could train with a less-complex model. Such a model could facilitate the retention of the vital components of a machine to form a mental model as a preparation for subsequent on-the-job training.

The content of the lessons could be configured automatically based on the qualification of the operator. Ulrich [71] proposes the inclusion of development goals and trainee experience in the selection of the content for the lessons for a support system. He introduces rules that automatically retrieve lesson materials from a domain ontology according to a user model. Such approaches could be evaluated in the domain of virtual training systems to provide consistent lessons that provide a structured improvement of the qualification of the trainee.

Adaptivity based on real-time measurements. The availability of tracking and sensor technology is seen as a key requirement for immediate and context-sensitive assistance systems [67]. Lindblom and Thorvald [47] suggest nine cognitive work environment problems such as "disruption of thought," where the interaction does not allow the operator to focus on the task or "cognitive tunnel vision," where humans have difficulty considering information they cannot access simultaneously when making evaluations and decisions. Different sensor technologies can measure the state of the trainee to identify cognitive load and derive adaptations to prevent such errors.

Stoessel et al. [67] applied tracking technology to measure the worker's performance during manual assembly and adapt the provided instructions. Eye-tracking allows estimating attention allocation and measuring performance to, for instance, optimize the workbench layout. Eye-tracking could also be applied in virtual training systems to identify states where the trainee is overloaded and has problems in following the training. Fixations on elements that are not related to the current lesson can indicate such problems. Eye-movement patterns may also indicate problems in cognitive processes such as information decoding (e.g., repeated saccades). Machine learning approaches allow the system to learn the behavior of trainees with different skill levels from previous training sessions to detect diversions from this behavior and adapt the instructions. Future work could explore the applicability and the benefits of such approaches in training systems.

6 Conclusions

We surveyed virtual training systems and analyzed their teaching styles using a classification scheme with four components. The classification scheme describes the virtual training systems according to the instructions, their presentation, the offered interaction modalities, and their adaptation capabilities.

The surveyed training systems apply similar teaching and lack capabilities for system-initiated adaptation, especially regarding the interaction modalities or presentation. The development of training systems that adapt their teaching styles to the characteristics and the mental workload of the trainee was identified as an avenue for future work. Adaptive training systems could support the increasingly diverse workforce by enhancing capabilities and compensating limitations. Doing so could support inclusion in the workforce and strengthen the manufacturing industry.

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Appendix

Table 1. Summary of the surveyed training systems. *See Table 2 – 5 for explanation.* **Instruction:** Abs = Abstract; Con = Concrete; Pre = Preview; Over = Overview; Lin = Linear; Oth = Other; Expl = Exploration; **Presentation:** Au = Auditive; Vi = Visual; Ve = Verbal; Ha = Haptic; Feedb = Feedback modality; R = realistic; Lr = less realistic; – **Interaction:** MK = Mouse and/or keyboard; MC = Motion capture; Data glove; Ha = Haptic devices (e.g. stylus); Ve = Verbal/Speech recognition; Oth = other (e.g. specific control panel); Freed = Freedom; Act = Activity; n/a = not available.

	Instruction								Presentation				Interaction			Adaptation		
					Structure				Output									
	Abs	Con	Pre	Over	Lin	Tree	Oth	Expl	Modality	Device	Feedb	Realism	Device	Freed	Act	Adaptiv.	Factors	Adapta.
Procedures																		
Abe et al. (1996) [1]	-	+	+	-	+	-	-	+	Vi, Ve, Ha	Vi, Au	Vi, Au	R	MC	-	+	-		-
Adams et al. (2001) [3]	-	+	+	n/a	+	-	-	-	Vi, Ha	Vi	Ha	Lr	MK	-	+	-		-
Al-Ahmari et al. (2018) [4]	-	+	-	-	+	-	-	-	Vi, Ha	Vi	n/a	Lr	MK, MC	-	+	-		-
Bao et al. (2011) [7]	-	+	n/a	n/a	+	-	-	-	Vi, Ve	Vi, Au	n/a	R	Ve, MK	-	+	-		-
Besbes et al. (2012) [9]	-	+	n/a	-	+	-	-	-	Vi, Ha	Vi	n/a	Lr	Oth	-	+	-		-
Bhatti et al. (2012) [10]	-	+	-	n/a	+	-	-	-	Vi, Ha	Vi	Vi, Au, Ha	Lr	MC, Ha	+	+	-		Level, Activity
Bluemel et al. (2003) [11]	-/+	+	-	-	+	-	-	-/+	Vi, Ha	Vi	Ve	Lr	MK	+	+	-		-
Borro et al. (2004) [12]	-	+	n/a	n/a	n/a	n/a	-	n/a	Vi, Ha	Vi, Ha	Ha	R	Ha	+	+	-		-
Boud et al. (1999) [13]	-	+	n/a	n/a	+	-	-	-	Vi, Ha	Vi	n/a	R	MK	-	-/+	-		-
Brough et al. (2007) [15]	-	+	+	-	+	-	-	-	Vi, Ha	Vi, Ve	Vi, Ve	Lr	MC, Oth	+	-/+	+	Errors	Activity
Cao et al. (2013) [17]	-	+	n/a	+	+	-	-	n/a	Vi, Ha	Vi, Au, Ha	Vi	R	MK	-	+	-		-
Funk (2017) [28]	-	+	n/a	n/a	+	-	-	-	Vi, Ha	Vi	Vi	Lr	n/a	n/a	+	(+)	Performance	-
Gutiérrez et al. (2010) [33]	-	+	-	+	+	+	-	-	Vi, Ha	Vi,Ve	Vi, Ha	Lr	MC, Ha	+	-/+	-		-
Hoedt et al. (2017) [35]	-	+	+	+	+	-	-	-	Vi, Ha	Vi	-	Lr	MC, Oth	-	+	-		-
Jia et al. (2009) [37]	-	+	-	-	+	-	-	-/+	Vi, Ha	Ha	Vi, Au, Ha	Lr	MC	+	-/+	-		-
Li et al. (2014) [44]	-	+	-	n/a	+	-	-	-	Vi, Ha	Vi	Vi	Lr	MK, MC	-	+	-		-
Lim et al. (2007) [46]	-	+	-	n/a	+	-	-	-	Vi, Ha	Vi	Vi, Ha	Lr	Ha	-	+	-		-
Loch, Vogel-Heuser (2017) [48]	-	+	n/a	n/a	+	-	-	+	Vi, Ha	Vi	Vi	R	MK	-	+	-		Present., Interaction
	Abs	**Con**	**Pre**	**Over**	**Lin**	**Tree**	**Oth**	**Expl**	**Modality**	**Device**	**Feedb**	**Realism**	**Device**	**Freed**	**Act**	**Adaptiv.**	**Factors**	**Adapta.**
Loch et al. (2018) [49]	(+)	+	-	-	+	-	-	-	Vi	Vi	Vi	R	MC	-	+	-		-
Matsas, Vosniakos (2017) [51]	-	+	n/a	n/a	+	-	-	+	Vi, Ha	Vi, Au	Vi	R	MC	-	+	-		-
McLaurin, Stone (2012) [52]	+	+	-	-	-	-	+	+	Vi, Ha	Vi	Vi	R	n/a	-	+	-		-
Neges et al. (2018) [55]	+	+	n/a	n/a	-	-	+	+	Vi, Ha	Vi, Ha	Ha	R	MC, Ha	-	+	-		-
Olive, Moutappa (2011) [56]	-	+	n/a	n/a	-	-	+	+	Vi, Ha	Vi	Vi	R	Ha, Oth	-	+	-		-
Ordaz et al. (2015) [57]	-	+	-	-	+	-	-	-	Vi, Ha	Vi	Vi	R	Ha	-	+	-		-
Peninche et al. (2011)[58]	-	+	-	-	+	-	-	-	Vi, Ha	Vi	Vi	Lr	Ha	-	+	-		-
Ponder et al. (2010) [59]	-	+	n/a	n/a	-	-	+	+	Vi, Ha	Vi, Au	Vi, Au	R	Ve, MC	-	+	-		-
Ritchie et al. (2016) [61]	-	+	-	+	+	-	+	-	Vi, Ha	Vi	Vi, Au	Lr	MK	-	+	-		-
Rodriguez et al. (2012) [62]	-	+	-	n/a	+	-	-	-	Vi, Ha	Vi	Vi, Ha	Lr	Ha	-	-/+	-		-
Saggardia et al. (2016) [63]	-	+	n/a	n/a	+	-	-	-	Vi, Ha	Vi, Ha	Ha	Lr	MC, Ha	-	+	-		-
Santoni et al. (2007) [64]	+	+	n/a	n/a	-	-	+	+	Vi, Ha	Vi	n/a	Lr	MK	-	+	-		-

Vélaz et al. (2014) [72]	-	+	-	+	+	-	-	-	Vi, Ve	Vi, Au	Vi	Lr	MK, MC, Ha	+	-/+	-		-
Vergnano et al. (2017) [73]	-	+	n/a	n/a	+	-	+	n/a	Vi, Ha	Vi	Vi	R	Oth	n/a	+	-		-
Waller, Miller (1998) [74]	-	+	-	-	+	-	-	-	Vi, Ha	Vi	-	Lr	MK	-	+	-		-
Wang et al. (2012) [75]	-	+	n/a	n/a	-	+	+	-	Vi, Ha	Vi	-	R	MK	+	+	-		-
Wang et al. (2013) [76]	-	+	n/a	n/a	-	-	+	+	Vi, Ha	Vi, Au	n/a	R	Ve, MC, Oth	-	+	-		-
Wang et al. (2012) [77]	-	+	n/a	n/a	+	-	-	-	Vi, Ha	Vi	Vi, Au, Ve	R	MK	-	+	-		-
Wu et al. (2012) [79]	-	+	n/a	n/a	+	+	-	+	Vi, Ha, Ve	Vi	n/a	Lr	MK	+	+	-		-
Xia et al. (2011) [80]	-	+	n/a	n/a	+	-	-	n/a	Vi, Ha	Vi	Ha	Lr	Ha	-	+	-		-
Yin (2014) [84]	-	+	+	-	+	-	-	-	Vi, Ha	Vi	Vi	Lr	MK, Oth	n/a	+	-		-
Skills																		
Antonietti et al. (2011) [6]	+	+	n/a	+	+	+	-	-	Vi, Ve, Ha	Vi	Vi	R	MK	+	-/+	-		Activity
Crison et al. (2005) [21]	+	+	n/a	+	-	-	+	+	Vi, Ha	Vi, Ha	Vi, Au, Ha	R	Ha	+	+	-		-
Jo et al. (2010) [38]	+	+	n/a	+	-	-	+	n/a	Vi, Ha	Vi, Ha	Vi	R	MK	+	+	-		-
Kim et al. (2007) [39]	+	+	-	+	-	-	+	+	Vi	Vi	Vi	R	n/a	+	+	-		-
Kim et al. (2009) [40]	+	+	-	+	-	-	+	+	Vi, Ha	Vi, Ha	Vi, Ha	R	Ha	+	+	-		-
Konieczny et al. (2008) [41]	+	+	-	n/a	-	-	+	n/a	Vi, Ha	Vi	Vi	R	MK	+	+	-		-
Liang et al. (2012) [45]	-	+	n/a	n/a	-	-	+	-	Vi, Ha	Vi, Au	Vi, Au, Ha	R	Ha	-	+	(+)	Progress	-
Mechlih (2016) [53]	(+)	+	n/a	n/a	-	-	+	+	Vi, Ha	Vi	Vi	R	MK	+	+	-		-
Xiaoling et al. (2004) [81]	-	+	n/a	+	+	+	-	+	Vi, Ha	Vi, Au	Ve, (Vi)	R	MK	+	+	-		-