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Adaptive 3D Virtual Learning Environments – A Review of the Literature

Ezequiel Scott, Alvaro Soria and Marcelo Campo

Abstract—New ways of learning have emerged in the last years by using computers in education. For instance, many Virtual Learning Environments have been widely adopted by educators, obtaining promising outcomes. Recently, these environments have evolved into more advanced ones using 3D technologies and taking into account the individual learner needs and preferences. This focus has led a shift to more personalized learning approaches, requiring that the environments adapt themselves to the learner. Then, many adaptive 3D environments have explored adaptive features to create new and enhanced learning experiences in different contexts. However, very little is known about both what factors are involved with adaptive 3D environments to achieve learning benefits and what assessment factors are present in current studies. For this reason, this review analyzes the recent publications on Adaptive 3D Virtual Learning Environments. Findings have revealed that these have covered factors on defining the learner's model, the instructional strategies and contents, and the adaptations mechanisms. Nearly half of the environments have addressed thorough assessments whereas the rest has not reported any evaluation at all. Moreover, when they report assessment, promising outcomes have also been shown not only in multiple domains of knowledge but also at various stages of education. These findings indicate that the field of Adaptive 3D Virtual Learning Environments is an active and ongoing area, and this study highlights several promising directions and suggestions for future research.

Index Terms—Adaptive Virtual Environments, 3D Virtual Learning Environments, Personalized Virtual Environments

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1 INTRODUCTION

NOWADAYS, learning is being influenced by both the incremental ease of access to technology and the increasing use of computers in education. Furthermore, technology has become more suitable to address particular issues of the individual learner such as the interests, background, and abilities, so that diversity concerning learners is taken into account. This focus has led a shift to more learner-centered approaches, usually taking advantages of educational systems [1], [2]. Within a broad range of these kind of systems, adaptive approaches have received considerable attention in recent years [3]. Adaptive approaches refer to techniques that allow software systems to dynamically change their system behavior according to the feedback received from the environment. In educational contexts, these techniques help educational systems to tailor the provided content for the students' needs, interests, goals and background [2], [4]. The adaptive approaches often take advantage of several services to achieve adaptation; for example, the learner context [5], performance assessment [6], and feeling evaluation [7].

In this context, adaptive approaches have been included by many Virtual Learning Environments (VLEs). In fact, there have been several literature reviews on adaptive VLEs studying their advantages and disadvantages. Some of them review personalized information retrieval techniques [8], and hypermedia methods [5]. These reviews have shown promising results of adaptive VLEs in different educational settings, yet with several limitations. Some examples of these are the frequent use of small-scale applications, the use of small samples of students to assess these environments and their ill-defined learning outcomes. Furthermore, these reviews only concentrate on systems in which learners mainly interact with 2D environments such as hypermedia websites or 2D games, neglecting other environments that use more advanced technologies to provide new learning experiences.

Three-Dimensional VLEs are an example of such environments since they allow learners to have 3D-inmersive experiences. These 3D VLEs not only show educational 3D-contents to the learners but also give them the chance to have a 3D representation, explore the 3D environment and interact with it [9]. These features make possible to offer unique environments that provide several benefits to learning such as keeping learners highly motivated and engaged as well as providing useful learning experiences through simulations and intuitive spatial awareness of their location and actions [10], [11], [12], [13]. Moreover, several environments have also implemented adaptive features providing even more personalized learning approaches. Surprisingly, none of the review papers on the field have completely devoted to Adaptive 3D VLEs or their respective applications for learning. Thus, a review that provides understanding on how these adaptive 3D environments contribute to learning is still lacking.

To deal with this issue, we analyze different 3D VLEs and their approaches to include adaptive features. Thus, we describe how the Adaptive 3D VLEs can benefit learning by analyzing three important adaptive factors [1], [14]: defining the learner model, the instructional strategies, and the adaptation mechanisms. Moreover, we analyze the assessment of Adaptive 3D VLEs studying the learning outcomes, the target students for whom these environments are designed,

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and the domain explored by them. We also discuss future directions and open-ended issues to provide stimulation on the field. Findings show that adaptive 3D VLEs have used approaches based on both explicit and implicit data collection to build the learner model, being simulations and interactive 3D objects the most used ones for instructional strategies. Furthermore, these environments have afforded several features that potentially contribute to learning such as increasing the learners' motivation, enhancing the spatial knowledge representation, and allowing learners to experience impractical tasks; however, collaborative features in Adaptive 3D VLEs have been less explored. Finally, regarding the assessment of these environments, nearly half of the environments have addressed thorough assessments whereas the rest has not reported any evaluation at all.

We organize this paper as follows. In the next section, we show the methods applied for the analysis. Section three reviews the articles on adaptive 3D VLEs. Section four presents the discussion and future lines of work. Finally, in the last section, we show a conclusion on this review.

2 METHODS

The purpose of this article is to review critically the literature that reports on the use of adaptive 3D VLEs, focusing not only on critical factors of these environments but also on the quality of the learning outcomes obtained. To achieve this, we follow the Systematic Review methodology, a research methodology widely used in many fields and in software engineering in particular [15]. The methodology allows for identifying, analyzing and interpreting any available evidence related to a specific topic of interest. Furthermore, this kind of review is useful for collecting and summarizing the evidence related to the topic as well as identifying gaps in current research.

Following the guidelines suggested by Kitchenham [15], we firstly define the search strategy. It consists in retrieving the publications from commonly-used digital libraries including Google Scholar, Science Direct, SpringerLink, Eric, JSTOR and IEEE Xplore. We have searched for keywords such as “adaptive 3D”, “adaptive 3D virtual environment”, “adaptive 3D virtual learning environment”, “three-dimensional personalized learning environment”, “personalized educational simulation”, “personalized game”, and “adaptive game”. We have also included searches on the authors and the citations of the relevant papers to find related works on adaptive 3D VLEs. It is worth noting that we have discarded publications having neither 3D nor adaptive features. Thus, we analyze 3D educational environments with adaptive features implemented in several ways; for example, they can be built as desktop applications or even web systems that project 3D onto 2D media.

Secondly, we explain the purpose of the review. This review aims at expanding the literature in several ways. First, as most part of the current research have focused only in 2D systems, the primary objective of this paper is to analyze the current research on adaptive VLEs that include 3D features. Second, we address three adaptive factors typically observed in these environments [14], [16], including the learner modeling, the instructional methods and the adaptation mechanisms. The importance of these factors is that they have an impact on the students' learning experiences as well as the potential learning contributions provided by the environments [11]. Third, we aim to assess the quality of the results obtained by adaptive 3D VLEs when they are used in educational settings. In this context, this review attempts to shed some shed light on the following research questions:

RQ1: What methods and techniques are used by adaptive 3D VLEs to address the typical adaptation issues?

RQ2: What learning features are more frequently provided by adaptive 3D VLEs?

RQ3: What is the quality of the assessments of adaptive 3D VLEs when used in educational settings?

Thirdly, we decide to use the following data extraction strategy to answer the previous research questions. We extracted the data according to a set of categories defined both deductively and inductively. According to [17], the deductive approach refers to the use of some categorical scheme suggested by a theoretical perspective. On the other hand, the inductive approach allows researchers to identify meaningful categories by using their own criteria, which is influenced by their previous experiences and the knowledge on the field. Figure 1 shows the complete list of the categories used in this review. The ones defined deductively are shown in italics whereas the remaining ones derived inductively are not italicized. In the next subsections, we explain both the adaptive and the assessment factors considered in detail.

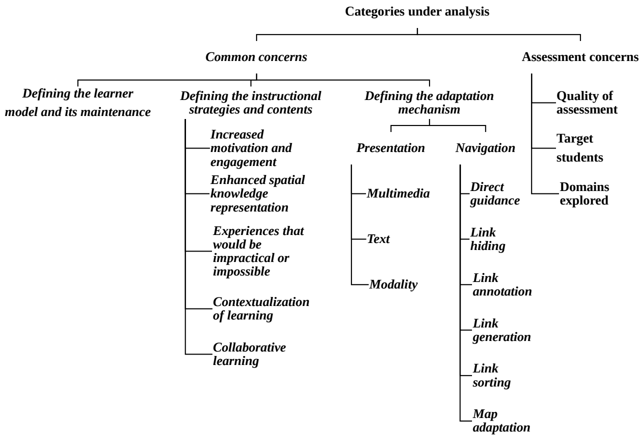

Figure 1. The categories considered in the present review.

2.1 Adaptive factors

Among the theoretically defined categories, some adaptive factors can be clearly identified in most adaptive educational systems [1], [14], [18]. As Adaptive 3D VLEs can be considered as adaptive educational systems, these factors are crucial for allowing the system to target the specific needs of each learner separately. Thus, we considered the following as main categories:

2.1.1 Defining the learner model and its maintenance

It involves any issues related to identifying, representing and updating the information of the learner, also known

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as the learner model. This model is considered to be as crucial since it is the main source used by adaptive systems to achieve the personalization of the learning. Thus, we analyze this factor according to the approaches used for collecting, maintaining and conforming the learning model [14], [19]:

- *Explicit approach:* this category refers to the variables in the learner model that have been collected using explicit approaches; that is, by directly eliciting data from the learner. For example, obtaining the student's level of knowledge on a given topic using an online test is an explicit approach. Possible values in this category can be *the level of knowledge* or another *phychophysiological index.*
- *Implicit approach:* this category defines the variables that have been collected using implicit approaches; that is, by observing the learners' tasks or actions in the environment so as to update the variables in a transparent way. The values in this category include *user interaction, level of knowledge,* and *social interaction,* among others.
- *Maintenance*: this refers to how to collect or update the data of the learner model to avoid a static learner profile. Under this category, we consider several mechanisms such as the use of User Interface agents that allow for collecting and updating the learner's model, the use of specific components built with special hardware, and the use of speech detection and recognition using Natural Language Processing (NLP) techniques. We label these mechanisms for the maintenance of the learner's model as *monitor agents*, *hardware components*, and *NLP techniques*.
- *Learner modeling:* in this category, we study the mechanisms used to represent the essential information of the learner. These mechanisms have a crucial role in adaptive environments since they behave differently according to such model. It usually represents many types of information collected by explicit and/or implicit approaches such as level of knowledge, background, user interaction, and individual traits. As these types are of different nature, they can be modeled in different ways by means of several techniques. Therefore, we relied on current literature to study the following student model mechanisms [20], [21]:
    - *Stereotype:* it is one of the oldest approaches to user modeling, but it is still used in adaptive environments. The approach attempts to cluster learners into several groups (stereotypes) according to some criteria; for example, according to a predefined stage in the system (level 1, level 2, level 3). Then, adaptive environments that use stereotypes consider all the users that belong to the same stereotype as equal, providing the same adaptive effect to each learner in the stereotype. Since these stereotypes are used as a whole, achieving the adaptation in the environment becomes simpler; however, stereotypes neglect learner features that can support a more fine-grained adaptation.
    - *Feature-based:* this approach attempts to model specific features of individual learners such as knowledge, interests, and goals. It is more dynamic since the approach considers that these features may change during the learner's interaction with the environment. In this sense, the main purpose of feature-based models is to track and represent an up-to-date state of the modeled features. Hence, by considering features in a fine-grained way, the adaptive effect can be more suitable for learners since it becomes less-generalized. Regarding how to model the information in feature-based approaches, there are several techniques such as the *overlay* approach, the use of *weighted vectors* and the *goal/task catalogs*.
    - *Overlay:* in this approach, the adaptive environments take into account the expert's knowledge, usually representing it with a domain model. On the other hand, the learner's knowledge is regarded as a subset of the expert's knowledge so that the learner's knowledge is described through the knowledge of the expert. Therefore, the domain model is crucial for the overlay approach since it represents the knowledge in a structured way by decomposing the entire body of knowledge into a set of elements. These smaller pieces of knowledge allow for a more fine-grained adaptation that may provide learners with more personalized experiences. The overlay approach is one of the most popular ones in the contexts of adaptive educational systems [20], and even there are even generalized overlay models that allow for modeling user features beyond knowledge.
    - *Weighted vectors:* this approach has mainly focused on modeling user interests and has been used by pioneer adaptive educational systems. In this approach, the predominant representation of user interests is the weighted vector of keywords. That is, the learner's interests are stored in a vector that has information about how important are each of these are for the learner. Having this information, the environment can match actions with the learner's interests and behave according to them.
    - *Goal/task catalog*: The learner's current goal is usually modeled with a goal catalog approach, which is similar to the overlay modeling. The main difference with this approach is a predefined catalog of possible user goals or tasks that the system can recognize. This catalog is often a small set of independent goals, yet some systems use a more advanced catalog in the form of a goal or task hierarchy. This way, the adaptive environments can recognize the goals and mark them as the current ones in the model. This allows the environment to fire

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the adaptation rules that refer to possible user goals specified in the catalog.

2.1.2 Defining the instructional strategies and contents

It involves selecting suitable strategies for the contents to be taught on the adaptive 3D VLEs. These strategies are relevant for them to determine the learning experience achieved by the learner. Moreover, these strategies and contents along with 3D features can enhance the learning in a unique way different from other learning environments. To include these potential learning benefits into the analysis, we consider the five potential learning features of 3D VLEs defined by Dalgarno & Lee [11]. To evaluate whether a study meets or not each of the learning features, a feature-related question is asked for each of them.

- *Increased motivation and engagement.* Have the authors of the adaptive 3D VLE reported any increase of the learner's motivation or engagement?
- *Experiences that would be impractical or impossible.* Does the adaptive 3D VLE allow students for doing any learning task which otherwise would be impractical or impossible in the real word?
- *Enhanced spatial knowledge representation.* Can the adaptive 3D VLEs enhance the spatial knowledge representation of the explored domain to facilitate any learning task?
- *Contextualization of learning.* Have the adaptive 3D VLE reported any improvement on the transfer of knowledge and skills through the contextualization of learning?
- *Collaborative learning.* Does the adaptive 3D VLE have any collaborative learning feature?

Furthermore, we focus on the instructional strategy as another important feature of adaptive 3D VLEs. In fact, the strategy, goals, and contents delivered to the learners are the key elements that distinguish learning environments from others, making them meaningful and adequate for learning purposes [14], [16]. Thus, we analyze:

- *Instructional strategy:* this category defines the possible instructional strategies used in adaptive 3D VLEs. These strategies refer to the method used by the environment for achieving the learning objectives pursued by the 3D VLEs. For instance, these objectives could be the teaching of some topic on science or the training on a particular specific skill. These strategies are critical in any educational system, and it is important that they are also motivating and engaging. Thus, the definition of the teaching strategy comprises determining both the teaching goals and the most suitable method to achieve them according to the learners' characteristics. Possible values in this category include *game-based, simulation-based,* and *exploratory learning*, among others.
- *Contents*: the contents in the course are also critical for the instructional strategy; thus, they have to be defined accordingly to the strategy. For this reason, we include this category to refer to the kind of content delivered by the adaptive 3D VLE such as *interactive 3D objects* or *2D objects.*

2.1.3 Defining the adaptation mechanisms

It involves the techniques used by the environments to adapt themselves according to the learner model and the instructional strategies. Although the two latter ones are closely related to the resulting learning experience, the adaptation mechanisms are also responsible for it. Thus, we analyze what mechanisms have been included in these environments to achieve the adaptation. Moreover, we match these mechanisms against a taxonomy defined by Brusilovsky [19]. It is worth noting that this taxonomy has its roots on hypermedia systems; nevertheless, as it has been shown by Hughes [22], it is possible to use the same taxonomy for 3D environments. The categories are:

- *Presentation*: this category refers to three possible ways of presenting contents to the user (i.e. the learner): *multimedia* and *text*.
- *Navigation*: this category defines the main strategy to adapt the navigation of the user (i.e. the learner) in the environment. Possible values in this category include *direct guidance to the user, hiding/disabling/removing, highlighting, generating,* and *sorting* objects on the scene.

2.2 Assessment Factors

In the field of Adaptive 3D VLEs, the assessment of the environments is typically made by empirical studies. This kind of studies allows researchers to assess the environments and verify their effectiveness on the learning of particular skills or the training on specific domains. The type of students that take part in the assessment of the environments is assumed to be of the same type of students for which these environments are designed for, and these types usually vary according to the domain of knowledge explored. For example, adaptive 3D VLEs designed to introduce elementary biology usually assist students in primary education whereas those providing military training usually consider adults as their target users. In this context, we analyze the quality of assessment of such empirical studies by considering the following factors:

2.2.1 Quality assessment

We determine the quality of the assessment of each study by taking into account a set of criteria. This set is based on quality standards that have been defined by the NIH in the U.S.[1] and the EPHPP in Canada[2] for carrying out quality assessments on other fields [23], [24]. Therefore, we analyze the following components:

- *The Outcome of Interest:* first, we analyze whether researchers have carried out some evaluation on the Adaptive 3D VLE that they propose. Additionally, we classify publications according to the kind of evaluation sought by researchers. For instance, we consider whether researchers seek learning outcomes, students' perception of learning, or the usability of the environment.

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[1] National Heart, Lung, and Blood Institute - https://www.nhlbi.nih.gov/

[2] Effective Public Health Practice Project - http://www.ephpp.ca/

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- *Selection Bias:* we study whether participants are representative of the target population for what the environment have been designed for. Then, we labeled the publications according to how they have selected the participants. We consider three cases: participants randomly selected from a comprehensive list of individuals in the target population; participants referred from a source (e.g. a particular course) in a systematic way; and participants self-referred (e.g. volunteers). Additionally, we study the proportion of individuals that agreed to participate in each study.
- *Study Design:* this component assesses the bias according to the allocation process in an experimental study. Generally, the type of design is a good indicator of the bias. In less-biased designs, a control group is present and the allocation process is such that the researchers are unable to predict the sequence. The types of design considered are:
  - Randomized Controlled Trial: in this design researchers randomly allocate eligible people to an intervention or control group.
  - Controlled Clinical Trial: the method of allocating subjects to intervention or control groups is transparent before assignment (e.g. an open list of random numbers or allocation by date of birth). It is also open to individuals responsible for providing the intervention.
  - Cohort analytic: groups are assembled according to whether or not exposure to the intervention has occurred; both groups also receiving pre and post tests.
  - Case Study: researchers define "cases" of people who already have the outcome of interest and "control groups" who do not; both groups are then questioned or their records examined about whether they received the intervention.
- *Confounders:* by definition, a confounder is a variable that is associated with the intervention and causally related to the outcome of interest. Examples of confounders are race, sex, age, education, and pre-intervention score on outcome measure. Even in a robust study design, groups may not be balanced with respect to important variables before the intervention. In this sense, researchers should indicate whether confounders were controlled in the design or in the analysis.
- *Blinding:* we study whether subjects in the study are aware of the research question. We include into the analysis not only the outcome assessors but also the study participants. The purpose of blinding the outcome assessors is to protect against detection bias. On the other hand, the purpose of blinding the participants is to protect against reporting bias.
- *Data Collection Methods:* the instruments for primary outcome measures should be described as reliable and valid. Commonly, reliability and validity of instruments are reported in the same study or in a separate one.
- *Withdrawals and drop-outs:* this component refers to the percentage of subjects remaining in the study until the final data collection period. Researchers should report both the numbers and reasons for withdrawals and drop-outs.
- *Intervention Integrity:* we study the number of participants receiving the intended intervention in the study, considering both frequency and intensity. The frequency refers to the percentage of the participants who receive the complete intervention. On the other hand, the intensity refers to the method for measuring whether the intervention is provided to all participants the same way. Moreover, researchers should indicate whether subjects receive an unintended intervention that may influence the outcomes.
- *Analysis:* we study whether the quantitative analysis is appropriate or not. In this sense, we take into account the unit of allocation, the unit of analysis and whether the statistical methods are suitable for those units.

2.2.2 Target students

This category defines the stage of education of the target students. This stages includes *primary education*, *higher education*, or *all the stages of education* for those environments designed to be used in any of them: primary or higher education.

2.2.3 Domains explored

This category refers to the domains explored by the reviewed adaptive 3D VLEs. Possible values in this category could be *topics on science (e.g. biology, physics, and astronomy)*, *topics on engineering*, *art*, and *language learning*, among others.

3 FINDINGS

In this review, we consider a total number of 43 studies from the 2000-2014 period. Figure 2 shows the growth of publications on adaptive 3D VLEs in the period. The bar chart allows for distinguishing the total annual number of studies through the height of each bar. As shown in the chart, the first publications on adaptive 3D VLEs came out between 2000 and 2002 with Chittaro and Ranon's articles [25], [26]. In the following years, the total number of publications increased to remain stable between 2004 and 2008, with around 4 of them being published per year. In 2009 this number went down, but then picked up in the following years. In fact, 50% of the studies came out in the last four years (2010-2014) and the number of journal articles published in the same period is greater than in the past. Additionally, by drawing a simple line of best fit over the total number of publications, their linear trend can be clearly observed in Figure 2. Thus, the number of scientific publications on adaptive 3D VLEs is likely to continue growing in the future.

3.1 Findings on adaptive factors

We analyze how the reviewed adaptive 3D VLEs have addressed the adaptive factors of adaptive educational systems in this section. These steps include *defining the learner model definition and its maintenance, defining the instructional strategies and contents,* and *defining the adaptive mechanisms.*

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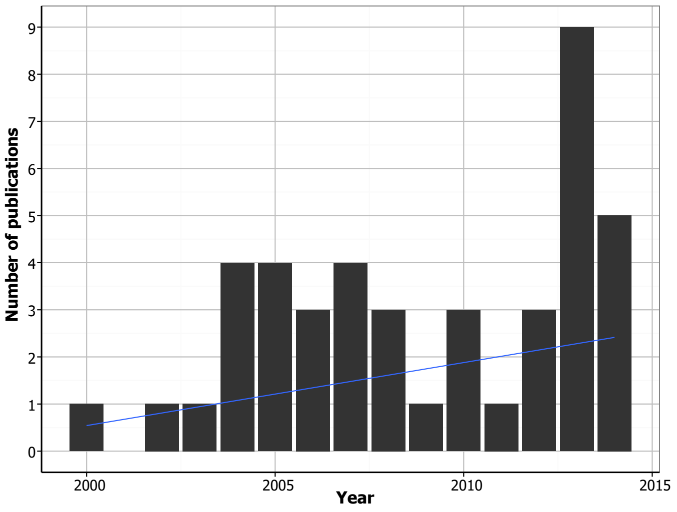

Figure 2. Growth trend of publications on adaptive 3D VLEs.

3.1.1 Defining the learner model definition and its maintenance

As we mentioned before, the variables defining the learner model can be collected using *explicit* or *implicit* approaches according to their nature. Table 1 shows the use of these approaches for defining the learner model in the analyzed publications. The *explicit approach* has been used in 9 publications (20.93%) to build the learner's model [25], [27], [28], [29], [30], [31], [32], [33], [34]. Among these publications, *psychophysiological indexes* to measure psychological constructs have been introduced by 2 studies (22.22%); such constructs are the learner's spatial ability [33] and stress [34]. In the same line, the learner's model have been defined by using *learning styles* in 2 publications (22.22%) [31], [32]. Additionally, several adaptive 3D VLEs have explored the *explicit approach* by collecting *general learner's data* such as gender, age, learner's interests, and feedback (4 publications; 44.44%) [25], [27], [28], [29]. The *learner's background knowledge* has also been explored by several authors (2 publications; 22.22%) [29], [30]. As an advantage, the *explicit approach* allows for collecting many reliable data from the user such as complex psychological constructs by using instruments and questionnaires. However, using only this approach, the model could become difficult to maintain and update.

On the other hand, 29 studies (67.44%) have implemented the *implicit approach*. Among them, 20 (68.97%) have used the *learner's behaviors and interactions* to build the learner's model relying on the pioneering adaptive hypermedia systems [25], [26], [27], [28], [30], [31], [32], [33], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46]. Moreover, some authors have explored adaptation based on *speech detection and analysis* by adapting the 3D VLEs according to learner's talk and actions (2 publications; 6.90%) [47], [48]. An interesting work (3.45%) [49] presents an environment that performs its adaptation according to physical gestures, eye tracking, and engagement detection; while another author has used information on the interaction of learners in *social networks* (1 publication; 3.45%) [50]. The learner's *knowledge level* has also been used to build the learner's model in several adaptive 3D VLEs (5 publications; 17.24%) [42], [43], [44], [45], [51], [52], [53]. Thus, this approach allows for the implicit collection of several learner's characteristics by using data from the 3D environment, although some psychological constructs that have been explicitly collected such as the learner's spatial ability [33], and *learning styles* [31], [32], [51], [52], [53] are disregarded.

Both *explicit* and *implicit* approaches commonly complement one another in a large proportion of the reviewed environments (15 publications; 34.88%) [25], [27], [28], [29], [30], [31], [32], [33], [54], [55], [56], [57], [58], [59], [60], yet they frequently use only one of them to collect the learner model. In fact, most of the publications (22 publications; 69.77%) [26], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [48], [49], [50], [51], [52], [53], [61], [62] use only the *implicit* approach whereas there are no studies that use only the *explicit* approach. Therefore, both methods allow for collecting several variables that can enrich the learner's model and achieve different results of adaptation. For this reason, it is important to bear in mind what kind of variables should be collected to achieve a suitable adaptation effect in an educational context. However, the more comprehensive the learner's model definition is, the more complex their maintenance and updating becomes. In this sense, as both approaches could record a great amount of data, there is a need of exploring ways not only to detect the model for the first time but also to keep the model updated.

Regarding the maintenance of the learner's model, a frequently used technique in these 3D environments is to have user interface agents monitoring the specific learners' interactions as well as recording the data in the model (3 publications; 6.97%) [27], [41], [45]. Other authors have used specific *hardware components* of their own design to obtain learner's measures that are impossible to collect by using software. For instance, Parsons and Reinebold have used this kind of hardware components to obtain the current cognitive state of the learner based on psychophysiological signals and task performance (1 publication; 3.45%) [34]. Moreover, another study (3.45%) [10] have delegated the maintenance of the model on *third-party software components* from platforms such as AHA! (1 publication; 3.45%) [63], while *Natural Language Processing techniques* are also being used among adaptive 3D VLEs capable of doing speech recognition and synthesis (2 publication; 6.90%) [48], [62].

Finally, we analyze the learner modeling mechanisms that allow for the selection of the instructional strategies and the modification of the domain contents. Figure 3 shows our findings. The most used approach for learner modeling is the *feature-based* one (19 publications; 44.18%) whereas the *stereotype* approach is another frequently used approach (9 publications; 20.93%) [25], [30], [33], [35], [39], [40], [41], [52], [59]. Among the *feature-based* approaches, adaptive 3D VLEs have used several techniques such as *overlay models* (8 publications; 18.60%) [28], [29], [34], [36], [37], [44], [47], [48], *weighted vectors* (3 publications; 6.97%) [26], [31], [46], and *goal/task catalogs* (7 publications; 16.27%) [32], [43], [45], [49], [51], [53], [57]. Surprisingly, only 1 publication (2.32%) [27] has reported the use of a combined approach mixing both the stereotype for avoiding the cold start problem and the weighted-vectors one to retrieve appropriate feedback.

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On the other hand, 15 publications (15.34%) [38], [42], [50], [54], [55], [56], [57], [58], [60], [61], [64], [65], [66], [67], [68] do not provide enough information to determine the learner modeling approach that they have used.

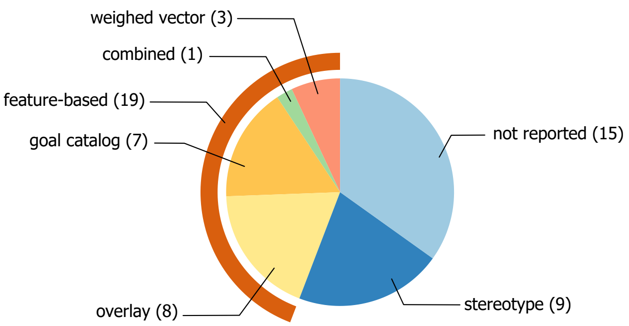

Figure 3. User modeling mechanisms on Adaptive 3D VLEs.

Taken together, all the aforementioned adaptive 3D VLEs revised from the literature have addressed both the definition of a learner model and its maintenance. In addition, it is important to know how the learner model relates to the adaptive effect achieved since the 3D VLE usually adapts itself according to the attributes in the model. This adaptation is performed by accommodating the 3D environment with educational contents delivered by different instructional strategies. We describe these strategies and contents in the following section.

Table 1
Distribution of the learner model definition approaches on Adaptive 3D VLEs.

Approach to collect the data	Attributes	*f*	%
Implicit		*29*	*67.44*
	user interaction	20	68.97
	level of knowledge	5	17.24
	general data	2	6.90
	talk and speech	2	6.90
	physiological data	1	3.45
	social interaction	1	3.45
Explicit		*9*	*20.93*
	general data	4	44.44
	level of knowledge	2	22.22
	learning styles	2	22.22
	phychophysiological indexes	2	22.22
Explicit and Implicit		*15*	*34.88*
Not reported		*6*	*13.95*
Total number of publications		43	100

3.1.2 Defining the instructional strategies and contents

Similarly to the learner's model, the instructional strategy used is critical for providing learners with successful learning experiences [14], [16]. In this sense, Adaptive 3D VLEs have used many instructional strategies, often simultaneously in the same environment as a complementary way. As Table 2 shows, from out of 43 publications, the use of *simulations* can be considered as the most used strategy to provide a contextualized learning in some domains such as physics and military training (9 publications; 20.93%) [32], [34], [38], [40], [44], [48], [52], [61], [65]. These real-world-like environments allow learners to learn concepts and train skills while exploring them. Other adaptive 3D VLEs have mainly focused on providing *skills development* (6 publications; 13.95%) [34], [38], [40], [49], [52], [61]. Moreover, strategies based on *game-based learning* have also been used for learning purposes in adaptive 3D VLEs (6 publications; 13.95%) [31], [32], [43], [51], [53], [61]. In 4 publications (9.30%) [39], [52], [65], [67], the authors claim that learning arises in an *exploratory* way, through the interaction and exploration of the environment. That is, there are no rules limiting the interactions and no need to achieve any goal or score in particular. Other authors have provided authoring tools allowing instructors to create their own instructional strategies for the environment; thus, the Adaptive 3D VLEs use *instructor defined* strategies (6 publications; 13.95%) [29], [57], [58], [59], [60], [66]. Furthermore, some publications have based their strategies on *tailoring feedback* messages according to the learners' actions (3 publications; 6.98%) [27], [54], [62], while others have proposed the use of interaction and explanation using *virtual tutors* such as 3D Non-Player Characters (NPC) (2 publications; 4.65%) [56], [58]. In addition, others ones have based their strategies on *demonstrations*, providing simple mechanisms based on demonstrations to show how some tasks should be done (2 publications; 4.65%) [34], [39]. Finally, the remaining publications have not reported the use of any instructional strategy (16 publications; 37.21%).

Focusing on the contents managed by adaptive 3D VLEs and how they are presented to the learner, publications have reported the benefits of interactive *3D objects* (28 publications; 65.12%) [29], [30], [32], [33], [34], [35], [36], [37], [39], [40], [43], [44], [45], [48], [49], [54], [55], [56], [57], [58], [59], [60], [62], [67]. Some others use *2D objects* for achieving a representation of content that serves as a complement for a 3D object. That is, the authors have used text, images, or videos inside the environment (7 publications; 16.28%) [29], [31], [33], [50], [54], [55], [62]. Regarding authoring tools, they usually provide mechanisms to link the contents to scenes according to the instructor's design. Out of 43 publications, nearly half of them do not mention how they represent the educational contents inside their adaptive 3D VLEs (19 publications; 44.19%).

As explained in section 2, useful learning experiences in 3D environments are the result of not only using suitable strategies but also exploiting potential learning features of 3D VLEs [11]. As shown in Table 3, most Adaptive 3D VLEs can achieve at least one of the features presented by Dalgarno & Lee or even many of them simultaneously. In particular, the feature *increased intrinsic motivation and engagement* is present in 23 adaptive 3D VLEs (53.49%) [27], [28], [34], [35], [41], [44], [45], [47], [48], [49], [54], [56], [62]. Regarding *enhanced spatial knowledge representation* with 3D objects, most of the publications reflected an improvement for learners to accomplish their tasks (22 publications; 51.16%) [33], [34], [40], [47], [48], [49], [62]. Furthermore, *experiencing impractical, unsafe or even impossible situations that could not be possible in either the real world or a hypermedia context* is another feature present in 13 publications

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(30.23%) [33], [34], [40], [47], [48], [49], [62]. The Adaptive 3D VLEs also give the learners the possibility of performing their learning tasks in the same context in which they are expected to be applied, that is, in a 3D model of the real world. This feature is also known as *contextualization of learning* and is achieved by 11 studies (25.58%) [34], [35], [36], [40], [47], [49], [62]. Although most features are covered by adaptive 3D VLEs, it is worth noting that *collaborative learning* has been disregarded since only two works (4.65%) has allowed learners to perform their tasks collaboratively [48], [50]. Regarding the authoring tools, the frameworks that support them [29], [55], [57], [58], [59], [60] have also allowed for the building of adaptive 3D VLEs bearing all the potential learning features introduced by [11]. However, to achieve them using authoring tools will depend on the instructor's design and creativity.

This section has reported on different instructional strategies as well as means to deliver the contents to the learners in the context of adaptive 3D VLEs. The following section moves on to consider the mechanisms to achieve the adaptation of 3D VLEs, using different approaches. These approaches take into account not only the learner's model but also the instructional strategies and contents, in which the latter are to comply with the former using an adaptation mechanism.

Table 2
Instructional strategies and contents delivered by adaptive 3D VLEs.

Instructional strategies and contents	*f*	%
Instructional strategy		
Simulation	9	20.93
Game-based learning	6	13.95
Instructor defined	6	13.95
Skills development	6	13.95
Exploratory	4	9.30
Tailoring feedback messages	3	6.98
Virtual tutors	2	4.65
Demonstrations	2	4.65
Not reported	16	37.21
Contents		
Interactive 3D objects	29	67.44
2D features	7	16.28
Not reported	19	44.19
Total number of publications	43	100

Table 3
Features achieved by Adaptive 3D VLEs.

Feature	*f*	%
Increased intrinsic motivation and engagement	23	53.49
Enhanced spatial knowledge representation	22	51.16
Experiencing impractical, unsafe or even impossible situations	13	30.23
Contextualization of learning	11	25.58
Collaborative learning	2	4.65
Total number of publications	43	100

3.1.3 Defining the adaptive mechanism

The adaptive mechanism in an adaptive educational system determines the adaptive effect and is the main responsible for customizing the environment in the best way possible for the learner. In literature, various approaches have been proposed to solve these issues and build effective mechanisms on adaptive 3D VLEs. For example, some studies have addressed adaptation issues by supporting 3D presentations with a well-known architecture such as AHA! [63] In adaptive environments based on AHA!, the mechanisms are provided by components determining the best adaptation for the student using adaptation rules, a user model and a conceptual model (2 publications; 4.65%) [35], [36]. The pipe-based architecture is another one that has been used in the design of adaptive 3D VLEs (1 publication; 2.32%) [33]. However, it is worth noting that most of the surveyed adaptive 3D VLEs have isolated different concerns into components.

These components usually implement conventional or AI-based techniques. Table 4 shows the distribution of these techniques on the reviewed adaptive 3D VLEs. Both kinds of techniques are meant to customize the environmental details in the 3D VLEs according to the learner's model. In particular, some authors have adapted each scene of the environment by adding or removing 3D learning objects (4 publications; 9.30 %) [35], [36], [39], [40]. For instance, Schartz et al. [40] use tailoring strategies for adjusting the environment by modifying several entities and their behaviors to reveal more or less information to the learners. This way, they are trained in analyzing the cues present in different scenarios to detect anomalies in the environment.

Nevertheless, adaptive systems are always aware of the learner's model by performing the adaptation using the learners' attributes. These range from simple data such as gender, age, and interest to more complex ones such as psychophysiological affective measures [49]. Another interesting approach that focuses on tactical language learning uses an adaptive hypertext glossary showing the vocabulary and grammar structures in each lesson (2 publications; 4.65%) [47], [62]. In recent years, research has also tended to focus on the use of AI techniques rather than conventional ones to customize the environmental details in the 3D VLEs according to the learner's model. In this context, the *rule-based* approach continues to be one of the most used ones [47], [62] (10 publications; 23.26%), whereas *classification* techniques are also used as the core of the adaptive mechanism [34], [39], [44] (4 publications; 9.30%). Others authors also use more than one AI technique, such as *clustering* and other machine learning approaches together to achieve the prediction of *feedback messages* [27], [46] (2 publications; 4.65%).

Furthermore, more specific AI techniques are also being used by adaptive 3D VLEs such as *intelligent agents* (3 publications; 6.98%), *ontologies* [39] (2 publications; 4.65%), *decision trees* [28] (1 publication; 2.33%), and particular *algorithms* such as MinMax [48] (2 publications; 4.65%). *Probabilistic methods* have also been used for adapting these environments in 3 publications (6.98%), whereas authoring tools have done so by basing on *narrative theory* (9 publications; 20.93%). Hence, it can be noted that most of the techniques implement either conventional or AI-supported adaptation strategies; furthermore, they often use 3D scenes as stories within a narrative to complement such strategies. In fact, the difference between traditional games and virtual learning

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environments lies in that the latter bear a narrative not only pursuing a learning objective but also providing the system with educational features. Along this line, authoring tools are often based on the narrative theory [69], allowing adaptive 3D VLE designers to create their own adaptation rules by defining a storyline [29], [55], [57], [58], [59].

The wide range of approaches aforementioned can be arranged into a taxonomy categorizing several adaptation mechanisms [19]. Although this taxonomy is specifically designed for adaptive hypermedia approaches, Hughes et al. [22] have explored the similarities between hypermedia approaches in the Brusilovsky's taxonomy and 3D VLE approaches. As a result, Hughes et al. highlight several adaptive techniques derived from hypermedia that are commonly used to achieve the adaptation in 3D environments. For this reason, we decide to include the taxonomy in the coding scheme to perform the analysis. Table 5 shows the taxonomy and the distribution of the adaptive mechanisms used in the publications. The most common techniques are the use of multimedia for learning objects (20 publications; 46.51%) [28], [29], [33], [34], [36], [39], [40], [44], [45], [46], [48], [58]; the use of *canned text* in 3D environments, such as labels and information panels (16 publications; 37.21%) [28], [35], [41], [44], [45], [47], [62]; and the processing of *natural language* in the environment, for both their recognition and synthesizing (4 publications; 9.30%) [27], [28], [48], [49]. Moreover, most adaptive 3D VLEs offer a *direct guidance* that walks the learner through the scene according to their model (25 publications; 58.14%) [27], [28], [34], [35], [41], [46], [47], [48], [49], [54], [55], [56], [57], [58], [59], [60], [62]. Many approaches address this guidance by means of *hiding* (15 publications; 34.88%) [28], [29], [34], [39], [40], [46], [59], [60], *sorting* (1 publication; 2.33%) [44], *generating* (2 publications; 4.65%) [28], [33], and *highlighting* (3 publications; 6.98%) [29] 3D objects in the scene.

All the approaches mentioned above suggest that different adaptation mechanisms can achieve many and meaningful results. These mechanisms implement several techniques in 3D environments ranging from simple ones such as rule-based adaptation to AI approaches. Thus, it is clear that the previous adaptive 3D VLEs have had to consider the learner's model to perform their adaptation of the instructional strategy and contents to be delivered.

Table 4
Adaptation techniques implemented in adaptive 3D VLEs.

Adaptation technique	*f*	%
Rule-based	10	23.26
Narrative theory	9	20.93
Classification	4	9.30
Agents	3	6.98
Probabilistic method	3	6.98
Algorithm	2	4.65
Clustering and machine learning	2	4.65
Ontologies	2	4.65
Decission trees	1	2.33
Not reported	10	23.26
Total number of publications	43	100

Table 5
Adaptation mechanisms implemented by adaptive 3D VLEs.

Adaptation mechanisms according to the Brusilovsky's taxonomy	*f*	%
Presentation		
Multimedia	20	46.51
Text		
Canned text	16	37.21
Natural language	4	9.30
Navigation		
Direct guidance	25	58.14
Link hiding, disabling or removal	15	34.88
Link *highlighting*	3	6.98
Link generation	2	4.65
Link sorting	1	2.33
Total number of publications	43	100

3.2 Findings on assessment factors

In this section, we analyze how the reviewed adaptive 3D VLEs have addressed their assessment. We include in the analysis the *quality assessment*, the *target students*, and the *domains explored*.

3.2.1 Quality assessment

In this section, we analyze the results and methods used to evaluate the reviewed Adaptive 3D VLEs. First, we analyze whether studies report some kind of evaluation; then, we analyze what outcome of interest have been sought by the researchers. Figure 4 shows a pie chart with the findings. Surprisingly, nearly half of the publications have reported the assessment of their proposed environments (19 publications; 44.2%) [28], [30], [32], [34], [37], [40], [42], [43], [44], [47], [48], [50], [52], [53], [54], [57], [58], [59], [68]. Out of them, 7 (36.8%) [34], [43], [44], [47], [48], [52], [53] have sought learning outcomes, 15 (78.9%) [28], [34], [37], [40], [42], [43], [47], [48], [50], [52], [53], [54], [57], [58], [59], [68] students' perceptions of learning, and 6 (31.57%) [34], [43], [48], [52], [53], [62] both of them. Moreover, 3 publications (15.7%) [28], [30], [32] have carried out other assessments such as predictions, examples, and prototypes of the environments. Then, out the total number of publications showing assessment, we analyze the set of criteria defined in Section 2.2.1. Table 6 summarizes the findings.

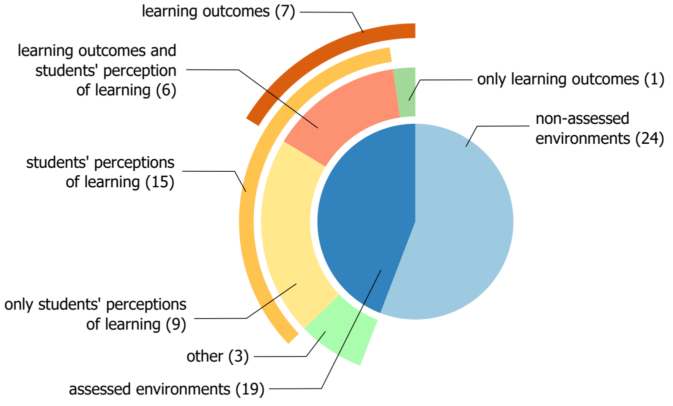

Figure 4. Assessment of Adaptive 3D VLEs and their outcomes of interest.

Regarding the *selection bias*, nearly three-quarters of the studies with assessment (14 publications; 73.7%) [34], [37], [40], [42], [43], [44], [48], [50], [52], [53], [54], [58], [59], [68] have reported participants were students taken from courses whereas 3 publications (15.8%) [28], [30], [57] have not reported any information about the selection criteria. Only 1 publication (5.3%) [47] has reported that participants were randomly selected from the target population, and another study (5.3%) [32] has informed that participants were self-referred. Furthermore, 13 publications (68.4%) [34], [37], [40], [42], [43], [44], [50], [52], [53], [54], [58], [59], [68] have described that most part of the selected individuals (80% to 100% of the individuals) agreed to participate whereas in the remaining ones it is impossible to determine the proportion because of the lack of information.

Once the participants are selected, they are allocated according to some *experimental design*. According to our findings, two designs are the most used ones to assess Adaptive 3D VLEs: *case-control studies [32], [40], [48], [58], [68]* and *controlled clinical trials [34], [47], [50], [53], [59] (5 publications; 26.3%)*. Moreover, authors often use *case-studies without considering any kind of control group* (4 publications; 21.1%) [37], [42], [52], [57] and *prototypes* to show the functionality of the environment (3 publications; 15.8%) [28], [30], [54]. Among the less used designs are the cohort based ones, being the *cohort analytic* and the *simple cohort* reported by 1 publication each (5.3%) [43]. It is also worth noting that only (5 publications; 27.8%) [32], [43], [47], [48], [50] have described the allocation of participants to groups as randomized.

Even in robust study designs, researchers should take care of several issues. For instance, *confounders* variables should be considered in the experiments. In the reviewed studies, nearly half of the publications with assessment have controlled *confounders* (9 publications; 47.4%) [37], [40], [42], [43], [44], [47], [50], [58], [68], either in their design or their analysis, whereas the remaining publications have neglected this kind of variables. The *blinding* in the design is another important issue that could introduce bias. Our findings show that most studies have reported the awareness of the outcome assessors regarding the intervention of the participants (14 publications; 68.4%) [32], [34], [37], [40], [44], [47], [48], [50], [52], [54], [58], [59], [68]; however, 18 publications (94.7%) of the studies have not mentioned whether the participants were aware of the research question. Therefore, only one study (5.3%) [43] has explicitly reported the blinding of participants.

The *data collection* is another important issue for the experimental design. Our findings show that only 4 publications (21.1%) [34], [50], [58], [68] have reported that the instruments used for collecting data were valid, and only 1 publication (5.3%) [34] has shown that they were reliable. Regarding *withdrawals and drop-outs*, most publications have not reported them in terms of numbers and/or reasons per group (13 publications; 68.4%) [28], [32], [37], [40], [42], [43], [44], [50], [52], [53], [54], [58], [59] whereas only 2 publications (10.5%) [47], [68] have described the drop-outs of the experiment. The remaining publications have not provided enough information to determine this issue. Furthermore, considering *intervention integrity* is also important to avoid bias in the experiment. In this sense, 6 publications (31.6%) [34], [43], [44], [47], [50], [53] have reported the number of participants who received full intervention, and only 3 publications (15.8%) [34], [43], [50] have measured the consistency of the intervention.

Finally, we study how researchers have carried out the analysis phase of their results. In this sense, it is important to use the same unit of allocation and unit of analysis. Our findings show that in the reviewed publications these units are always coincident, being university courses (10 publications; 52.6%) [30], [34], [43], [47], [48], [52], [57], [58], [68] and training courses (6 publications; 31.6%) [32], [37], [42], [44], [50], [59] the most used ones whereas 3 publications (15.8%) [28], [40], [54] have reported individual evaluations.

Table 6
Quality assessment of publications on Adaptive 3D VLEs.

Quality Assessment	*f*	%
Selection bias		
participants from a course	14	73.7
participants randomly selected	1	5.3
participants self-referred	1	5.3
criteria not reported	3	15.8
Study design		
case-control studies	5	26.3
controlled clinical trials	5	26.3
case-studies without control groups	4	21.1
case-study (prototype)	3	15.8
cohort analytic	1	5.26
simple cohort	1	5.26
Confounders		
present in the study	9	47.4
not reported	10	52.6
Blinding		
blinding of outcome assessors	14	73.6
blinding of participants	1	5.3
Data collection methods		
valid instruments	4	21.1
reliable instruments	1	5.3
Withdrawals and drop-outs		
reported	2	10.5
insufficient information to determine	17	89.4
Intervention Integrity		
completeness	6	31.6
consistency measurement	3	15.8
Analysis (unit of allocation and analysis)		
university courses	10	52.6
training courses	6	31.6
individual evaluations	3	15.8
Total number of publications with assessment	19	100

3.2.2 Target students

In their assessments, the environments have considered the students in their different stages of education. For this reason, it is also important to know the type of students that adaptive 3D VLEs are designed for. From out of 43 publications, 8 (18.60%) environments are not entirely designed with educational purposes so they were labeled as *N/A* (e.g. e-commerce adaptive 3D environments). About 16 (37.20%) of the adaptive 3D VLEs are designed to be used in *higher education*, whereas 5 (11.62%) of them are used in *primary education*. This difference might lie in the fact that most environments were evaluated using higher education learners. On the other hand, 14 publications (32.55%) have reported that their Adaptive 3D VLEs can be used in *all the stages*

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of education. It is worth noting that all the authoring tools reviewed fall into this category as they can create potentially suitable environments for any of the target students.

3.2.3 Domains Explored

Regarding the domain explored by the reviewed adaptive 3D VLEs, Table 7 shows the findings. These domains were explored using adaptive features not only to provide learning but also to evaluate the environment in the current field of study. Although a variety of domains have been explored, several Adaptive 3D VLEs (7 publications; 16.27%) have been made for providing learning on *engineering topics* such as electrical and mechanical ones, computer architectures and game design, digital logic, and programming. This trend on the creators of the environments could be explained as the result of using their domains of expertise as reference to build their prototypes and evaluate their hypothesis. These domains are also well suited to be represented in 3D environments as well as other ones on *science* such as biological topics and physical processes. In fact, 5 publications (11.62%) describe the use of adaptive 3D VLEs to support the learning of these fields of *science*. Additionally, *Art and Museums* (3 publications; 6.98%) as well as *Language Learning* (2 publications; 4.65%) have also been explored. Another one widely explored is the *e-commerce* field, with 6 publications (13.95%). As these environments have no educational features such as an underlying pedagogy, they cannot be recommended as suitable for learning. Despite this issue, some of these environments allow designers to customize their items and domains for learning. For instance, the items and the final users could become the educational contents and the learners correspondingly. On the other hand, some authoring tools allowing for creating *multi-domain* adaptive 3D VLEs (6 publications; 13.95%) only requires that the instructor models the desired domain. These environments could be powerful educational tools, but as shown by the quality assessment, there is a lack of thorough experiments (i.e. having *good* assessment) to validate their learning outcomes. Finally, out of 43 publications, 6 of them (13.95%) fail to report the domain explored by the environments.

Table 7
The domains explored by the adaptive 3D VLEs.

Domain	*f*	%
Engineering	7	16.27
Multiple domains	6	13.95
E-commerce	6	13.95
Topics on science (biology, physics, optics, astronomy)	5	11.62
Art and Musseums	3	6.98
Language learning (arabic, german)	2	4.65
Simulations of critical situations (emergency simulation, disaster management staff)	2	4.65
Training (military service, naval tasks)	2	4.65
Bussiness and Logistics	2	4.65
Skills improvement (children with ASD)	1	2.33
Physical Activity	1	2.33
Not reported	6	13.95
Total number of publications	43	100

4 DISCUSSION AND FUTURE LINES OF WORK

This review describes current research on adaptive 3D VLEs in the period 2000-2014, focusing on adaptive and assessment factors. Among the adaptive factors we analyze the *learner's model definition and maintenance; the instructional strategy and the content definition;* and *the adaptation mechanisms* that are responsible for delivering the instructional strategy according to the learner's model. Regarding the assessment, we take into account the quality of the assessment, the target students and the domains explored by the adaptive 3D VLEs. The review also aims at highlighting the research perspectives on the field. Although several adaptive 3D environments present promising results, many other open issues should be discussed first.

Regarding the first adaptive factor of adaptive systems, findings revealed that most Adaptive 3D VLEs have applied the same methods and techniques commonly used in hypermedia such as *explicit* and *implicit* approaches for data collection, or even a combination of both. However, only a few of them have been able to enrich the learner's model using features from the 3D environment. It might be done by using techniques such as including variables from the interactions with both 3D objects and their environment. For example, the learner's model could include information about the avatar chosen by the learners, the locations they frequently visited, or the 3D objects with which they prefer to interact with. This issue suggests a future line of work to know what the relationships between the 3D environment features and the learner's profile are. Although some authors have explored how some actions on 3D environments may serve for building a learner model in specific domains [70], more research would be needed to get a better insight of the learners' preferences and behaviors when interacting with 3D environments.

Among the variables usually included into the learner models, Adaptive 3D VLEs have reported the use of individual traits. They include several learner features such as personality traits, cognitive styles and learning styles. Although these traits represent important features to take into account, current approaches for achieving adaptation according to them show several drawbacks. For example, they neglect the use of suitable experimental designs that allow for showing the improvement of the learners' performance when they receive the strategies matching their individual traits [71]. Thus, this study suggests that further research should take into account stronger experimental designs for demonstrating the effectiveness of using individual traits.

Moreover, the learner modeling mechanisms reported by the studies show that feature-based approaches are currently the dominant user modeling approaches in Adaptive 3D VLEs, as occurs in Adaptive Hypermedia Systems. However, the stereotype approach is still used in the field despite their simplicity and their problems to achieve more fine-grained adaptive effects. Regarding the remaining approaches, the overlay and the goal/task catalog are the most used ones as well as the most promising since their have shown great potential for achieving adaptation. It is worth to mention that more than a third of the publications have not reported enough information to determine the learner modeling approach. Thus, this study suggest that learner modeling approaches should be appropriately mentioned in further research.

The learner's model is also linked to the definition of the instructional strategy and the contents delivered by the system. The reviewed adaptive 3D VLEs have implemented many strategies and different means to introduce the contents, being simulations and game-based learning the most used ones. These strategies allow adaptive 3D VLEs to achieve suitable learning experiences in line with pedagogical theories. However, a large number of the environments have not reported any instructional strategy, suggesting that authors have paid more attention to technical issues than pedagogical ones. Having no instructional strategy defined not only have implications on the learning outcomes but also hinder the introduction of the environment in real schools. In this sense, including established strategies is important for teachers since they can gain a better understanding of how to use the environments in the classrooms.

In line with the second research question, findings revealed that 3D VLEs also offer unique learning features that could not be achieved in real, 2D or hypermedia contexts. As the most relevant ones, it is worth mentioning the increased intrinsic motivation and engagement and the enhanced spatial knowledge representation. Surprisingly, there has been little discussion on how to include collaborative features to adaptive 3D VLEs, yet this is a promising feature. Furthermore, there is a lack of studies showing how to create, improve or deliver the syllabus of each subject matter making the most of the 3D features. For some specific domains such as physics, the contents are mainly delivered by using simulations in which phenomena such as velocity and gravity can offer successful learning experiences. In contrast, other domains such as language might require the use of metaphors among other resources to take a real advantage of 3D environments. Thus, this study suggests that more research is needed to clarify these issues.

Regarding the mechanisms to achieve the adaptation of the environment, a wide range of approaches are mentioned. An implication of this is the possibility of grouping the studies in a taxonomy of hypermedia nature, showing how the same techniques can be adapted to be used in 3D environments. Moreover, most of the adaptive 3D VLEs use rule-based, storyline or direct guidance techniques for achieving adaptation. These techniques are probably the easiest to implement with current 3D technologies, yet they have shown promising results. However, it is natural to suggest that new ways to achieve adaptation could also be explored. By doing so, the use of more advanced techniques might allow for more accurate adaptive behaviors. Examples of these techniques are the use of ontologies or case-based reasoning, both of them proving to be effective in hypermedia contexts.

So far, we have addressed the first two aforementioned research questions through the findings of the methods dealing with both the adaptive factors and the learning features. Then, by analyzing the assessment factors of the reviewed Adaptive 3D VLEs, we discuss the third research question. Findings revealed that the assessment is a major problem for the field as more than a half of the publications have not reported any kind of evaluation. Moreover, when researchers report assessment, they often analyze the students' perceptions of learning. Although these perceptions are useful indicators to understand the students' point of view, they may not be reliable enough to determine the effectiveness of the environment in terms of learning. For this reason, it is important to consider learning outcomes in the assessment, which have been sought by few publications. Assessments including not only the students' perceptions of learning but also learning outcomes could also be more useful since their complement provides thorough assessments. In further research, the use of stealth assessment could be a means of improving the evaluation of Adaptive 3D VLEs since students need to be assessed in meaningful environments rather than be measured through traditional exams [72].

Regarding the selection of the participants for the studies, publications have mainly reported the number of students participating. However, only a few studies have described the procedures used for selecting them as well as whether they are randomized or not. Dealing with the selection bias is an important issue of any study design, even for the most robust ones. In fact, the reviewed publications have reported the use of several studies for obtaining results in the field. However, it is worth mentioning that researchers should look for stronger designs such as randomized control trials and cohort studies rather than only show the functionality of the environment by using prototypes.

In addition to the study design, other components of the assessment are important to avoid bias. In this sense, researchers on Adaptive 3D VLEs have neglected to report the *confounders* variables considered, the *blinding* procedures used, the precaution about the *reliability* and *validity* of the instruments taken, and the *intervention integrity* achieved. These components should be considered in the analysis, describing both percentages and reasons, in order to provide less-biased findings. Additionally, the improvement of the reporting of such components may clarify experimental issues that remain open in many publications.

Notwithstanding, these environments have helped to explore learning in many fields, such as science, engineering, and e-commerce; and, in particular, authoring tools have allowed teachers to adjust the environments to specific fields of study. This way, adaptive 3D VLEs are likely to become a new promising tool to enhance learning in multiple domains of knowledge. However, it is important to keep in mind that Adaptive 3D VLEs are not the ultimate solution for all the educational problems. In this sense, we suggest that adaptive mechanisms should be taken into account in educational environments, but some effort should be spent to ensure that such environments also adhere to general principles. For example, current studies have shown that learning could be significantly improved when both visual and verbal materials are presented together, and also when coherence, redundancy, and personalization are taken into account [73]. On the whole, adaptive 3D VLEs are part of a promising but still complex field since the diversity of the environments, especially when they have a multi-domain scope, make their assessment challenging.

5 CONCLUSION

This review shows current publications on Adaptive 3D Virtual Learning Environments. For answering several questions arising from this field, a systematic review methodology has been carried out covering not only the common concerns on adaptive 3D VLEs but also their quality of the assessment. In this context, 43 studies in the field of adaptive 3D VLEs from the 2000-2014 period have been analyzed. As a result, findings have revealed significant implications for the understanding of current research on adaptive 3D VLEs.

Findings showed that Adaptive 3D VLEs have used the same methods than hypermedia systems to build the learner's model such as the explicit and implicit data collection. It suggests that previous research on hypermedia and web adaptive systems has served as the basis for defining the learner model on adaptive 3D VLEs. Additionally, the focus has mainly been set on defining the learning model considering traditional data such as users' level of knowledge, age, and gender. In this sense, future research should consider how 3D related data, such as level of immersion in the environment, can affect the adaptation of 3D VLEs.

Another important factor to achieve the adaptive effect is the definition of the instructional strategies that are to be used by the adaptive 3D VLEs. The results of this review support the idea that many learning features have been covered, except for the collaborative one. The lack of research on exploring collaborative features on adaptive 3D VLEs suggests an interesting research direction to validate and create new collaborative environments. It is worth noting that collaborative environments, unlike non-collaborative ones, may require new ways to achieve their adaptation due to their complexity. Hence, the use of different methods from the current ones should be explored to obtain effective adaptation on collaborative 3D VLEs.

Currently, most adaptation mechanisms are based on both conventional and AI techniques. However, we have observed that the trend in the field of adaptive 3D VLEs is the use of conventional techniques such as the rule-based approach. In consequence, exploring new techniques to address the adaptation mechanism could make the environments more accurate and efficient. Furthermore, it is recommended carrying out thorough experiments to assess the adaptation effect resulting from applying any kind of technique.

In fact, ensuring appropriate environments with well-designed assessments should be a priority for the research field as several publications have shown to be unreliable. Despite this fact, when environments have shown to be assessed, the outcomes reported have been encouraging. Additionally, these environments have been successfully used in many domains of knowledge, showing an optimistic perspective for further research. As a conclusion, it could be said that, despite the small number of publications per year and their smooth growth, the field of Adaptive 3D VLEs is on the cusp of becoming a more prominent issue in learning technology.

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REFERENCES

[1] V. J. Shute and D. Zapata-Rivera, "Adaptive educational systems," *Adaptive technologies for training and education*, vol. 7, p. 27, 2012.

[2] O.-c. Park and J. Lee, "Adaptive instructional systems," *Educational Technology Research and Development*, vol. 25, pp. 651–684, 2003.

[3] P. J. Durlach and A. M. Lesgold, *Adaptive technologies for training and education*. Cambridge University Press, 2012.

[4] A. A. Kardan, M. Aziz, and M. Shahpasand, "Adaptive systems: a content analysis on technical side for e-learning environments," *Artificial Intelligence Review*, vol. 44, no. 3, pp. 365–391, 2015.

[5] E. Knutov, P. De Bra, and M. Pechenizkiy, "Ah 12 years later: a comprehensive survey of adaptive hypermedia methods and techniques," *New Review of Hypermedia and Multimedia*, vol. 15, no. 1, pp. 5–38, 2009.

[6] O. Biletska, Y. Biletskiy, H. Li, and R. Vovk, "A semantic approach to expert system for e-assessment of credentials and competencies," *Expert Systems with Applications*, vol. 37, no. 10, pp. 7003–7014, 2010.

[7] S. D'Mello, A. Olney, C. Williams, and P. Hays, "Gaze tutor: A gaze-reactive intelligent tutoring system," *International Journal of human-computer studies*, vol. 70, no. 5, pp. 377–398, 2012.

[8] B. Steichen, H. Ashman, and V. Wade, "A comparative survey of personalised information retrieval and adaptive hypermedia techniques," *Information Processing & Management*, vol. 48, no. 4, pp. 698–724, 2012.

[9] M. D. Dickey, "Brave new (interactive) worlds: A review of the design affordances and constraints of two 3d virtual worlds as interactive learning environments," *Interactive Learning Environments*, vol. 13, no. 1-2, pp. 121–137, 2005.

[10] L. Chittaro and R. Ranon, "Web3d technologies in learning, education and training: Motivations, issues, opportunities," *Computers & Education*, vol. 49, no. 1, pp. 3–18, 2007.

[11] B. Dalgarno and M. J. Lee, "What are the learning affordances of 3-d virtual environments?" *British Journal of Educational Technology*, vol. 41, no. 1, pp. 10–32, 2010.

[12] I. Duncan, A. Miller, and S. Jiang, "A taxonomy of virtual worlds usage in education," *British Journal of Educational Technology*, vol. 43, no. 6, pp. 949–964, 2012.

[13] S. K. L. Riley, "Teaching in virtual worlds: Opportunities and challenges," *Setting Knowledge Free: The Journal of Issues in Informing Science and Information Technology Volume 5, 2008*, vol. 5, p. 127, 2008.

[14] A. Cristea and F. Garzotto, "Designing patterns for adaptive or adaptable educational hypermedia: a taxonomy," in *World Conference on Educational Multimedia, Hypermedia and Telecommunications*, vol. 2004, no. 1, 2004, pp. 808–813.

[15] B. Kitchenham and S. Charters, "Guidelines for performing systematic literature reviews in software engineering," Technical report, EBSE Technical Report EBSE-2007-01, Tech. Rep., 2007.

[16] E. Brown, A. Cristea, C. Stewart, and T. Brailsford, "Patterns in authoring of adaptive educational hypermedia: A taxonomy of learning styles," *Journal of Educational Technology & Society*, vol. 8, no. 3, pp. 77–90, 2005.

[17] B. L. Berg and H. Lune, *Qualitative Research Methods for the Social Sciences, 8th Edition*. Pearson, 2011, ch. An Introduction To Content Analysis, pp. 239–267.

[18] Y. Akbulut and C. S. Cardak, "Adaptive educational hypermedia accommodating learning styles: A content analysis of publications from 2000 to 2011," *Computers and Education*, vol. 58, no. 2, pp. 835–842, 2012.

[19] P. Brusilovsky, "Adaptive hypermedia," *User modeling and user-adapted interaction*, vol. 11, no. 1-2, pp. 87–110, 2001.

[20] P. Brusilovsky and E. Millán, "User models for adaptive hypermedia and adaptive educational systems," in *The adaptive web*. Springer-Verlag, 2007, pp. 3–53.

[21] A. Kavcic, "The role of user models in adaptive hypermedia systems," in *Electrotechnical Conference, 2000. MELECON 2000. 10th Mediterranean*, vol. 1. IEEE, 2000, pp. 119–122.

[22] S. Hughes, P. Brusilovsky, and M. Lewis, "Adaptive navigation support in 3d e-commerce activities," in *Proceedings Of Workshop On Recommendation And Personalization In Ecommerce At The 2nd International Conference On Adaptive Hypermedia And Adaptive Web-based Systems (AH'2002) Proceedings*, 2002, pp. 132–139.

[23] L. National Heart and B. Institute, "Quality assessment of systematic reviews and meta-analyses," March 2014. [Online].

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Available: https://www.nhlbi.nih.gov/health-pro/guidelines/in-develop/cardiovascular-risk-reduction/tools/sr_ma

[24] B. Thomas, D. Ciliska, M. Dobbins, and S. Micucci, "A process for systematically reviewing the literature: providing the research evidence for public health nursing interventions," *Worldviews on Evidence-Based Nursing*, vol. 1, no. 3, pp. 176–184, 2004.

[25] L. Chittaro and R. Ration, "Adding adaptive features to virtual reality interfaces for e-commerce," in *Adaptive Hypermedia and Adaptive Web-Based Systems*. Springer, 2000, pp. 86–97.

[26] L. Chittaro and R. Ranon, "Dynamic generation of personalized vrml content: a general approach and its application to 3d e-commerce," in *Proceedings of the seventh international conference on 3D Web technology*. ACM, 2002, pp. 145–154.

[27] L. S. Moualed, V. M. Jones, H. J. Hermens *et al.*, "A self-learning personalized feedback agent for motivating physical activity," in *Proceedings of the 4th International Symposium on Applied Sciences in Biomedical and Communication Technologies*. ACM, 2011, p. 147.

[28] C. T. dos Santos and F. S. Osorio, "Adaptive: an intelligent virtual environment and its application in e-commerce," in *Computer Software and Applications Conference, 2004. COMPSAC 2004. Proceedings of the 28th Annual International*. IEEE, 2004, pp. 468–473.

[29] A. Ewais and O. De Troyer, "Authoring storyline-based adaptive 3d virtual learning environments." in *CSEDU*, 2013, pp. 15–24.

[30] S. Leung, S. Virwaney, F. Lin, A. Armstrong, and A. Dubbelboer, "Tsi-enhanced pedagogical agents to engage learners in virtual worlds," *International Journal of Distance Education Technologies (IJDET)*, vol. 11, no. 1, pp. 1–13, 2013.

[31] S. Arnold, J. Fujima, A. Karsten, and H. Simeit, "Adaptive behavior with user modeling and storyboarding in serious games," in *Signal-Image Technology & Internet-Based Systems (SITIS), 2013 International Conference on*. IEEE, 2013, pp. 345–350.

[32] K. A. McCusker, J. Harkin, S. Wilson, and M. Callaghan, "Intelligent assessment and content personalisation in adaptive educational systems," in *Information Technology Based Higher Education and Training (ITHET), 2013 International Conference on*. IEEE, 2013, pp. 1–7.

[33] H.-C. Wang, T.-Y. Li, and C.-Y. Chang, "Adaptive presentation for effective web-based learning of 3d content," in *Advanced Learning Technologies, 2004. Proceedings. IEEE International Conference on*. IEEE, 2004, pp. 136–140.

[34] T. D. Parsons and J. L. Reinebold, "Adaptive virtual environments for neuropsychological assessment in serious games," *Consumer Electronics, IEEE Transactions on*, vol. 58, no. 2, pp. 197–204, 2012.

[35] L. Chittaro, R. Ranon, and L. Ieronutti, "Guiding visitors of web3d worlds through automatically generated tours," in *Proceedings of the eighth international conference on 3D Web technology*. ACM, 2003, pp. 27–38.

[36] L. Chittaro and R. Ranon, "Adaptive hypermedia techniques for 3d educational virtual environments," *Intelligent Systems, IEEE*, vol. 22, no. 4, pp. 31–37, 2007.

[37] A. Ewais and O. De Troyer, "Authoring adaptive 3d virtual learning environments," *International Journal of Virtual and Personal Learning Environments (IJVPLE)*, vol. 5, no. 1, pp. 1–19, 2014.

[38] T. Reiners, L. Wood, and J. Dron, "From chaos towards sense: A learner-centric narrative virtual learning space," 2014.

[39] M. S. d. Aquino, F. d. F. d. Sousa, and A. C. Frery, "Three-dimensional virtual environments adaptive to the student's profile for distance learning," in *Anais do Simpósio Brasileiro de Informática na Educação*, vol. 1, no. 1, 2005, pp. 424–433. [Online]. Available: http://www.br-ie.org/pub/index.php/sbie/article/view/427

[40] S. Schatz, R. Wray, J. Folsom-Kovarik, and D. Nicholson, "Adaptive perceptual training in a virtual environment," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 56, no. 1. SAGE Publications, 2012, pp. 2472–2476.

[41] A. Celentano, M. Nodari, and F. Pittarello, "Adaptive interaction in web3d virtual worlds," in *Proceedings of the ninth international conference on 3D Web technology*. ACM, 2004, pp. 41–50.

[42] M. Vayanou, A. Katifori, M. Karvounis, V. Kourtis, M. Kyriakidi, M. Roussou, M. Tsangaris, Y. Ioannidis, O. Balet, T. Prados *et al.*, "Authoring personalized interactive museum stories," in *Interactive Storytelling*. Springer, 2014, pp. 37–48.

[43] N. Peirce and V. Wade, "Personalised learning for casual games: The'language trap'online language learning game," in *Proceedings of the 4th European Conference on Games-Based Learning: ECGBL 2009*. Academic Conferences Limited, 2010, p. 306.

[44] A. Johnson, Y. Tang, and C. Franzwa, "knn-based adaptive virtual reality game system," in *Networking, Sensing and Control (ICNSC), 2014 IEEE 11th International Conference on*. IEEE, 2014, pp. 457–462.

[45] H. V. Diez, S. García, J. R. Sánchez, and M. del Puy Carretero, "3d animated agent for tutoring based on webgl," in *Proceedings of the 18th International Conference on 3D Web Technology*. ACM, 2013, pp. 129–134.

[46] B. Xu and Y. Yu, "A personalized assistant in 3d virtual shopping environment," in *Intelligent Human-Machine Systems and Cybernetics (IHMSC), 2010 2nd International Conference on*, vol. 2. IEEE, 2010, pp. 266–269.

[47] W. L. Johnson and C. R. Beal, "Iterative evaluation of a large-scale, intelligent game for language learning." in *AIED*, 2005, pp. 290–297.

[48] A. C. Graesser, P. Chipman, B. C. Haynes, and A. Olney, "Autotutor: An intelligent tutoring system with mixed-initiative dialogue," *Education, IEEE Transactions on*, vol. 48, no. 4, pp. 612–618, 2005.

[49] E. Bekele, M. Young, Z. Zheng, L. Zhang, A. Swanson, R. Johnston, J. Davidson, Z. Warren, and N. Sarkar, "A step towards adaptive multimodal virtual social interaction platform for children with autism," in *Universal Access in Human-Computer Interaction. User and Context Diversity*. Springer, 2013, pp. 464–473.

[50] J. Konert, S. Göbel, and R. Steinmetz, "Video game personalization via social media participation," in *Games for Training, Education, Health and Sports*. Springer, 2014, pp. 35–46.

[51] D. Albert, C. Hockemeyer, M. D. Kickmeier-Rust, N. Peirce, and O. Conlan, "Microadaptivity within complex learning situations–a personalized approach based on competence structures and problem spaces," in *15th International Conference on Computers in Education, ICCE 2007*, 2007.

[52] M. P. A. de Sousa, M. V. A. Nunes, A. d. C. Lopes *et al.*, "A 3d learning tool for a hydroelectric unit," *Computer Applications in Engineering Education*, vol. 20, no. 2, pp. 269–279, 2012.

[53] N. Peirce, O. Conlan, and V. Wade, "Adaptive educational games: Providing non-invasive personalised learning experiences," in *Digital Games and Intelligent Toys Based Education, 2008 Second IEEE International Conference on*. IEEE, 2008, pp. 28–35.

[54] L. Ieronutti and L. Chittaro, "Employing virtual humans for education and training in x3d/vrml worlds," *Computers & Education*, vol. 49, no. 1, pp. 93–109, 2007.

[55] S. Sauer, K. Osswald, X. Wielemans, and M. Stifter, "U-create: Creative authoring tools for edutainment applications," in *Technologies for Interactive Digital Storytelling and Entertainment*. Springer, 2006, pp. 163–168.

[56] C. Kelleher and R. Pausch, "Using storytelling to motivate programming," *Communications of the ACM*, vol. 50, no. 7, pp. 58–64, 2007.

[57] S. Gobel, L. Salvatore, and R. Konrad, "Storytec: A digital storytelling platform for the authoring and experiencing of interactive and non-linear stories," in *Automated solutions for Cross Media Content and Multi-channel Distribution, 2008. AXMEDIS'08. International Conference on*. Ieee, 2008, pp. 103–110.

[58] J. Robertson and J. Good, "Adventure author: an authoring tool for 3d virtual reality story construction," in *Proceedings of the AIED-05 Workshop on Narrative Learning Environments*, 2005, pp. 63–69.

[59] E. J. Marchiori, J. Torrente, Á. del Blanco, P. Moreno-Ger, P. Sancho, and B. Fernández-Manjón, "A narrative metaphor to facilitate educational game authoring," *Computers & Education*, vol. 58, no. 1, pp. 590–599, 2012.

[60] J. Torrente, Á. Del Blanco, G. Cañizal, P. Moreno-Ger, and B. Fernández-Manjón, "< e-adventure3d>: an open source authoring environment for 3d adventure games in education," in *Proceedings of the 2008 International conference on advances in computer entertainment technology*. ACM, 2008, pp. 191–194.

[61] G. Te Brake, T. de Greef, J. Lindenberg, J. Rypkema, and N. Smets, "Developing adaptive user interfaces using a game-based simulation environment," *Proceedings of ISCRAM*, 2006.

[62] W. L. Johnson, H. H. Vilhjálmsson, and S. Marsella, "Serious games for language learning: How much game, how much ai?" in *AIED*, vol. 125, 2005, pp. 306–313.

[63] P. De Bra, A. Aerts, B. Berden, B. De Lange, B. Rousseau, T. Santic, D. Smits, and N. Stash, "Aha! the adaptive hypermedia architecture," in *Proceedings of the fourteenth ACM conference on Hypertext and hypermedia*. ACM, 2003, pp. 81–84.

[64] A. Celentano and F. Pittarello, "Observing and adapting user behavior in navigational 3d interfaces," in *Proceedings of the working conference on Advanced visual interfaces*. ACM, 2004, pp. 275–282.

[65] S. DiPaola and C. Akai, "Designing an adaptive multimedia interactive to support shared learning experiences," in *ACM SIGGRAPH 2006 Educators program*. ACM, 2006, p. 14.

[66] M. Hendrix, E. Knutov, L. Auneau, S. Arnab, I. Dunwell, P. Petridis, P. Lameras, and S. de Freitas, "Integrating serious games in adaptive hypermedia applications for personalised learning experiences," in *eLmL 2013, The Fifth International Conference on Mobile, Hybrid, and On-line Learning*, 2013, pp. 43–48.

[67] Í. B. G. de Moura, F. M. M. Neto, P. S. M. Sousa, and J. de Deus Lima, "Using intelligent agents with educational goals in personalized recommendation of content in virtual learning environments 3d," in *Proceedings of International Conference on Engineering and Computer Education*, vol. 8, 2013, pp. 90–94.

[68] A. M. Devlin, V. Lally, M. Sclater, and K. Parussel, "Inter-life: A novel, three-dimensional, virtual learning environment for life transition skills learning," *Interactive Learning Environments*, no. ahead-of-print, pp. 1–20, 2013.

[69] H. Jenkins, "Game design as narrative architecture," *Computer*, vol. 44, p. s3, 2004.

[70] E. Scott, G. Rodríguez, Á. Soria, and M. Campo, "Are learning styles useful indicators to discover how students use scrum for the first time?" *Computers in Human Behavior*, vol. 36, pp. 56–64, 2014.

[71] H. Pashler, M. McDaniel, D. Rohrer, and R. Bjork, "Learning styles concepts and evidence," *Psychological science in the public interest*, vol. 9, no. 3, pp. 105–119, 2008.

[72] V. J. Shute and M. Ventura, *Measuring and supporting learning in games: Stealth assessment*. Cambridge, MA: The MIT Press, 2013.

[73] R. E. Mayer, "Multimedia learning," *Psychology of learning and motivation*, vol. 41, pp. 85–139, 2002.

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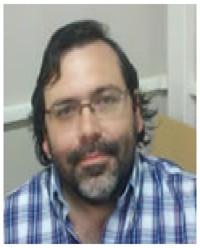

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