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ORIGINAL ARTICLE

Adaptive virtual reality-based training: a systematic literature review and framework

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Abstract

Virtual reality (VR) provides the capability to train individuals to deal with complex situations by immersing them in a virtual environment. VR-based training has been used in many domains; however, in order to be effective, the training should be adapted based on user's capabilities, performance, and needs. This study provided a framework for adaptive VR-based training including performance measures, adaptive logic, and adaptive variables. A systematic review of literature was conducted using Compendex, Web of Science, and Google Scholar databases to identify the adaptive VR-based training approaches used in different domains. Results revealed that adaptive VR-based training can be improved by using real-time kinematic/kinetic data and physiological measures from the user, incorporating offline measures such as trainee's profile information, providing adaptations on controlled elements in the simulation, adjusting feedback content, type, and timing, and using reinforcement learning algorithms. The recommendations provided in this study need to be further validated using longitudinal studies comparing adaptive and non-adaptive training approaches.

Keywords Virtual reality · Adaptive training · Framework · Personalization

1 Introduction

Virtual reality (VR) is defined as a "real or simulated environment in which a perceiver experiences telepresence" (Steuer 1992). Milgram and Kishino (1994) provided a representation of how reality and virtuality are connected, which consisted of a continuum including real and virtual objects and environments. The current study focuses on a particular subclass of VR in which the user is immersed in and able to interact with a synthetic world (virtual environment). Immersion is defined as "the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding, and vivid illusion of reality to the senses of a human participant" (Slater and Wilbur 1997). The immersive experience provided by VR can be used for numerous purposes such as training, education, therapy, and entertainment. The current study focuses on the use of VR for training which is defined as provision of knowledge and skills (Antonacopoulou 2001).

VR provides the capability to train individuals to deal with complex and dangerous situations by immersing them in a virtual environment and enabling them to learn (i.e., process of acquiring knowledge and skills, Antonacopoulou (2001)) by doing. VR-based training has been used in many domains including patient rehabilitation (Lafond et al. 2010; Rossol et al. 2011), medical training (Pham et al. 2005; Vaughan et al. 2016a, b), military training (Bhagat et al. 2016; Pallavicini et al. 2016), etc. However, due to learning style differences and task needs, VR-based training should ideally include personalization approaches (Vaughan et al. 2016a, b). The National Academy of Engineering (NAE) emphasizes this point by proposing "Enhancing Virtual Reality" and "Personalized Learning" topics among the top grand challenges of Engineering for the twenty-first century (NAE 2017). Although adaptive VR-based training has been used extensively in different domains especially rehabilitation, there is no unified framework which describes its essential components and process. Such framework can be used as a standard for developing future adaptive systems to improve personalized training experience and avoid over/under training, frustration or boredom, and cognitive overload.

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On this basis, the objectives of this study were to: (1) develop a framework for adaptive VR-based training; (2) review prior adaptive VR-based training in different domains; (3) identify future needs and areas of research to promote adaptive/personalized training; and (4) identify other domains/occupations that adaptive training using VR simulations can be useful.

2 Adaptive training framework

2.1 What is adaptive training?

Adaptive training is defined as "the training in which the problem, the stimulus, or task is varied as a function of how well the trainee performs." (Kelley 1969). In order for a training system to be adaptive, it should have three fundamental components: (1) trainee's performance measurement; (2) adaptive variable; and (3) adaptive logic. Performance measures can be collected prior to training (e.g., user's profile information, learning style) or using formative (e.g., monitoring trainee's movement during training and in real time) or summative (e.g., accuracy after each training session) evaluation methods. Adaptive variable is an adjustable feature that changes based on the trainee's performance (e.g., difficulty level of the simulation, feedback). Adaptive logic is the underlying logic behind all adaptive training systems in which the adaptive variable automatically changes based on the trainee's performance (e.g., fuzzy inference system) (Kelley 1969). For example, in an on-road driving training study with novice drivers, Malik et al. (2015) used a combination of real-time eye-tracking, driving performance, and in-vehicle sensors data (i.e., performance measures) and fuzzy logic (i.e., adaptive logic) to provide personalized feedback messages (i.e., adaptive variable) for drivers and to encourage safe driving habits.

2.2 Why adaptive training?

Non-adaptive training systems in which one training procedure is used for all trainees might be easier and cheaper to implement but have not been found as effective as adaptive training approaches due to trainee's disengagement and boredom, cognitive overload, and excessive training time. For example, providing customized training duration based on user cognitive abilities was found to be more beneficial as compared to the non-adaptive training approach for improving older adult cognitive performance (Peretz et al. 2011). Adaptive training is also a well-established approach in professional athletes' physical training. Research has shown that the athletes whom the intensity of training was matched to their genetic profile had significant increased performance as compared to the control group (Jones et al. 2016). The examples of other areas in which adaptive training found to be beneficial includes game-based training (Schwaninger et al. 2007), rehabilitation (Heloir et al. 2014), medical training (Pham et al. 2005), and strategic decision-making training (Cesta et al. 2014).

Advantages of adaptive training can also be explained by different theories including Yerkes–Dodson law (Yerkes and Dodson 1908), cognitive load theory (CLT) (Sweller 1988), expertise reversal effect (ERE) (Kalyuga et al. 2003), and theory of learning and retention (Ritter et al. 2013). Based on Yerkes–Dodson law, adaptive training can provide optimal level of physiological or mental arousal to maximize trainee's performance and learning. On the other hand, non-adaptive training may impair the performance due to low (boredom) or high (increased anxiety) levels of arousal (Bian et al. 2016). Based on the CLT and in order for the training to be effective, intrinsic load (e.g., inherent complexity of the information) should be managed, extraneous load should be reduced (e.g., by using appropriate training medium), and germane load should be increased (e.g., by increasing the training variability). The ERE which is focused on adaptive feedback content suggests that the content needs to constantly change as the trainee becomes more familiar with the material. Based on this theory, novice learners should be provided with adaptive bottom-up feedback strategy in which they will initially be provided with more detailed instruction and as they become more familiar to the task, the training should become more general. On the other hand, more experienced users should be provided with top-down feedback in which the instruction is general at the beginning and if they make mistakes, it becomes more detailed. Based on the theory of learning and retention, adaptive training can be beneficial in different stages of learning and retention including declarative knowledge, mixed knowledge (declarative and procedural knowledge), and procedural knowledge. In the first stage (i.e., declarative knowledge), adaptive training can help the trainee achieve long-term retention by providing training on the least learned skills. In the second stage (i.e., mixed knowledge), the training can be adapted to provide variations of tasks in order to avoid catastrophic failures that can occur due to inability of the trainer to retrieve declarative knowledge. Finally, in the third stage of learning and retention (i.e., procedural knowledge), adaptation can help provide training on uncommon tasks which still require declarative retrievals (e.g., emergency situations).

2.3 Adaptive variable classification

Adaptive variables can be classified into two main categories of adaptive simulation content and adaptive feedback. Kelley (1969) provided the first classification of adaptive simulation content in driving domain, which includes adapting: (1) the simulated environment (e.g., illumination, sound level, etc.), (2) stress or physical-based features applied to the trainee (e.g., gravity, force, vibration, etc.), (3) controlled element in the simulation (e.g., self-avatar), (4) the trainee's control (e.g., gain, simulated feel), (5) display features (e.g., gain, lag of the display), (6) training scenario difficulty, and (7) the secondary task load. Except the last category (i.e., secondary task load) which refers to adjusting the load of the distraction task (e.g., cognitive and/or visual distraction) while driving, the other categories can also be applied to VR-based training in order to provide adaptive simulation content. Although Kelley's classification covers a wide range of adaptable features, it does not specify the timing of adaptation. Another classification by Gerbaud et al. (2009) resolves this issue by providing two categories of adaptation. The first adaptation (also called "parametering") refers to adapting the parameters of the simulation prior to the execution of the training session and can be based on the trainee's prior knowledge, level, preferences, and experience. The second level adaptation (also called "dynamic adaptation") occurs during the execution of the training in which the training content dynamically adapts itself based on real-time performance measures. Both Kelley's and Gerbaud et al.'s classifications are focused on simulation content adaptations. Feedback can also be adapted based on different performance measures to improve learning. Feidakis (2016) said that the feedback can be changed based on timing (i.e., knowledge of performance (KP), knowledge of results (KR), or combination), or type (e.g., verbal or written explanation, hint, multi-modal feedback). Beyond this, feedback content (i.e., personalized messages, bottom-up, top-down) can be adapted to improve trainees' performance based on CLT and ERE theories (Billings 2012; Pozueco et al. 2015).

Based on these classifications and literature on adaptive training, we have developed a framework for adaptive VR-based training. As shown in Fig. 1, the first stage is to collect performance measures. These measures can be collected through a combination of offline and real-time measures including trainee's profile information (e.g., experience, age, learning style), physiological (e.g., eye tracking, heart rate, galvanic skin response), task performance (e.g., error rate and type), and kinematic/kinetic (e.g., range of motion, force) measures. Some of these performance measures such as kinematic/kinetic measures may not be useful in other simulation-based training systems if the trainee is in a stationary position (e.g., driving simulation-based training) and the task does not require too much force. Once the performance measures have been collected, the adaptive logic module will use classification algorithms, optimization approaches, or rule-based systems to adjust the simulation and feedback content based on trainee's performance measures. The results will then be used by the training system or an instructor to select the best or combination of adaptive variables. Adaptations can be made prior or during the training session and can be focused on different aspects including the training content and feedback. It is important to note that the overall framework might be used in other simulation-based trainings (e.g., driving simulation-based training). However, some adaptations might not be relevant to other training media. For example, the general structure of this framework including performance measures, adaptive logic, and variables has been used in driving training (Zahabi et al. 2019). However, some adaptive variables such as display features (e.g., changing the gain or lag of the display) might not be relevant to driving training.

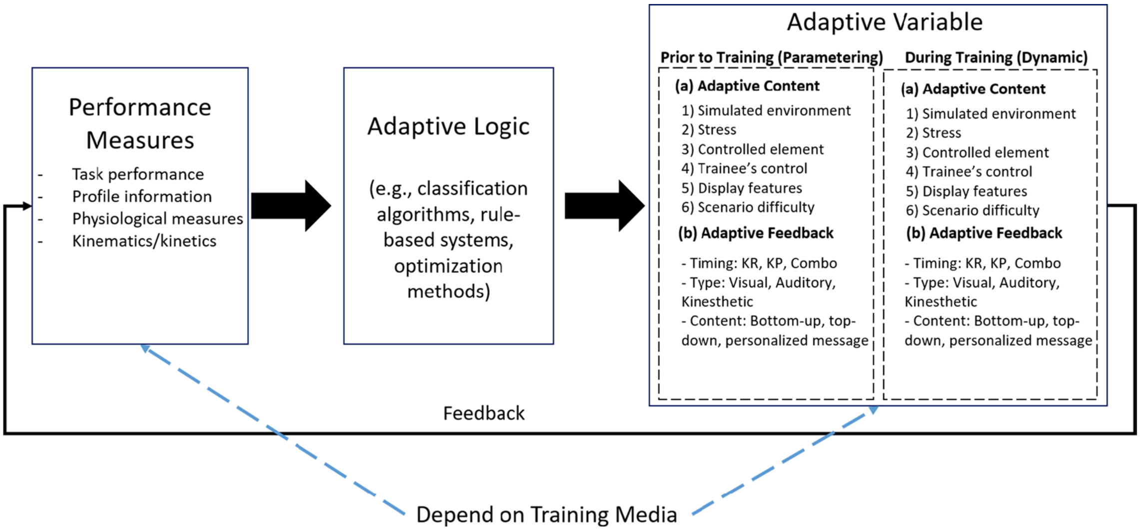

Fig. 1 Framework of adaptive VR-based training

Once the adaptations have been implemented, the system will provide feedback to the performance measure module to collect trainee's responses to ensure effective customization. This closed-loop human-in-the-loop system has the potential to keep the trainee in the optimal cognitive and performance state during the training. We have used this framework in order to identify the gaps and future areas of research in adaptive VR-based training.

3 Literature review

A systematic literature search was conducted using Compendex, Web of Science (WOS), and Google Scholar databases to find relevant research published since 2000. These databases were selected since they are the most common databases for science and engineering. Search terminology included *personalized* or *adaptive* or *customized training* combined with *virtual reality*. Inclusion criteria were determined as relevant English-language articles published in peer-reviewed journals or conferences with subsets of the keywords as well as any research studies (manually) identified with a focus on adaptive training in VR. Technical reports or online presentations were excluded from the review because of the lack of peer-review process. The literature search was completed in 2019. Initially, relevance of literature returned through the searches was assessed via review of the titles. Literature found relevant via title review was assessed for relevance again via abstract review. (Articles appearing without abstracts were excluded.) If the study was identified to be relevant based on its title and abstract review, the full reference was saved for further evaluation. Subsequently, the full text of all the references deemed relevant by both title and abstract was reviewed by the authors independently ($n = 84$). Discrepancies between the reviewers' findings were discussed and resolved. Of the initial records found ($n = 4005$), 69 studies were found to meet the inclusion criteria and were included in this review per PRISMA methodology (Moher et al. 2009) shown in Fig. 2. An annotated bibliography was developed with a structured format, including the following subsections: (1) citation information, (2) study objective, (3) research methodology, (4) significant results, and (5) conclusions. In addition, each study was classified in terms of the three components of adaptive training systems (i.e., performance measure, adaptive logic, and adaptive variable). The studies were categorized based on their application areas.

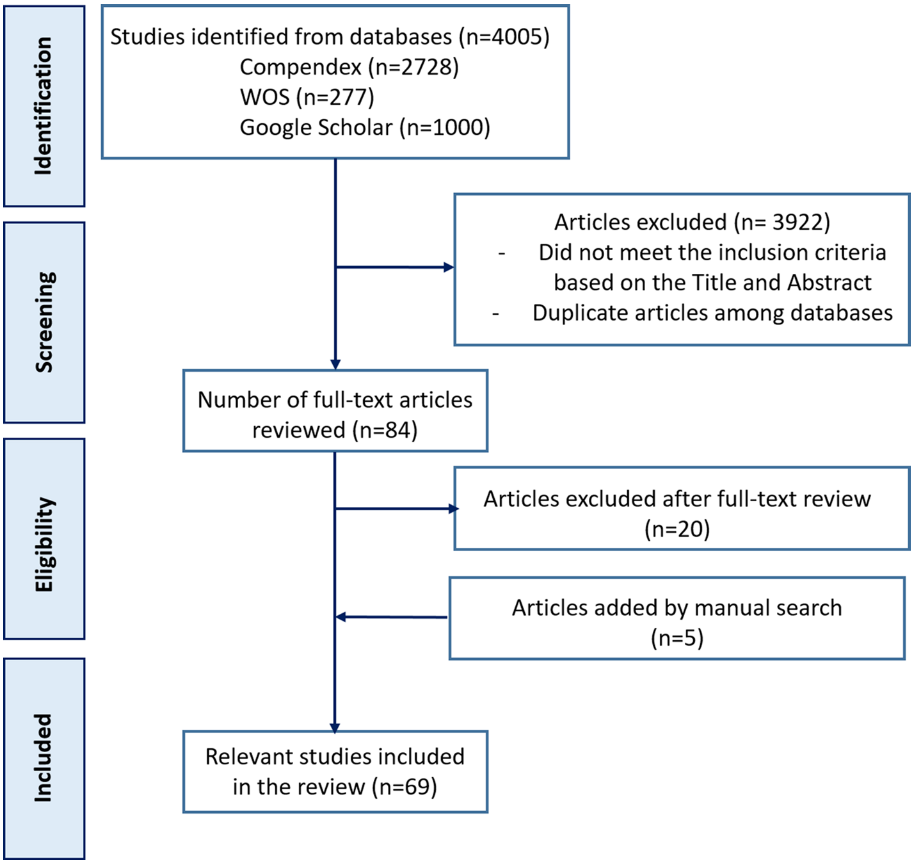

Fig. 2 Summary of the literature review process

4 Results

Tables 1 and 2 summarize the findings of the reviewed studies with a focus on the application domain, study design, VR setup, performance measures, adaptive logic, and adaptive variable classifications. Due to substantial differences among the performance measures and adaptive variables used in rehabilitation domain as compared to other areas and in order to provide a fair comparison, we have presented the findings in two separate tables. These tables are discussed in detail in the following sections. In this review, rehabilitation refers to a care that can help a patient get back, keep, or improve abilities that he/she needs for daily life. These abilities may be physical, mental, or cognitive. The patient may have lost these abilities because of a disease or injury, or as a side effect from a medical treatment (NIH 2019). All the reviewed studies except Schatz et al. (2012) used adaptive virtual reality training for individual training. Schatz et al. (2012) developed an adaptive training system for team-based military training. The study design included laboratory experiments including inferential statistics (sample size: $N \geq 10$), pilot or case studies for initial validation of the system ($N < 10$), or proof of concept (no human subject testing).

4.1 Performance measures

In rehabilitation (Table 1), performance measures were mainly collected during the training session and in real time (i.e., online measures) as compared to offline measurement. In terms of the classifications of performance measures based on the adaptive training framework (Fig. 1), a majority of studies ($n = 17$) used kinematic/kinetic data including speed, accuracy and range of movement, force, or muscle activity during the training as well as task performance ($n = 17$) in terms of accuracy and task completion time. However, only three studies (Dhiman et al. 2016; Koenig et al. 2011; Matthias and Beckhaus 2012) used physiological responses to identify the trainee's cognitive load, stress level, and emotions as a basis for providing personalized training. Furthermore, five studies used patient's profile information including level of dexterity and impairment and patient's history as offline performance measures (Chen et al. 2011; Ma and Bechkoum 2008; Ma et al. 2007; Rossol et al. 2011; Wu et al. 2016).

In other domains (Table 2), performance measures were mainly based on trainee's task performance ($n = 25$) such as accuracy, speed, and reaction time. These measures were collected either during the training session or after the completion of the training session as a basis to adapt the following training sessions based on users' performance. Physiological measures were also collected in real time in 16 studies to assess trainees' cognitive state, attention allocation, stress, engagement, and emotions. Furthermore, 11 studies considered trainee's profile information including knowledge and skill level, age, and gender as offline performance measures to provide personalized training. As compared to rehabilitation studies, use of kinematics and kinetics performance measures was very limited in other adaptive VR-based trainings (Bayart et al. 2005; Yang et al. 2016). A majority of studies used a combination of real-time and offline performance measures including trainee's task performance, physiological, and profile data.

4.2 Adaptive logic

Twenty-one (21) out of the 69 reviewed studies did not identify the underlying logic used to provide adaptive training. From those who mentioned the logic, a majority of them ($n = 25$) used machine learning (ML) or optimization algorithms including artificial neural network (ANN) (Barzilay and Wolf 2009, 2013; Bekele et al. 2013; Huang et al. 2018), support vector machines (SVM) (Bekele et al. 2013; Wang et al. 2017), random forest (Bian et al. 2016), fuzzy inference system (Mourning and Tang 2016; Rezazadeh et al. 2011), etc. The algorithms were used for extracting features from various sources of performance measures, classifying trainee's state, and providing an optimized adaptation to match the trainee's performance, cognitive and physical capabilities. Beyond this, 19 studies used conditional statements or rule-based systems as their adaptive logic. These conditional statements were mainly developed to compare the performance of trainees with some threshold values and adjust the difficulty level of the scenario (e.g., make the scenario easier if the user did not pass a minimum task requirements) or feedback content (e.g., detailed or general feedback) accordingly.

4.2.1 Adaptive variable

A side-by-side comparison of adaptive VR-based training in rehabilitation and other areas is shown in Fig. 3. A majority of studies in rehabilitation provided adaptive training by adjusting the difficulty level of the scenario ($n = 23$). The main objective for this adaptation was to match the simulation to the physical capability of the patient in order to avoid fatigue, injury, and frustration during training. The difficulty of the scenario was adjusted by changing the speed, size, position, or distance of the target or changing the exercise trajectory. Adapting the display or scenario features was also used in previous studies ($n = 13$) mainly through changing the speed, spacing, number and ratio of objects,

Table 1 Summary of literature review findings in rehabilitation

References	Rehabilitation type	Study design	Target population	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
								Content						Timing		Feedback		
								1	2	3	4	5	6	P	D	Timing	Type	Content
Lafond et al. (2010)	Upper-extremity rehabilitation	Proof of concept	Stroke patients	Desktop system	Range of motion, speed and accuracy of shoulder and elbow movements	Optimization algorithm	Speed, spacing, number of objects and the relative frequency of the targets in the simulation, damping added to help participants with tremors, anti-gravity assistance to reduce shoulder fatigue		✓		✓	✓		✓	✓			
Rossol et al. (2011)	Power wheelchair training	Pilot/case study	Patients using power wheelchairs	Desktop system	dexterity level, patient confidence, task completion time, and number of collisions	Bayesian network	Difficulty level of the scenario						✓	✓				
Ma et al. (2007); Ma and Bechkoum (2008)	Physical therapy	Pilot/case study	Stroke patients	HMD	Patient impairment measurements and profile data, accuracy	N/A	Size of the target area and objects in the simulation, size, timing and location of the stimuli, gravity	✓	✓			✓	✓	✓	✓			

Table 1 (continued)

References	Rehabilitation type	Study design	Target population	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
								Content						Timing		Feedback		
								1	2	3	4	5	6	P	D	Timing	Type	Content
Wu et al. (2016)	Physical therapy	Pilot/case study	Stroke patients	Desktop system	Posture and force measurement using sensors, historical patient information and inherent condition	N/A	Training movements and schedule, feedback						✓	✓	✓			✓
Chen et al. (2011)	Upper-extremity rehabilitation	Pilot/case study	Stroke patients	Desktop system	kinematic features captured by sensors, patient's history	Network analysis and decision making using utility function	Object's position and type, feedback timing and modality	✓						✓	✓	✓	✓	
Heloir et al. (2014)	Upper-limb rehabilitation	Laboratory experiment	Patients with upper-limb injuries	Desktop system	Trainee's hand motion performance	Rule-based system	System's reactivity and sensitivity to the user				✓				✓			
Cameirão et al. (2008); Cameirão et al. (2010)	Upper-extremity rehabilitation	Laboratory experiment	Stroke patients	Desktop system	User performance (i.e., number of touched spheres)	Conditional Statements	Task difficulty level in terms of speed of the target, intervals of appearance between consecutive targets, and range of dispersion in the field					✓	✓	✓				

Table 1 (continued)

References	Rehabilitation type	Study design	Target population	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
								Content						Timing		Feedback		
								1	2	3	4	5	6	P	D	Timing	Type	Content
Nirme et al. (2011)	Upper-extremity rehabilitation	Laboratory experiment	Stroke patients	Desktop system	User performance (i.e., percentage of touched spheres)	Random line search, predictive search	Task difficulty level in terms of speed of the target, intervals of appearance between consecutive targets, and range of dispersion in the field					✓	✓		✓			
Kumar et al. (2018); Verma et al. (2017)	Balance rehabilitation	Pilot study and Laboratory experiment	Stroke patients	Desktop system	Task performance, center of mass estimation	Conditional statements	Difficulty level of the scenario						✓	✓				
Grimm et al. (2016)	Robot-assisted rehabilitation	Pilot/case study	Stroke patients	Desktop system	User performance in the game	N/A	Difficulty level of the scenario (by adjusting the distance between the ball and basket), grip force, feedback content (score)				✓		✓	✓				✓
O Barzilay and Wolf (2009); Ouriel Barzilay and Wolf (2013)	Upper-limb rehabilitation	Pilot/case study	Patients with neuromotor disorders	HMD	Trainee's kinematics and muscle activity signals	Neural network	Exercise trajectory						✓	✓				
Wang et al. (2017)	Physical therapy	Pilot/case study	Stroke patients	Desktop system	Brain and muscle fatigue	Support vector machines (SVM)	Difficulty of the scenario						✓		✓			

Table 1 (continued)

References	Rehabilitation type	Study design	Target population	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
								Content						Timing		Feedback		
								1	2	3	4	5	6	P	D	Timing	Type	Content
Saurav et al. (2018)	Upper-limb rehabilitation	Pilot/case study	Stroke patients	Desktop system	Trainee's performance measured by range of hand motion and flexion angle	Conditional statement	Difficulty of the game in terms of the sensitivity level				✓		✓	✓				
Koenig et al. (2011)	Robot-assisted rehabilitation	Laboratory experiment	Stroke patients	Desktop system	Patient's cognitive load detected by physiological data (HR, GSR, skin temperature, breathing), task performance	Kalman adaptive linear discriminant analysis	Task difficulty level in terms of time and distance between objects on the display and question difficulty					✓	✓		✓			
Huang et al. (2018)	Robot-assisted rehabilitation	Pilot/case study	Stroke patients	Desktop system	Finger range of motion, force, and position	ANN	Assistive force intensity, difficulty of the scenario		✓				✓	✓	✓			
Adamovich et al. (2009)	Finger motion therapy	Pilot/case study	Patients with hemiparesis	Desktop system	Finger fractionation score	Self-developed algorithm	Target fractionation score						✓	✓				
Chemuturi et al. (2013)	Upper-arm rehabilitation	Laboratory experiment	Stroke patients	Desktop system	Leading/lagging performance of trainee in following a path	Conditional statements	Task duration					✓			✓			
Dhiman et al. (2016)	Upper-extremity rehabilitation	Pilot/case study	Stroke patients	Desktop system	Task completion time, error rate, stress level measured by physiological data	Conditional statements	Difficulty of the trajectory						✓	✓				

Table 1 (continued)

References	Rehabilitation type	Study design	Target population	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
								Content						Timing		Feedback		
								1	2	3	4	5	6	P	D	Timing	Type	Content
Kommalapati and Michmizos (2016)	Sensorimotor rehabilitation	Proof of concept	Physically impaired children	Desktop system	Trainee's movement and time to reach targets	Conditional statements	Difficulty of the scenario in terms of changing the display visual gain					✓	✓	✓	✓			
Tsiakas et al. (2015)	Physical therapy	Proof of concept	N/A	N/A	Trainee's body motions, pain expression, speech, task completion time, and performance	Markov decision process, Dyna-Q reinforcement learning algorithm	Difficulty level of the scenario						✓	✓				
Kizony et al. (2003)	Neurological rehabilitation	Pilot/case study	Patients with stroke and spinal cord injury	Desktop system	User's task performance	N/A	Speed, location, type, and direction of the stimuli, difficulty of the scenario					✓	✓					
Summa et al. (2015)	Physical therapy	Pilot/case study	Parkinson's patients	Desktop system	Trainee's movement time	N/A	Difficulty level of the scenario by adjusting target distance					✓	✓		✓			
i Badia et al. (2013)	Neuro-rehabilitation	Pilot/case study	Stroke patients	Desktop system	Control of the virtual arm	N/A	Difficulty of the scenario defined by speed, distance, and time interval between stimuli					✓	✓	✓	✓			

Table 1 (continued)

References	Rehabilitation type	Study design	Target population	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
								Content						Timing		Feedback		
								1	2	3	4	5	6	P	D	Timing	Type	Content
Merians et al. (2009)	Upper-extremity rehabilitation	Pilot/case study	Stroke patients	Desktop system	Trainee's task performance, range and speed of motion	N/A	Difficulty of the scenario in terms of fractionation angle, target size, position, and timing, gravity force, anti-gravity assistance force by robot		✓		✓	✓	✓	✓				
Padilla-Castaneda et al. (2013)	Robotic-assisted therapy	Pilot/case study	Patients with upper-limb reduced mobility	Desktop system	Trainee's task performance and kinematics	N/A	Difficulty of the scenario in terms of game workspace, size and timing of stimuli, and haptic forces of the robotic arm	✓			✓	✓	✓	✓				
García-Vergara et al. (2013)	Physical therapy	Laboratory experiment	Children with cerebral palsy	Desktop system	Trainee's task accuracy, fine motor skills, and speed of movement	N/A	Difficulty of the scenario in terms of game duration, levels, speed, size and ratio of the stimuli					✓	✓	✓				

Table 1 (continued)

References	Rehabilitation type	Study design	Target population	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
								Content						Timing		Feedback		
								1	2	3	4	5	6	P	D	Timing	Type	Content
Matthias and Beckhaus (2012)	Neuro-rehabilitation	Laboratory experiment	Stroke patients	CAVE	Measurement of trainee's emotion	N/A	Difficulty of the scenario in terms of navigation speed, simulated environment (e.g., sunset, thunderstorm, soft colors)	✓					✓		✓			

Simulation content categories: (1) simulated environment, (2) stress or physical-based features applied to the trainee, (3) controlled element, (4) trainee's control, (5) display features, (6) scenario difficulty. Adaptive variable timing classification: *P* parametering, *D* dynamic, *HMD* head-mounted display, *N/A* not assigned

task duration, and display visual gain. Few other studies provided adaptive simulation content by adjusting the simulation environment (Chen et al. 2011; Ma and Bechkoum 2008; Ma et al. 2007; Matthias and Beckhaus 2012; Padilla-Castaneda et al. 2013), stress or force on the trainee (Huang et al. 2018; Lafond et al. 2010; Ma and Bechkoum 2008; Ma et al. 2007; Merians et al. 2009), and the trainee's control (García-Vergara et al. 2013; Grimm et al. 2016; Heloir et al. 2014; Lafond et al. 2010; Padilla-Castaneda et al. 2013; Saurav et al. 2018). However, none of the reviewed studies provided adaptations on the controlled element (e.g., virtual arm or avatar) in the simulation.

As compared to the studies that provided adaptive simulation content, adaptive feedback was rarely provided in rehabilitation. Chen et al. (2011) was the only study that provided adaptive feedback type using different modalities (i.e., visual or auditory) and changed the feedback timing (i.e., KP or KR) to facilitate the training and accommodate more complex tasks. Feedback content was adapted through providing personalized instructions on how to make limbs stretching and strength exercises (Wu et al. 2016) or via a point score system (Grimm et al. 2016).

Similar to rehabilitation studies, the most common simulation content adaptation in other domains was through adjusting the difficulty of the scenario ($n = 17$). Scenario difficulty was adjusted by using harder/easier paths and manipulating the speed and number of stimuli. These adaptations were mainly provided to match the trainee's task performance, cognitive or emotional states. Other common simulation content adaptations were related to adjusting the simulation environment ($n = 6$) by changing the lighting and visibility of the environment, emotions, and looks of other entities or avatars in the scenario, manipulating the force/stress on the trainee ($n = 6$), and providing display variations ($n = 7$) by changing the speed and probability of stimuli. Feedback adaptation was mainly provided by adjusting the feedback content ($n = 12$) through personalized messages (Johnson et al. 2014; Mourning and Tang 2016) based on user's task performance or top-down or bottom-up feedback adaptation based on the ERE theory (Billings 2012; Serge et al. 2013). Feedback type was also adapted in some studies ($n = 6$) by providing feedback in different modalities (i.e., visual or auditory) or by using different types of cues (e.g., text messages, demonstrations, prompts, and highlighted areas) (Lopez-Garate et al. 2008; Mourning and Tang 2016; Yang et al. 2016).

4.2.2 Application domain

Adaptive VR-based training has been used extensively in rehabilitation ($n = 31$) and especially for upper-extremity rehabilitation, physical therapy, and robot-assisted rehabilitation. However, its application in other domains is limited

Table 2 Summary of literature review findings in other areas

Domain	References	Study design	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
							Content						Timing		Feedback		
							1	2	3	4	5	6	P	D	Timing	Type	Content
Driving training	Lang et al. (2018)	Laboratory experiment	HMD	Pretest driving performance, gaze behavior	Markov chain Monte Carlo optimization	Difficulty level of the scenario						✓		✓			
	Lopez-Garate et al. (2008)	Proof of concept	Projector screen	number and nature of the committed mistake, the student's level	Foundation of Intelligent Physical Agents (FIPA)/rule-based system	Feedback intrusiveness and modality								✓	✓	✓	
	Bian et al. (2016)	Pilot/case study	Desktop system	physiological measures including photoplethysmogram, galvanic skin response, and respiration, driving performance	Random forest algorithm	Intensity of light, speed of vehicles, responsiveness of brake and accelerator pedals, and steering wheel	✓			✓				✓			
Medical training	Pham et al. (2005)	Laboratory experiment	Desktop system	User performance (details were not specified)	N/A	Task environment parameters (details were not specified) to reduce trainee's frustration and stress		✓						✓			
	M. A. Yovanoff et al. (2018)	Laboratory experiment	Desktop system	Performance in central venous catheterization	N/A	Feedback content											✓
	Mariani et al. (2018)	Laboratory experiment	Desktop system	Trainee's task performance	Self-developed algorithm	Difficulty level of the scenario						✓	✓				
	Siu et al. (2016)	Pilot/case study	Desktop system	Trainee's skill and task performance, experience	N/A	Complexity of the task						✓	✓				

Table 2 (continued)

Domain	References	Study design	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
							Content						Timing		Feedback		
							1	2	3	4	5	6	P	D	Timing	Type	Content
Social training for ASD	Mourning and Tang (2016)	Proof of concept	N/A	User performance in the game	Neural network, fuzzy inference system	Feedback type (text message, highlighted path, additional dialog), feedback content								✓		✓	✓
	Lahiri et al. (2013)	Pilot/case study	Desktop system	Trainee's performance score, eye-tracking measures	Conditional statements	Scenario difficulty, individualized feedback (story)						✓	✓				✓
	Bekele et al. (2013)	Proof of concept	Desktop system	Eye-tracking measures, physiological data, and performance	ANN, SVM, rule-based system	Difficulty level of the training						✓		✓			
	Blankendaal and Bosse (2018)	Pilot/case study	HMD	Trainee's stress level measured by skin conductance	Conditional statements	The content of the dialog between the agent and trainee and the animation of the agent								✓			✓
Cognitive training	Shochat et al. (2017)	Pilot/case study	Desktop system	Trainee's task performance and reaction time	N/A	Difficulty level of the game, probability and speed of stimuli presentation					✓	✓		✓			
	Chan et al. (2010)	Laboratory experiment	Projector screen	N/A	N/A	Difficulty of the scenario, speed, direction, and number of distractors					✓	✓	✓				

Table 2 (continued)

Domain	References	Study design	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
							Content						Timing		Feedback		
							1	2	3	4	5	6	P	D	Timing	Type	Content
Attention training	Yang et al. (2016)	Pilot/case study	HMD	Trainee's performance in terms of force magnitude, tolerance, and allowable response time	N/A	Difficulty level of the scenario in terms of target fingertip, force magnitude, and tolerance between adjacent trials Feedback modality (visual and/or audio)					✓	✓		✓		✓	
	Amat et al. (2018)	Pilot/case study	Desktop system	Trainee's task performance	Conditional Statements	Difficulty of the scenario in terms of avatar's speed and time to respond					✓	✓	✓				
Stress management training	D. Jones and Dechmerowski (2016)	Literature review, proof of concept	N/A	Stress measured by physiological responses, trainee's performance and characteristics	Linear classifier	Activate or deactivate stressors in the simulation		✓						✓			
	Popovic et al. (2009)	Proof of concept	N/A	Trainee's emotional state as measured by physiological measures	N/A	Intensity, duration and type of the stressful stimuli		✓					✓				

Table 2 (continued)

Domain	References	Study design	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
							Content						Timing		Feedback		
							1	2	3	4	5	6	P	D	Timing	Type	Content
Construction and safety training	Jeelani et al. (2017)	Pilot/case study	HMD	User performance (hazard identification accuracy)	N/A	Feedback content											✓
	Rezazadeh et al. (2011)	Pilot/case study	Desktop system	Trainee's affective state measured by facial bioelectric signals	Fuzzy inference system	Difficulty level of the scenario by manipulating the speed of the crane					✓	✓		✓			
Game-based training	Serge et al. (2013)	Laboratory experiment	Desktop system	Percentage of correct actions	Conditional statements	Feedback content (bottom-up, top-down)							✓				✓
	Abdessalem and Frasson (2017)	Laboratory experiment	HMD	Trainee's frustration and excitement measured by sensors (e.g., EEG, eye-tracker)	Rule-based system	Speed and difficulty of the scenario					✓	✓		✓			
Fluvial navigation	Fricoteaux et al. (2011); Fricoteaux et al. (2012); Fricoteaux et al. (2014)	Laboratory experiment, proof of concept	Projection screen	Trainee's mistakes and risk-taking behavior, stress, cognitive load, gesture, and profile	Evidential network with conditional belief (ENC)	Multi-modal feedback; Difficulty level of the scenario, navigation aid						✓	✓	✓		✓	
Airplane assembly training	Carpentier and Lourdeaux (2013)	Proof of concept	N/A	Material type, time pressure, trainee's quality of work after each trial	Zone of proximal development (ZPD)	Task type, time pressure on the trainee, feedback content		✓				✓	✓	✓			✓
Aggression de-escalation training	Bosse et al. (2014a, b)	Pilot/case study	HMD	User performance in the game	Conditional Statements	Difficulty level of the scenario						✓	✓				

Table 2 (continued)

Domain	References	Study design	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
							Content						Timing		Feedback		
							1	2	3	4	5	6	P	D	Timing	Type	Content
Handwriting and maintenance training	Bayart et al. (2005)	Pilot/case study	Desktop system	User's motion performance	Conditional Statements	Kinesthetic force applied to the operator		✓						✓			
Military training	Schatz et al. (2012)	Proof of concept	Projector screen	Trainee's pretest skills (communications, baseline construction and anomaly identification, sociocultural sensemaking), trainee's performance in the game	N/A	Simulated environment features (e.g., entities' behavior, visibility of events), communication content	✓						✓	✓			✓
Mission-based training (e.g., food distribution game)	Luo et al. (2013)	Laboratory experiment	Desktop system	A priori knowledge about the trainee's skills and performance	Genetic algorithm	Sequences and intensity of scenario beats	✓						✓				
Electronic education	Johnson et al. (2014)	Pilot/case study	Desktop system	Student's answers, online communication, time spent on tasks, frustration, and frequency of reviewing help material	*k*-nearest neighbor (kNN)	Content of instructions and format (text-based or video prompts)								✓		✓	✓

Table 2 (continued)

Domain	References	Study design	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
							Content						Timing		Feedback		
							1	2	3	4	5	6	P	D	Timing	Type	Content
Vocational training	Nazemi et al. (2007)	Pilot/case study	Desktop system	Trainee's profile, interaction with the system, time and accuracy of the response	N/A	Feedback content (behavioristic, constructivistic, cognitivistic), difficulty level of the training, feedback type (demo, help)						✓	✓	✓		✓	✓
Public safety training	Bosse et al. (2014a, b)	Proof of concept	Desktop system	Trainee's emotional state (physiological measures), and task performance	Temporal trace language (TTL), domain model (LEADSTO)	Difficulty of the scenario, stress on the trainee, feedback content		✓				✓		✓			✓
Mental readiness training	Cosic et al. (2010)	Proof of concept	N/A	Trainee's emotional state extracted from physiological measurement	Neural network	Stimulus modality, emotion, and content	✓				✓			✓			
Electrician training	Hernández and Ramírez (2016)	Proof of concept	Desktop system	trainee's profile, affect, and knowledge level	Bayesian network	look and empathy of the animated instructor	✓						✓	✓			

Table 2 (continued)

Domain	References	Study design	VR setup	Performance measure	Adaptive logic	Adaptive variable description	Adaptive variable classification										
							Content						Timing		Feedback		
							1	2	3	4	5	6	P	D	Timing	Type	Content
General	Mohamed et al. (2017)	Proof of concept	N/A	Learning session duration and difficulty level, trainee's gender, age, knowledge level, and desired language	Fuzzy logic	learning activities (details were not specified)							✓				
	Billings (2012)	Laboratory experiment	Desktop system	Task performance	Conditional statements	Feedback content (bottom-up vs. top-down)							✓				✓
	Dey et al. (2019)	Laboratory experiment	HMD	Workload and engagement measured by EEG	N/A	Difficulty of the scenario						✓		✓			
	Magerko et al. (2005)	Proof of concept	Desktop system	Trainee's skill level and previous experience	Self-developed heuristics	Simulated environment (e.g., spawning characters, environmental sounds)	✓						✓				

Simulation content categories: (1) simulated environment, (2) stress or physical-based features applied to the trainee, (3) controlled element, (4) trainee's control, (5) display features, (6) scenario difficulty. Adaptive variable timing classification: *P* parametering, *D* dynamic, *HMD* head-mounted display, *N/A* not assigned

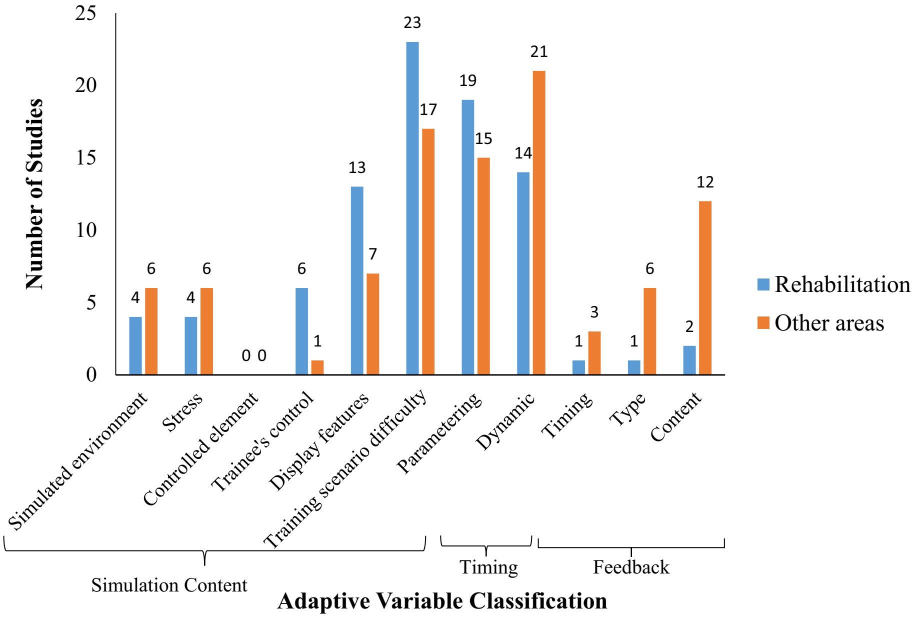

Fig. 3 Comparison of adaptive variables used in rehabilitation and other training areas. *Note*: number of studies in rehabilitation area = 31, number of studies in other training areas = 38. A majority of studies used multiple adaptive variables

to few studies in driving (Bian et al. 2016; Lang et al. 2018; Lopez-Garate et al. 2008), social training for individuals with autism spectrum disorder (ASD) (Bekele et al. 2013; Blankendaal and Bosse 2018; Lahiri et al. 2013; Mourning and Tang 2016), surgery (Mariani et al. 2018; Pham et al. 2005; M. Yovanoff et al. 2017), cognitive and attention training (Chan et al. 2010; Shochat et al. 2017; Yang et al. 2016), construction and safety (Jeelani et al. 2017; Rezazadeh et al. 2011), stress management (Jones and Dechmerowski 2016; Popovic et al. 2009), military training (Schatz et al. 2012), fluvial navigation (Fricoteaux et al. 2011, 2012, 2014), etc. VR-based training has been used extensively for medical training especially laparoscopic surgeries (Gurusamy et al. 2009; Kühnapfel et al. 2000; Larsen et al. 2009) and has been found to significantly improve the trainees' task performance and accuracy (Gurusamy et al. 2008). However, these training approaches have not been adaptive to individual's capabilities and skill set. Driving simulators have been used for decades in training novice drivers, elderly and special population (Cox et al. 2017; Pradhan et al. 2006; Roenker et al. 2003). Unfortunately, in a majority of applications (e.g., STISIM, DriveSafety, Forum 8, and RTI), the scenario is not capable of dynamic adaptation (i.e., the scenario cannot be adapted in real time based on driver performance measures). Although VR provides the capability to customize scenarios and is an easier, much cheaper, and more immersive tool than off-the-shelf driving simulators, its application in driving training is still limited. VR training for treating patients with ASD has also been used since late 90s (Strickland 1997). The ASD patients vary in their capabilities, skills, and behaviors. VR has the potential to provide personalized training for these individuals by controlling input stimuli, providing dynamic environments to compensate for their inconsistent responses, and real-time measuring of their stress level and physical activities (Strickland 1997). VR has also been used extensively in military for stress inoculation training (SIT) to desensitize individuals to the stressful situation by exposing them to gradual, controlled, and repeated exposure to stress stimuli (Stetz et al. 2008; Wiederhold and Wiederhold 2008). However, Popovic et al. (2009) was the only study that provided adaptive training intensity, duration, and type of the stressful stimuli based on the trainee's emotional state as measured by physiological data.

4.2.3 Effectiveness of adaptive VR training

The review of rehabilitation domain revealed that prior studies either did not conduct any assessment regarding the effectiveness of the adaptive VR training (Kommalapati and Michmizos 2016; Lafond et al. 2010; Tsiakas et al. 2015) or only conducted usability or feasibility studies (Adamovich et al. 2009; Chen et al. 2011; Dhiman et al. 2016; Grimm et al. 2016; Rossol et al. 2011; Wu et al. 2016) to validate their proposed system with small sample size ($N < 10$) and without any comparison with the non-adaptive training approach. The small sample size was mainly due to the difficulty of finding the patients who meet the study inclusion criteria (e.g., patients with upper or lower limb amputations, stroke, etc.). Therefore, it is difficult to come to strong conclusions regarding the effectiveness of adaptive VR-based training as compared to non-adaptive training in this domain. However, based on the studies that compared adaptive and non-adaptive approaches (Cameirão et al. 2008; Ma and Bechkoum 2008; Wang et al. 2017), it was found that the adaptive training approach was beneficial in terms of reducing patients' physical fatigue, leading to sustained improvement during the training, and providing faster recovery of movements in the actual task and in-game performance. Again, these results should be interpreted with caution due to small sample sizes (i.e., 7–8 participants).

Out of 38 studies reviewed in other domains, 12 studies (Bekele et al. 2013; Carpentier and Lourdeaux 2013; Lopez-Garate et al. 2008; Mourning and Tang 2016; Popovic et al. 2009) did not assess the effectiveness of their proposed adaptive VR training and 13 studies provided case studies or feasibility studies with small sample size to validate their approach without any comparison with non-adaptive training (Bian et al. 2016; Blankendaal and Bosse 2018; Lahiri et al. 2013; Shochat et al. 2017; Siu et al. 2016). From the remaining studies, which compared adaptive and non-adaptive training approaches, mixed results have been found. In driving training, Lang et al. found that drivers trained by the adaptive training approach had better driving performance and reaction time to hazards as compared to drivers trained by non-adaptive simulation, video instruction, handbook, and the no-training group. This effect was observed immediately after the training session. In addition, in a second assessment after 1 week, the adaptive training group achieved similar performance as they did a week ago, but the performance of other groups degraded (Lang et al. 2018). This is an evidence for higher retention rate for adaptive VR-based driving training as compared to non-adaptive training approaches. In medical training, studies by Yovanoff et al. (2018) and Mariani et al. (2018) revealed that the adaptive VR-based training led to performing higher number of tasks (i.e., reducing the training time), improved residents' task performance and self-efficacy, and reduced the variability in performing different tasks. The increase in self-efficacy was observed over 6-month training period (Yovanoff et al. 2018), while the improvement in task performance was observed during a single training session (Mariani et al. 2018). In another study, Pham et al. (2005) did not find any significant difference between adaptive and non-adaptive training approaches in terms of task performance and training time. However, the trainees reported less frustration with the adaptive training approach as compared to the non-adaptive training. In other domains including mission-based training (Luo et al. 2013), fluvial navigation (Fricoteaux et al. 2014), and cognitive training (Chan et al. 2010), adaptive VR-based training outperformed the non-adaptive training approach by improving users' task performance, efficiency (less time for training), effectiveness (better understanding of errors), cognitive functioning, and volition in engagement in VR activities.

Serge et al. (2013) and Billings (2012) compared adaptive and non-adaptive feedback content (i.e., static detailed or general feedback vs. bottom-up and top-down feedback) and did not find any significant difference between these two training methods. More specifically, these studies found both non-adaptive detailed and adaptive bottom-up feedback types to be the best in terms of improving trainees' performance. Although these findings are contradictory to the CLT and ERE, it is important to note that both studies assessed the impact of feedback content in relatively short training duration (one training session consist of four missions). With a longer training periods, the ERE might have been detected.

4.2.4 Types of VR systems

VR system configurations fall into two main categories of non-immersive (desktop computers, projection screens) and immersive systems (head-mounted displays (HMD), CAVE). Non-immersive systems do not require highest level of graphic performance and therefore are the lowest cost VR solutions. Projection screens are more advanced non-immersive systems, which provide capabilities for collaboration training or interaction. However, they are more expensive as compared to desktop systems (Sharples et al. 2008). Immersive systems such as HMDs are affordable VR solutions. However, due to issues such as visual stress, simulation sickness, and blocking user's view (Sharples et al. 2008), the setup might not be feasible for some rehabilitation trainings. The CAVE system is also an immersive VR system in which the user is surrounded by 3D screen displays and all images are automatically adjusted to the user's position at each time (Ohno and Kageyama 2007). However, the CAVE systems are usually large and expensive which limit their use in some training applications (e.g., home-based rehabilitation).

Based on our review, a majority of studies in adaptive training used non-immersive VR systems especially desktop computers due to their accessibility and cost (Fig. 4). Few studies used immersive VR systems using HMDs (Barzilay and Wolf 2009, 2013; Lang et al. 2018; Yang et al. 2016), and only one study used CAVE setup in rehabilitation

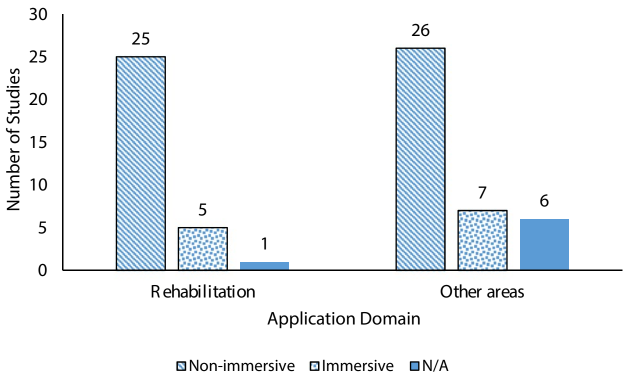

Fig. 4 Types of virtual reality systems used in prior studies

training (Matthias and Beckhaus 2012). Few studies (Mohamed et al. 2017; Mourning and Tang 2016; Tsiakas et al. 2015) did not identify their experiment setup or only provided a proof of concept for their adaptive training system (shown by "N/A" in Fig. 4). Findings suggested that adaptive training can be provided in both immersive and non-immersive VR systems depending on the task and user needs, cost, and application.

5 Discussion

5.1 How to improve adaptive VR-based training?

Based on the literature review and the developed framework, we provide the following recommendations to improve adaptive VR-based training:

- *Use physiological data and patient's profile information in rehabilitation training* Our review revealed that there is lack of adaptation based on users' physiological measures in rehabilitation training. Based on the CLT and Yerkes–Dodson law, in order to improve performance and learning, the training should keep the users in an optimal level of physiological and mental arousal and optimize their cognitive load. Rehabilitation training is a costly and time-consuming process, and the patient can get frustrated or bored due to long hours and repetitive activities. With advances in wearable technologies, physiological measures can be captured in real time through unobtrusive wearable devices such as smart watches (e.g., Empatica E4), wearable sensors (e.g., Biostamp nPoint), and eye-tracking glasses (e.g., Pupil Labs). These devices can detect patient's deviation from optimal physiological and mental state and adapt the training content and feedback accordingly. In addition, patient's profile information such as age, learning style, and history can be used as initial measures to adjust the scenario or feedback prior to the training session (i.e., parametering). Using both offline (e.g., a priori knowledge, profile information) and online performance measures (e.g., task performance, physiological responses) will provide more holistic assessment of patient's capabilities, cognitive, and physical states.
- *Use trainee's kinematic/kinetic information in providing real time adaptations* While the use of kinematics/kinetics data including speed, range of movement, force or muscle activity was very common in rehabilitation training, in other areas these performance measures were usually not captured. With recent advances in motion capture systems (e.g., Vicon, Xsens) and their integration with VR, trainee's motion and muscle activities can be captured in real time for providing adaptive training experience. This is especially critical in training for tasks that require hand–eye coordination, psychomotor tasks, and physical activities such as surgery, assembly operations, maintenance, writing, etc. Using kinematic/kinetic data from sensors located on different parts of the body, the system can observe the user's performance and provide real-time feedback (i.e., KP) or adjust the simulation content to improve learning.
- *Provide adaptations on controlled elements in the environment* No prior study provided adaptation on the controlled elements in the simulation (e.g., virtual arm, self-avatar). The controlled element in the simulation can be adapted to the capability and characteristics of the trainee. For example, the gain and sensitivity of the virtual arm to the trainee's movements can be adjusted in order to simulate different levels of task difficulty and make the training more or less challenging for the user. In addition, the appearance of the self-avatar can be personalized based on the trainee's look or task. The use of self-avatar has been shown to have positive impact on presence (i.e., a state of consciousness and sense of "being there" in a virtual environment (Slater and Wilbur 1997) or sense of being physically present with visual, auditory, or force displays generated by a computer (Sheridan 1992), motor-related, and cognitive tasks (Slater et al. 1995; Steed et al. 2016). More importantly, personalized appearance of self-avatars has been found to significantly increase body ownership, co-presence (sense of being together and perceive each other in virtual environment (Bulu 2012; Nowak 2001), and dominance in virtual environments as compared to generic avatars (Waltemate et al. 2018). In computer-based training, avatar customization resulted in increased user's engagement and ultimately increased training efficacy (Birk and Mandryk 2019). These findings provide evidence on the effectiveness of controlled element adaptation.
- *Provide adaptive feedback* As compared to simulation content, adaptive feedback was rarely provided in rehabilitation training. Based on the theory of adult learning, these learners are typically self-directed, motivated by internal incentives, and are problem centered (Knowles 1990). Also, based on the ERE, depending on patient's level, performance, and progress in training, detailed or general feedback might be more effective. Human therapist is very helpful because he/she considers patient's history, performance, fatigue, and frustration and can provide customized feedback to encourage and engage the patient during the training session. However, due to the cost of individual tutor and therapy sessions, the use of adaptive VR training can be helpful especially in outpatient rehabilitation by providing personalized feedback content. Regarding feedback type and based on Sarasin (1999), learners can be classified as visual, auditory or

kinesthetic learners depending on how they perceive and process the information (also known as VAK learning styles). Personalized feedback modality needs to be provided based on individuals' learning style, which can be captured using their profile information and prior to training (i.e., parametering). In addition, the frequency of feedback should be adjusted based on trainees' age, complexity, and intensity of the task, to avoid frustration and cognitive overload during training.

Although adaptive feedback content and type were used frequently in other domains, adaptations on feedback timing were rarely provided. Feedback can be provided during the training (instant feedback or KP) to inform the trainees of their real-time performance and movements. It can also be provided after the completion of each trial or the entire training session (summary feedback or KR). Prior studies comparing KP and KR in motor skill training found the KP was superior to KR for overall task performance retention, whereas KR was beneficial for training specific aspects of performance (e.g., accuracy) (Zhu et al. 2019). KP was also found to be more effective than KR in repetitive movement practice (Sharma et al. 2016). However, increasing the frequency of feedback during training especially for experienced users might result in frustration and quitting. Adaptive feedback training is necessary in order to engage the trainee during the session and improve performance, which can ultimately lead to reduction in training time and cost.

- *Use reinforcement learning algorithms as adaptive logic* A majority of studies in adaptive VR-based training used supervised learning algorithms (e.g., ANN, SVM, decision trees, *k*-nearest neighbor). In supervised learning, the algorithm is first trained on a dataset (training data). Subsequently, it will be used to predict the output values (e.g., workload level, difficulty level of the scenario, performance) based on the relationships learned from the training data. However, creating such training dataset might be expensive or not possible in some domains (e.g., rehabilitation). This issue can be resolved by reinforcement learning (RL). Tsiakas et al. (2015) was the only study that used RL for adaptive VR training in rehabilitation. Here, we described the adaptive training process using RL components including *state*, *action*, and *reward*. The goal of adaptive training is to keep the users in an optimal zone of cognitive and physical load and arousal to maximize their performance and engagement in the training session. In order to achieve this, the adaptive logic must learn the optimal policy (which action(s) will have the highest cumulative reward). During the training, the adaptive logic will define its current state (e.g., difficulty level of the scenario is "normal"). Then, it will perform a specific action (e.g., increase the speed of the target) and observes the new state and the reward based on the feedback from the trainee (e.g., physiological measures, task performance, kinematics/kinetics). Based on the received knowledge, the system then updates cumulative rewards (also known as *Q*-values) and the process continues until the optimal policy is reached and the final state is achieved (Fig. 5).

5.2 What occupations/areas can benefit from adaptive training?

The use of VR for training purposes is not a new concept and has been used in different areas. Here, we discussed how three specific applications (i.e., space mission preparation, driving, and emergency response training) can benefit from adaptive VR-based training. These applications were selected due to extensive use of VR or simulators for their training purposes. However, very few (or in some cases none) of these approaches provided personalized training.

Probably one of the areas that can significantly benefit from adaptive VR-based training is space mission preparations. NASA has been using VR training since the Hubble Space Telescope repair and servicing mission in 1993 to train mission operations flight control and engineering personnel to support the shuttle astronauts in space (Loftin and Kenney 1994). More recent studies have used VR for astronauts spatial orientation training (X. Zhu et al. 2015), 3D navigation training (Aoki et al. 2008), space motion sickness (Stroud et al. 2005), and intra-vehicular layout familiarization training (Liu et al. 2016). Personalized VR-based training can be useful in these applications considering offline performance measures such as astronauts' experience and duration of the mission, and real-time measures such as balance, simulator sickness level, physiological measures, and performance. Adaptive VR-based training can also improve learning and retention of knowledge and ultimately increase the effectiveness of the training by focusing on the least learned skills and providing variations of scenarios.

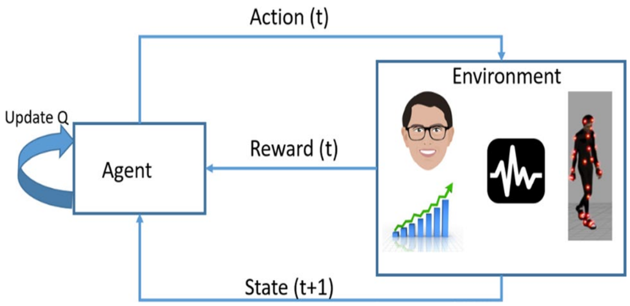

Fig. 5 Structure of reinforcement learning for adaptive VR-based training

Another area that can benefit from adaptive training is driving. Driving training has been traditionally performed through manuals, classroom education, demonstrations, videos tutorials, and on-road skill training. However, these approaches have been found to be ineffective in improving roadway safety (Christie 2001; Peck 2011). Although driving simulators provide a safe and controlled environment for driving training, they are usually very expensive to implement depending on their fidelity. Furthermore, current driving simulator software (e.g., Forum 8, RTI, and Drive Safety) are not capable of providing real-time adaptation. The scenario is usually pre-coded and cannot be adjusted during the session. VR is a cost effective tool that can provide immersive and adaptive driving training especially for elderly and novice drivers and for individuals with cognitive or physical disability (e.g., ASD and Parkinson disease). Advanced driver assistance systems (ADAS) and automated vehicles have also significantly changed transportation systems (Hancock et al. 2019). Providing personalized training is critical to prepare the driver in handling complex human–automation interaction scenarios especially in takeover situations.

VR has been used extensively for emergency response training especially in dealing with disasters and was found to be more effective as compared to conventional training approaches such as classroom training and table-top exercises (Stansfield et al. 2000; Wilkerson et al. 2008). However, none of these trainings adapted simulation content or feedback. This area can be improved by using a number of adaptive variables. For example, the simulation content can be adjusted based on the specific requirements of the environment (category 1) such as weather and lighting condition, buildings, geographical location, etc. The responders can be trained on scenarios with different levels of stress or temporal demand (category 2). The difficulty level of the scenarios can be adapted based on responders' progress in the training or extent of the emergency situation encountered (category 6). Feedback content can be adjusted based on responders' level of experience, duties, and performance. Feedback type and timing can be adjusted based on responders' learning style, performance, and training scenario. The suggested adaptive variables should be further evaluated to assess their effectiveness in improving trainee's engagement and performance (see Sect. 5.3).

5.3 How to assess the effectiveness of adaptive training?

Our review of literature revealed that a majority of studies did not assess the effectiveness of their proposed systems or only conducted feasibility or proof of concept studies. Kelley (1969) said that a well-designed adaptive training system should definitely be more effective than a similar non-adaptive training system and there is no need for experimental validation of this obvious point. Although a majority of studies who did compare adaptive and non-adaptive VR-based training found positive effects (Cameirão et al. 2008; Lang et al. 2018; Ma and Bechkoum 2008; Wang et al. 2017), some other studies did not find any improvement in task performance and training time despite well-designed training systems (Billings 2012; Pham et al. 2005; Serge et al. 2013). The effectiveness of adaptive VR-based training should be assessed with larger sample size, and in long-term to assess the impact on retention of learned activities and transfer of knowledge to real-world situations. For example, in rehabilitation, there is a need to evaluate the impact of learned skilled on performance of activities of daily living (ADLs). In addition, the effectiveness of adaptive feedback content (bottom-up vs. top-down) should be further evaluated in long-term to see whether the ERE is supported. We believe that the comparison of adaptive and non-adaptive VR-based training is essential to understand what types of adaptations would result in the most improvement in the aspects that are the targets of the training regimen. For example, if the objective of the training is to prepare emergency responders for dealing with severe weather conditions, the training system should focus on adaptive the simulating environment (Category 1 in the simulation content), whereas if the training objective is stress management in hazardous situations, then adaptation on stress applied to the trainee (Category 2) or difficulty level of the scenario (Category 6) might be more effective. Providing adaptive simulation content or feedback in training is a time-consuming and costly process. Appropriate selection of performance measures, logic, and adaptive variables is critical in order to optimize users' performance and retention of learned skills.

6 Conclusion

The objectives of this study were to: (1) develop a framework for adaptive VR-based training; (2) review the approaches used in adaptive VR-based training in different domains; (3) identify future needs and areas of research to promote adaptive/personalized training; and (4) identify other domains/occupations that can benefit from adaptive training using VR simulations. Adaptive VR-based training is a closed-loop system consisting of performance measures (collected in real time or based on offline measures), adaptive logic (AI algorithms, optimization, or rule-based systems), and adaptive variables (simulation content, timing, and feedback). The results of literature review revealed that a majority of studies used a combination of offline and online performance measures. Very few studies in rehabilitation training used physiological responses, while the use of kinematic and kinetic data in other areas was also limited.

In terms of adaptive logic, results indicated that supervised ML algorithms, optimization methods, and conditional statements were frequently used in previous studies with more emphasis on ML and optimization approaches in recent years. Most adaptations were related to simulation content especially adjusting the difficulty level of the scenario. Very few studies used adaptive feedback type, content or timing. In terms of the effectiveness of the adaptive VR-based training, although a majority of studies found positive effects, in some cases mixed results have been found. Based on the literature review, recommendations have been provided on how to improve adaptive VR-based training in future. These guidelines need to be further validated using well-controlled and long-term learning and retention studies comparing adaptive and non-adaptive approaches.

This study had some limitations. First, although the selected databases are the most common databases for science and engineering, it is possible that some relevant studies were not available through those databases and subsequently were not included in our review. Second, the findings of this study were based on the papers that were included in the review following the criteria established by the authors. Different inclusion criteria could have resulted in a different set of papers, and therefore, a subsequent analysis would have been different. Third, the guidelines provided in this study were based on the theories of cognitive load, feedback, learning, prior studies in VR-based training, and the authors' knowledge. Future investigations should further evaluate the impact of adaptive training and the provided recommendations on improving trainee's learning and performance using VR.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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