Computers & Graphics 77 (2018) 166–182

Contents lists available at ScienceDirect

Computers & Graphics

journal homepage: www.elsevier.com/locate/cag

Survey Paper

Design considerations for combining augmented reality with intelligent tutors

Bradley Herbert[a,*], Barrett Ens[a], Amali Weerasinghe[b], Mark Billinghurst[a], Grant Wigley[a]

[a] School of Information and Mathematical Sciences, University of South Australia, Australia
[b] School of Computer Science, University of Adelaide, Australia

ARTICLE INFO

Article history:
Received 4 May 2018
Revised 21 September 2018
Accepted 24 September 2018
Available online 4 October 2018

Keywords:
Intelligent tutoring systems
Computers and learning
Augmented reality
Human computer interaction
Psychomotor learning
Kinaesthetic learning
Experiential learning

ABSTRACT

Augmented Reality overlays virtual objects on the real world in real-time and has the potential to enhance education, however, few AR training systems provide personalised learning support. Combining AR with intelligent tutoring systems has the potential to improve training outcomes by providing personalised learner support, such as feedback on the AR environment. This paper reviews the current state of AR training systems combined with ITSs and proposes a series of requirements for combining the two paradigms. In addition, this paper identifies a growing need to provide more research in the context of design and implementation of adaptive augmented reality tutors (ARATs). These include possibilities of evaluating the user interfaces of ARAT and potential domains where an ARAT might be considered effective.

1. Introduction

Augmented Reality (AR) overlays virtual 3-Dimensional (3D) objects on the real-world and is starting to emerge in training and education [1,2]. Intelligent Tutoring Systems (ITSs) are computer-based systems that provide personalised learning support (such as error detection, feedback, and task selection) [3], according to a learner's current (or projected) performance or skill in a task [4]. Combining AR with intelligent tutoring systems can potentially enhance learning on psychomotor and kinaesthetic tasks. In this paper, we describe the potential benefits of combining these two paradigms; present a series of design considerations and some possible areas for future research. Psychomotor learning involves using motor skills and precision in physical tasks to integrate domain knowledge. For example, learning how to effectively use tools to administer wound care [5,6]. Similarly, kinaesthetic learning involves learning in a hands-on, practical way. For example, rather than reading about chemistry in a text book, the learner performs a hands-on experiment to further understand the chemical interactions [7].

Previous work has explored designs for AR training systems and ITSs, but very little work has focused on combining the two together [8–11], even though doing so improves knowledge retention up to 25% in psychomotor tasks [12]. The two paradigms complement each other's weaknesses. For instance, AR is well suited for improving skills in tasks that have a spatial component [13–15], but it has limited learning support, whereas ITSs have been shown to provide effective learning support in mathematics, engineering, science and technology, but has limited capabilities of providing intuitive instruction [8,16–18]. Using AR with ITSs could enable AR annotations to be shown when an error is made by the learner, leading to higher knowledge gains compared to using AR alone [9]. However, there are no established guidelines for designing and implementing such systems. So, the aims of this paper are as follows:

1. Summarise existing AR training systems and ITSs, including their strengths, and weaknesses, and outline the key lessons they provide for building AR\ITS systems (Section 2)
2. Development of a cohesive definition for Augmented Reality Adaptive Tutors (ARATs) (Section 3)
3. Development of a series of guidelines for designing and implementing ARAT systems. (Section 4.1)
4. Highlight key research gaps, limitations, trends and opportunities for further research (Section 5)

In achieving these aims, this paper makes the following contributions:

* Corresponding author.
E-mail addresses: bradley.herbert@mymail.unisa.edu.au (B. Herbert), barrettens@acm.org (B. Ens), amali.weerasinghe@adelaide.edu.au (A. Weerasinghe), mark.billinghurst@unisa.edu.au (M. Billinghurst), grant.wigley@unisa.edu.au (G. Wigley).

https://doi.org/10.1016/j.cag.2018.09.017
0097-8493/

Fig. 1. Example of AR: ScopeAR Training Application [26].

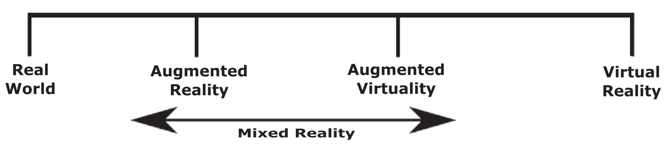

Fig. 2. Adaptation of reality-virtuality continuum [21].

1. A review of the state of the art of AR and Intelligent Tutoring System (ITS) learning experiences (Section 2)
2. A proposed system, including a design space for categorising AR\ITS systems (Section 3).
3. A set of design and implementation guidelines for AR\ITS systems (Section 4.1)

The structure of this paper is as follows: Section 2 reviews AR and various AR training systems, their features and what lessons they provide; ITSs, their architecture and the different types of ITSs; a rationale for combining AR with ITSs and a list of some example AR training systems that have integrated ITSs. Section 3 proposes an ideal ARAT system, including its key architectural components and requirements. Section 4 details the design requirements for combining AR with ITSs and as such is the core focus of the paper. Section 5 details opportunities for future work such as user interface evaluation and finally, section 6 summarises the paper.

2. Related work

This section highlights current work on AR training systems; ITSs and systems which combine AR and ITSs. Although, ITSs and AR are broadly mentioned in the literature, only few works [10–12] discuss the concept of combining them together. A simple Google scholar search on "Intelligent Tutoring Systems" returns more than 57,000 results, whereas search on "Intelligent Tutoring Systems and Augmented Reality" returns a mere 57 results. Applications of AR to training systems [19,20] tend to focus on design requirements for an AR training system, but little is said about how to provide instruction using the AR training system.

2.1. Augmented reality

AR is a real-time, interactive experience that combines both real and virtual 3-Dimensional (3D) objects together into the one unified space (Fig. 1) [1,21]. AR is a subset of "mixed reality", the blending of physical and virtual worlds (Fig. 2) [21]. AR is used in a variety of domains like aeroplane maintenance [22]; machine assembly and repair [9,13,23]; visualising magnetic fields in real-time [24]; medical training [11,25] and machinery manipulation [25].

2.1.1. Technological components

AR consists of three fundamental requirements [1]: (1) the experience must combine both real and virtual objects; (2) the virtual content must be registered in 3D in real time and (3) the virtual content must be interactive in real time. To satisfy these requirements, there are three major technological components of AR systems: (1) tracking; (2) display and (3) interaction technologies [27].

2.1.1.1. Tracking. Tracking (and registration) encompasses the techniques for locating real world objects and aligning them with virtual objects. Tracking can range from simple tracking techniques like marker-based tracking, which uses computer vision algorithms to identify an image in the real world, to 3D object tracking to natural feature tracking. A variety of inexpensive software libraries exist that provide marker-based tracking including: Vuforia [28,29] and ARToolkit [30,31]. More recently 3D and natural feature tracking libraries are starting to emerge. This includes the ARKit [32] and ARCore [33] libraries which enable compatible mobile phones to have accurate AR tracking from natural features in the real world. Many of these libraries can be integrated with existing software development tools like the Unity3D gaming engine [34], making authoring of AR applications easier. Location-based tracking, which exploits Global Positioning System (GPS) and inertial sensors in mobile technology to track a user's position and rotation, are also becoming more widespread. A popular application of this technology was in the commercial AR game, Pokemon Go [35].

2.1.1.2. Display. Display components enable displaying AR content to end users. Three common types of display technology include: (1) Head-Mounted Display (HMD); (2) Hand-held and (3) projector-based AR and two different means of displaying the content: video-see through and optical see through. Video see through systems overlay digital content onto a live video feed of the real world and typically use a HMD or a hand-held device such as a tablet or smartphone. An example of a video-see-through system is Pokemon Go, an AR game [35]. Optical see-through systems, use a transparent display to show graphics directly over a view of the real world, preserving the original resolution of the real world [36]. An example of an optical-see-through HMD is the Microsoft HoloLens, a HMD that has been used in some prototype AR assembly systems [37]. Projector-based AR, or Spatial Augmented Reality (SAR) projects virtual 3D images directly onto the real world [38]. An example of projected AR is an automotive design system [39].

2.1.1.3. Interaction. Interaction encompasses the ability for a user to interact with and experience the augmented environment. Interaction provides both the techniques for interacting with the augmented environment and an impression that superimposed objects are real and tangible, rather than just being an 3D image blended with the real world [1]. For example, manipulating or seeing an object from multiple angles, are cases of interaction. More complex forms of interaction include using stylus input, hand gestures or tangible user interfaces [40–43].

2.1.2. AR training applications

AR has broad applications in training. In psychomotor training, AR is used for: (1) assembly and maintenance [12,13,23,44]; (2) Engineering and problem solving [45]; (3) Military training [10] and (4) medical training [11]; (5) AR-based simulations [46]; (6) Interactive chemistry systems [47]; (7) 3D visualisation systems [24];

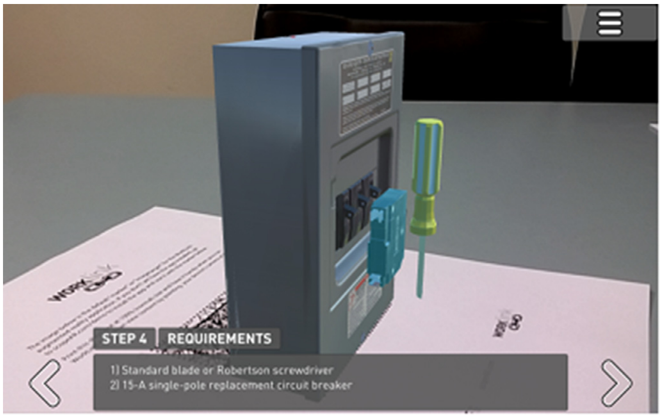

Fig. 3. ScopeAR WorkLink Application: Circuit Board Repair [26].

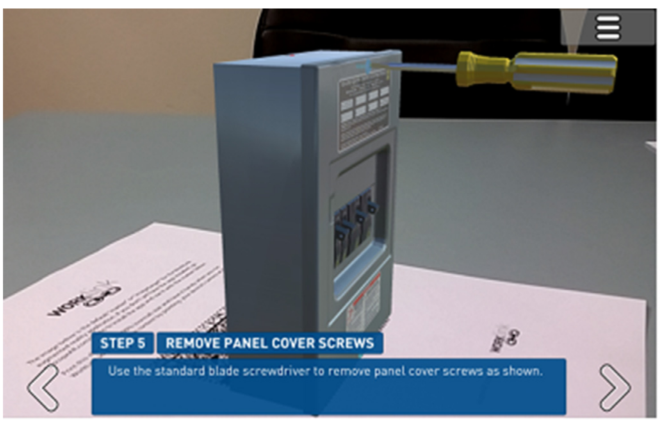

Fig. 4. ScopeAR WorkLink Application: A Maintenance Task [26].

(8) spatial language learning [48] and (9) Gas flow visualisation through a medical machine [25].

2.1.2.1. ScopeAR WorkLink. ScopeAR WorkLink is a cloud-based AR training authoring application for creating maintenance and assembly training tasks [26] (Figs. 3 and 4). It guides learners through procedural maintenance tasks like repairing a damaged circuit board by overlaying AR annotations on the real world [49]. This makes it well suited for structured tasks such as learning a safety procedure, but less suited for non-linear tasks. This means that ScopeAR is less suitable for training tasks that involves learning by exploring openly. ScopeAR is noteworthy because of it is one of the few commercial AR training systems, at time of writing.

2.1.2.2. VR&AR combined manual operation instruction system. The Virtual Reality & Augmented Reality Combined Manual Operation Instruction System (VR&ARCMOIS) is a mixed-reality training system that guides workers through the steps of a factory assembly task [44]. It is composed of two main subsystems: (1) A Virtual Reality (VR) authoring tool for designing and editing the instructional experience and (2) the Mixed Reality (MR) training system. The MR training system overlays annotations on the real-world, which are tied to a step in the logical fixed sequence of steps. Instruction is created using the VR authoring tool. VR&ARCMOIS does not provide personalised instruction. VR&ARCMOIS is noteworthy for these reasons. First, it gives insight on tracking issues and how to mitigate them. Second, it combines Augmented Reality (AR) and VR interfaces into the one system, making it unique in that sense. Finally, it visualises the parts instead of simply providing annotations like arrows and text.

The strengths of VR&ARCMOIS include: enhanced tracking capabilities; an authoring tool to author logically-sequenced instructions and visualisation of 3D parts to enhance mental model construction. VR&ARCMOIS uses a multi-markup to reduce registration and tracking errors caused by occlusion. Since VR&ARCMOIS uses a multi-marker setup, registration and tracking errors caused by occlusion are reduced [44]. The authoring interface allows experts to author the sequence of steps, making it possible to apply this system to a variety of industry-focused assembly and de-assembly manufacturing settings [44]. The use of 3D models is also a useful way of conveying instruction, for instance, VR&ARCMOIS overlays a virtual 3D hand to show the positions and gestures that the human hand should follow to manipulate a given part [44].

Limitations of VR&ARCMOIS are: (1) It has limited adaptive or task sequencing capabilities; (2) It mixes two user interface (UI) paradigms; (3) It uses a desktop-based AR display, which can create divided attention. Since VR&ARCMOIS does not use any modelling capabilities of an ITS, the AR annotations are simply events that are tied to a given step. When a step happens, AR annotations appear. It requires users to view the AR display on a desktop monitor and also use a keyboard to progress to the next step. Users must progress the training manually with the increased risk of creating divided attention or reduced usability [50]. Lastly, VR&ARCMOIS is a desktop-based AR display, so does not immerse the user in the experience. Although, the user's hands are freed using this design, the user must still glance at the screen, rather than being focused on the assembly task.

2.1.2.3. Virtual and augmented reality design system. The Virtual and Augmented Reality Design System (VADS) is a training system that uses both AR and VR to help mechanical engineers develop their own problem solving and mechanical ability using a personalised learning approach. The design is based on the premise that learners often request steps to complete a learning task and that by providing these steps, creates a more effective learning experience [45]. VR is used to enable manipulation of virtual parts, whereas, AR annotations (such as text) provides feedback. Each part of a complex machine assembly/de-assembly is presented as steps that the learner works through to accomplish the learning goals.

VADS implements tracking, display and interaction for facilitating AR. Tracking is implemented using a marker-based approach with the ARToolkit library [31,45]. Markers are attached to each individual component interacted with by the learners. The system uses a VR1280 video-see-through VR Head-Mounted Display (HMD), modified for use with AR [45].

However there are limitations with VADS. First, the system has some usability and contrast issues. There is no background behind the text, so the text may be difficult to read in bright environments. The text is overlaid in the centre of the user's view, which can obscure the workspace. Second, although steps are shown, the chosen pedagogy is unlikely to provide sufficient learner gains. The system lacks feedback mechanisms typically found in ITSs, such as scaffolding feedback [18], or learning support to foster deeper learning [51]. Third, because learners are simply guided through the process, reduced learning is likely to occur. Mistakes are unlikely to be detected because the system does not leverage modelling techniques used in ITSs.

2.1.2.4. Visual assembling guidance system. The Visual Assembling Guidance System assists factory workers perform their work more efficiently. It uses a modified Oculus Rift VR Head-Mounted Display (HMD) to provide a video-see through AR experience [52], which help reduce lag [52], although it can limit visibility in manufacturing settings. The use of a modified Oculus Rift extends the field of view, allowing for a user to better see their surroundings. The system provides visual guidance for assembly by guiding the user through each step in a logical sequence but provides limited personalised learning support for psychomotor learning.

A user evaluation found that paper-based instructions were easier to use for people without prior experience with AR [52]. However, AR was only slightly less intuitive than the paper-based solution, and the assembly task was very simple. In more complex assembly settings where the mental model is not necessarily developed, AR tends to provide superior performance [14]. Participants rated daily access to the AR technology highly [52], which indicated a high usability acceptance.

This system is noteworthy because it provides several usability insights. It is designed to be acceptable to users, rather than simply being efficient [52], and to be used by novice users potentially unfamiliar with the technology. The system also gives an example of how to present annotations, with light green arrows used to show object orientation and numbered virtual boxes to illustrate the sequence of placement.

2.1.2.5. Augmented anaesthesia machine. The Augmented Anesthesia Machine (AAM) is a Mixed Reality (MR) training system that aims to help learners understand the correct operation of a medical anaesthesia machine [25]. It does this by using AR to visualise the flow of gas through the machine's internal mechanics. AAM differs from other traditional forms of AR-based training systems in two senses: (1) The overlaid content directly represents a physical element that is invisible and (2) It does not aim to facilitate a step-by-step process, but understanding of a mechanical process.

AAM illustrates a valid pedagogical aim of AR: the integration of concrete knowledge, such as physical operation of a machine, with abstract principles that cannot be conveyed in the physical environment alone. Consequently, AAM is designed to address limitations with transferring abstract knowledge to real world scenarios. The strength of AAM is the potential to use the physical machine as a tangible user interface. Studies by [25] showed that AAM improved both concrete knowledge retention and subsequent transfer of abstract knowledge to real world scenarios. However, they noted that abstract knowledge was more efficiently imparted using a traditional web-based 2-Dimensional (2D) interfaces.

There are two notable limitations with AAM: (1) It contains limited mechanisms to convey abstract knowledge and (2) It uses a hand-held AR system that may have usability issues. First, [25] noted that the 2D web-based interface was more efficient at imparting abstract knowledge, but that AR was more suited for knowledge transfer. The weakness of AAM was that there was only limited instruction to explain the gas flow process, which is a necessary component of instructional design [53]. The inclusion of more advanced feedback could have enhanced development of abstract concepts. This would help connect abstract knowledge with concrete knowledge. Second, AAM used a hand-held tablet which restricts hand movement and may make use of the anaesthesia machine difficult.

2.1.2.6. The Pepper's ghost mixed-reality work support system. The Pepper's Ghost MR Work Support System is an alternative to HMD-based MR and Spatial Augmented Reality (SAR) systems [54]. It combines the HMD benefits of freed hands with the need to not wear a HMD. The system is noteworthy for two reasons. First, the technique for displaying registered AR content is unusual [54], so could be deployed to overcome shortcomings of other similar systems and second, it focuses on a psychomotor assembly task. The system visualises an ideal solution state by overlaying virtual 3D boxes, but unlike the Visual Guidance System [52] does not use arrows for guiding the user through the assembly task. A *Pepper's Ghost* solution can be done at a low cost [54]. However, unlike SAR, the Pepper's Ghost solution does not provide tracking capabilities. This needs to be implemented separately, for instance, [54] used marker-based tracking in conjunction with Pepper's Ghost.

2.1.3. Limitations of AR training systems

Currently, three major limitations of most AR training systems are: (1) They tend to provide instructions in a linear way, providing no detection on the correct step being performed; (2) They do not model the domain so cannot provide deeper analysis of the learner's actual knowledge and (3) They do not provide scaffolded feedback since any such feedback given relates to the immediate step being performed. Many of these limitations result from the primitive feedback logic algorithms used in these systems, if any.

2.1.3.1. Linear learning support. Although some AR training systems provide annotations and other forms of feedback (as noted by [19]), it is evident that such form of instructional feedback can fall short of what is necessary for learning [53,55]. Others may provide general instruction or permanently show annotations, but contain no logic to only show what is contextually appropriate for the learner [12,19]. This may result in the same feedback always being issued. The learner then must selectively ignore any feedback that does not apply with the added risk of ignoring critical feedback in error.

Many AR training systems (such as the "Pepper's Ghost" system [54]) do not even provide any sort of instruction or feedback at all, but simply show annotations. Such systems are unlikely to provide any learning benefit. In fact, according to [55], such limited instruction is likely to damage the individual's learning. Other systems like ScopeAR WorkLink do infer a correct solution, typically based on user's responses, but cannot infer deep learning.

Many existing AR training systems only provide linear learning support. For example, ScopeAR WorkLink presents instructions in a linear fashion which is problematic when steps that are completed in a different order can still result in a correct solution [8]. Forcing one to complete a task in a fixed order may present learning challenges because learners cannot use their own mental perception of the problem [56]. Furthermore, when a mistake is made, the system does not have the capacity to provide remediation since it provides linear, predetermined forms of instruction. Due to this, such systems are neither suited for problem solving pedagogies, where the solution is not known [57], or for enabling an individual approach to develop critical thinking styles.

2.1.3.2. Deep knowledge checking. Standalone AR training systems generally lack the sophistication to provide detection of flawed logical reasoning and misconception checking. In many cases, feedback can only be provided on the immediate step or process being undertaken, and such feedback is generally designed to evaluate procedural knowledge. However, while the solution may be correct, there could be a logical fallacy in the learner's thinking, which would indicate a misconception [58]. Such deep learning detection typically requires modelling techniques like those used in ITSs. AR training systems tend not to provide such modelling capabilities.

2.1.3.3. Scaffolded instruction. In addition to step-by-step guidance, some complex domains may require additional learning support that gradually guides the learner through the process of troubleshooting until they gradually master the concept [18,59]. Two purposes for this are necessary: (1) The initial feedback or instruction may not be provide enough information to help the learner; and (2) A learner's morale may drop when they realise continuing difficulty that they cannot solve without assistance. Affective modelling can detect certain behaviour, such as distraction and employ different pedagogical strategies to refocus the learner [60–62].

2.2. Intelligent tutoring systems

An intelligent tutoring system (ITS) is a computer-based training system that provides personalised learner support including error detection, remediation, and task selection, according to a series of rules, patterns, or constraints [3]. Typically, when certain rules or constraints are violated, the ITS flags an incorrect action and responds accordingly. ITSs can respond to incorrect solutions in several ways such as: (1) Do nothing; (2) Provide feedback; (3) Change the exercise or some other notification.

There are three broad characteristics which an ITS should have [3,59]: (1) error detection (and correction); (2) problem solving support (i.e. providing feedback to the learner to help them problem solve it for themselves) and (3) task sequencing (i.e. the appropriate selection and sequencing of tasks). However, the manner and kinds of traits that an ITS adapts is a matter for design.

2.2.1. Empirical basis for using intelligent tutoring systems

Instruction and learning support delivered using an ITS tends to provide higher learning gains than classroom and static instruction [18,63,64]. Studies have evaluated the effectiveness of ITSs across a variety of domains including: mathematics [65], physics, software engineering [17,66] and genetics [67,68]. For example, [69] found that technicians training just 20–25 hours on an ITS to diagnose electrical faults produced learning results comparable to four years of on-the-job experience. Similarly, [70,71] found that learners who learned on an ITS had, on average, higher exam grades. VanLehn et. al. [18] suggests that ITSs are more effective than classroom instruction because, like human tutors, they facilitate an individual's learning by gradually providing more instruction.

Other researchers have proposed different explanations for why ITSs effectively improve learning such as [18]: (1) Task selection based on the learner's strengths and weaknesses; (2) Identification of learner misconceptions by asking the learner questions and (3) Adapting the task to motivate the learner. However, according to [18], an ITS's real strength lies in its capability to provide a scaffolded learning approach so that design and implementation of a computer-based training system should focus on this key characteristic.

2.2.2. Architecture

There are various kinds of ITSs, but which tend to share a common architecture consisting of: (1) A domain model; (2) A pedagogical model and (3) A learner model. The domain model stores and forms a conceptual map of the subject domain and evaluates the learner's solution to it to determine what errors have occurred. The learner model models the learner's performance, cognition and/or affection and tries to understand the current state of the learner and their task progress. The pedagogical model aims to understand how learners learn and provides instructional strategies. Some ITS systems also include an authoring interface for allowing training scenarios and solutions to be created [72].

Some modern ITSs are based on a modular architecture that provides a framework for easily developing ITS systems, such as the Generalized Intelligent Framework for Tutoring (GIFT) [60]. GIFT modularises the functionality of each component: domain, learning, pedagogical into separate applications that communicate with one another over a computer network as shown in Fig. 5.

2.2.3. Intelligent tutoring systems paradigms

ITS paradigms have evolved over time due to technical advancements and changes in pedagogical research. Corbett et. al. [51] differentiated between three different generations of ITS. The first generation ITS, developed in the early 1970s [16,51], provided simple text-based feedback depending on the student's answers [51,74]. Next, second-generation ITSs emerged in the mid to late 1990s, providing multi-step feedback [51,74]. Third generation ITSs began to emerge in the early-mid 2000s, which detect shallow or limited learning by monitoring eye movement and other physiological measures [51,71].

We extend on the categorisation used by [51] by adding two additional generations: fourth and fifth generation ITSs that have since emerged. Graesser et. al. [75] presents a mixed initiative design, as a next generation ITS. These have the ability to ask the tutor questions, request hints, misconception checking and asks the student to verify understanding [74]. Examples of such systems include: Oscar, AutoTutor, PC-based Open-Architecture Reconfigurable Training System (PORTS) and *Ms. Lindquist* [59,71,74]. Finally, [76,77] identify a major paradigm pertaining to the integration of ITS logic with external applications to provide the tutor with the capability to interact with the real-world. For example, ARWild, extended the learning experience to the real world to provide psychomotor skill development.

The list below summarises the different generations of ITSs based on our adaptation of the classification by [51].

1. *First generation ITS*: Answers questions and issues basic feedback and rated about 25% as effective as human tutors. [51] (early 1970s).
2. *Second generation ITS*: Flags errors and provides multi-step learner feedback [51] (such as SQL-Tutor) (mid-late 1990s)
3. *Third generation ITS*: Monitors and detect learner affective states to determine possible distraction [51] (such as AutoTutor) (late 1990s to mid 2000s)
4. *Fourth generation ITS*: Facilitates deep learning by employing a mixed initiative design [75] (such as Oscar) (mid 2000s to late 2000s).
5. *Fifth generation ITS*: Interfacing with and getting information from outside the ITS itself such as from the real world [77] (such as ARWild) (early-mid 2010s)

Traditionally, ITSs have used two modelling paradigms to determine correct learning: Constraint-Based Modelling (CBM) and Model-Tracing (MT) [78,79]. However, since the emergence of fourth and fifth generation ITSs, two new modelling paradigms have been developed: (1) A hybrid modelling solution that combines both CBM and MT [58] and (2) An example-tracing algorithm that uses examples to determine correct solutions [80].

First, CBM tutors encode a series of constraints to form an ideal solution state, facilitating a systems approach where the ideal process cannot be known in advance, such as engineering, design or fault finding tasks [78,81]. Examples of constraint-based tutors include: a palm-oil manufacturing tutor [82] and the Motherboard Assembly Tutor (MAT) [8]. These were authored using the ASPIRE authoring system [8,83,84].

Second, cognitive tutors use a MT approach to maximise accuracy in learning the process of a given task or domain [17]. Cognitive tutors use predefined rules to determine correct solutions [17]. Examples of cognitive tutors include: RIDES [85], REEDEM [72], xPST [86], GnuTutor [87] and AutoTutor [71]. Koedinger et al. [17] suggests that MTs tutors provide more useful remediation than constraint-based tutors. However, constraint-based tutors are empirically easier to implement [82] and they tend to more flexible in domains that emphasise an open-ended problem-solving approach over a closed-ended, procedural approach, like software engineering [66].

Third, [58] presented a hybrid domain modelling algorithm that combines CBM and MT together to leverage the benefits of both modelling techniques. For example, MT checks domain-specific rules, whereas, CBM provides support for open-ended and ill-defined solutions that cannot be easily expressed as rules. For example, MT is used to point out errors in design logic in the science domain, whereas, CBM is used to check for equally valid so-

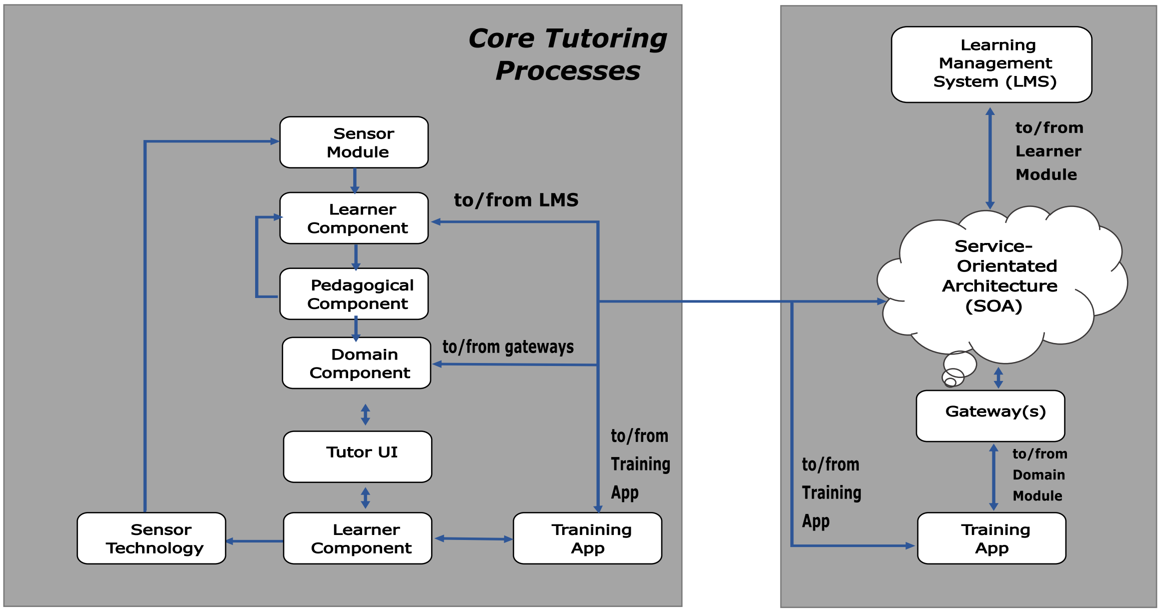

Fig. 5. Adaptation of GIFT architecture [73].

lutions that satisfy logic, but which have not been envisioned by the educator [58].

Fourth, Aleven et. al. [80] presented an entirely new method for modelling the domain: Example-Tracing. In general, Example-Tracing (ET) tutors record the correct solution as a graph based on correctly completed examples using a programming-by-demonstration technique. It then employs the same technique to record the graph of the students solution. The two graphs are compared and if differences are found, the system deems the solution to be incorrect.

2.2.4. Limitations of intelligent tutors

Limitations of ITSs are: (1) Instruction may not intuitively convey what needs to be done, such as adjustment to objects in the real-world; (2) Text-based instruction in a computer program is cumbersome, as it leads to misapplied attention [60,76], (3) Errors in psychomotor tasks may not be due to misunderstanding, but due to an incomplete mental model [53].

2.2.4.1. Intuitively conveying instruction. Spatial details such as where to place objects and how they need to be rotated can be ambiguous to explain in words [13]. For example, an instruction, Rotate 90° assumes understanding of spatial concepts by the learner, but research shows that learners experience greatly difficulty with such concepts [9,13,14,23,88]. Even skilled persons like undergraduates can experience such difficulty.

2.2.4.2. User interface design. Existing ITS applications are based on a desktop paradigm, but this creates a disconnect between the real-world and the tutoring instruction. For example, learners may perceive that the task is not an accurate depiction of reality, degrading interest and motivation [62,89] When performing hands-on tasks in the real-world, users may become distracted or overwhelmed by switching attention between the workspace and the user interface [50]. Moreover, desktop interfaces may not be suitable to convey the feedback in an intuitive manner, leading to user confusion [41]. For example, use of a keyboard and/or mouse may also break the learners sense of connectedness with the real environment [41].

2.2.4.3. Incomplete mental model. Even after the learner has mastered the knowledge necessary to perform a psychomotor task, the learner may continue to make mistakes. Errors are not necessarily due to incomplete knowledge, but can be due to performing a given action in an incorrect context [90].

For example, with machinery tasks, the learner must envision how the said machine looks in its completed and perfected form, by creating an internal mental model. However, this mental model tends to be inaccurate due to limited learner experience. Currently, ITSs with a desktop interface have limited means of presenting an ideal vision of the perfected system to the learner, even though, instructional design suggests that providing this information is necessary for mental model development [53].

2.3. Rationale for integrating AR with ITS

There are several reasons why it is beneficial to integrate an ITS into an AR training system: (1) Enhanced Usability in ITS-integrated training systems; (2) Intuitively conveying of instruction; (3) Enhanced Mental Model Development and finally, (4) Enhanced learning experiences.

Integrating an ITS with an AR training system improves learning by adding personalised instruction [8]. The AR technologies balance out the user interface limitations of desktop-based ITSs and the ITS balances out the limited learning support that most commercial AR training systems tend to provide [91].

2.3.1. Enhanced usability of ITS-integrated training systems

AR provides a more usable experience compared to paper-based instruction manuals and untracked 3-Dimensional (3D) interfaces, typically used by ITSs [92]. AR intuitively appears on the real world, helping to enhance motivation, engagement and usability [93]. Users perceive AR to be fun and exciting [48,93,94]. Maintenance and assembly tasks can also be performed more efficiently and quicker in an AR environment [12,92].

2.3.2. Intuitive conveying of instruction

ITSs are an effective way of providing a personalised learning experience. Combining them with AR provides the mechanisms for conveying spatial information that is fixed to a real world location [1,9,13,14,23]. This enables an AR training system to provide deeper

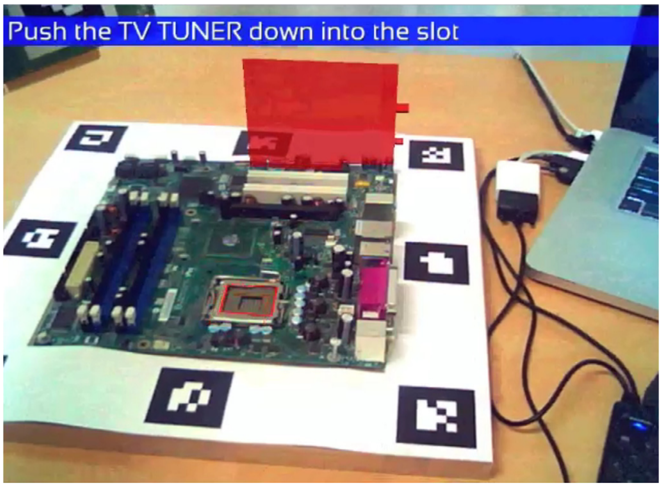

Fig. 6. Motherboard Assembly Tutor (MAT) (Used with permission) [8].

levels of feedback. Learners identify and correct their misconceptions in real-time, which improves learner retention and engagement, leading to higher learner gains [3,18,71].

2.3.3. More accurate mental model development

Psychomotor learning errors are generally the result of a mismatch between one's mental perception of the spatial environment, such as how the parts should be rotated [8]. Even experienced or trained professionals may make mistakes in this regard. AR helps mitigate these errors by imparting spatial information using tracked annotations [13,23,92]. Evidence of a more accurate mental model is faster performance in users of AR compared to non-AR interfaces [38,92]. Key studies have noted faster cognitive processing with AR compared to untracked 3D interfaces or paper [13,23,92]. Moreover, because AR overlays annotations directly on the workspace, users are not distracted due to looking at instruction manuals. This maximises cognitive resources and allows better focus on learning [50]. The creation of a mental model also uses cognitive resources, which is reduced when the learner can directly map the real-world with the virtual, as in the case with AR.

2.3.4. Experience shaped by environment

The Experiential Learning Theory (ELT) [95] suggests that learning involves interacting with the environment. For example, children develop their a mental model of how things work by playing with things in the environment [88,95,96]. This suggests that the combination of the real-world with AR annotations creates an environment, whereby the learner can construct their own mental model of the domain [97].

2.4. Example AR intelligent tutoring systems

In this section we review several previous training systems that combine ITS and AR.

2.4.1. Motherboard assembly tutor

Motherboard Assembly Tutor (MAT) is a prototype AR training system that is integrated with an ITS to provide a personalised training experience [12]. It focuses on correctly rotating, aligning and positioning of computer parts onto a motherboard [98]. The infrequent movement of the motherboard and the relatively large components makes it an ideal case study for investigating assembly tasks. Fig. 6 shows the prototype.

Although, MAT is domain-specific, its architecture can be adapted to similar psychomotor domains [12]. The architecture consists of three core components: (1) The ITS layer; (2) the communication layer and (3) the AR interface layer. The ITS layer is the external ITS, which in the case of MAT, was an ITS authored using ASPIRE [12,83]. It communicates with the communication layer using Extensible Markup Language Remote Procedure Call (XML-RPC) over a local area network. The communication layer translates messages from the AR front-end into a format compatible with the ITS. The AR component provides the tracking, display and interaction. The tracking was implemented using ARToolkit markers [31] physically attached to the individual hardware components and to the motherboard, as shown in Fig. 6. MAT used a video-see-through HMD to provide a live video feed with the annotations overlaid, so users were required to wear a HMD tethered to a desktop computer. Finally, interaction was implemented by creating 3D models of the motherboard to show where (and how) to place the components.

MAT provides feedback from the ITS to show learners the steps to be completed, which were presented in a logical, structured sequence. The system does not proceed to the next step until the learner requests it [12,92]. The ITS then validates the student's solution and issues appropriate feedback. The learner would then be required to fix any errors in their solution before being presented with the next step. MAT additionally used a Heads-Up Display (HUD) to overlay text-based instruction in the HMD, which was anchored to a fixed position in the view, regardless of the surroundings [12].

The learning effectiveness of MAT was evaluated using a between participant study design to compare a standalone AR training system with an ITS enabled AR training system [12]. On average, the MAT with ITS enabled was rated higher in terms of its effectiveness by participants, produced fewer errors and retained more knowledge as measured by a post knowledge test held one week after the initial experiment [8]. Users also performed fewer errors in a hands-on practical test that was issued after the learning exercise, compared to the control group without the ITS enabled. Combining AR with ITS increased task performance by 30% and knowledge gains by 25% [9].

However, there are several limitations with MAT: limited deep learning detection; limited learning support and limited affective modelling. First, because the task is structured in such a way, it is possible to brute force the possibilities to force a correct answer. This effect, known as shallow learning, is a common shortcoming of second generation ITSs. Second, while MAT provides steps and issues feedback pertaining to each step, it falls short of the advanced learning support found in mixed-initiative ITSs. Since the early 2000s, ITSs have included the ability to request help, additional hints or even hold a natural conversation with the learner. Third, MAT prevents succession to the next step when a solution is invalid. The perceived lack of feedback pertaining to how to correct the problem may be a source of learner frustration, which in turn, may degrade their motivation [60,61].

2.4.2. ARWILD

ARWILD combines a spatial model of the real world with AR and an ITS to create realistic training scenarios that support military training tasks in environments, which are not specially designed to support combat training [10]. This system is a paradigm shift in ITSs because not only does it change the interface layer of the training experience by swapping the desktop for an augmented environment [10], but it also seeks to combine the environment itself with the ITS as shown in Figs. 7 and 8.

ARWILD is the first example in the literature where an ITS-based framework, the Generalized Intelligent Framework for Tutoring (GIFT) is integrated with AR. It is not intended to teach as-

Fig. 7. ARWild Illustration (Used with permission) [10].

Fig. 8. ARWild Illustration (Used with permission) [10].

sembly or maintenance tasks, so does not use traditional annotations like text, or arrows. Rather, the purpose of AR is to add virtual objects and avatars to enhance the sense of realism of the training scenario. A modified Oculus Rift VR Head-Mounted Display (HMD), was converted into a video-see-through AR HMD. A lightweight depth sensor [10,99], was attached to the Oculus Rift to provide depth tracking. This allows virtual avatars to perceive real and virtual objects in the augmented environment and hide behind them during simulated combat scenarios [10]. The scene itself was authored using Unity3D, a commercial gaming engine. GIFT was used as the back-end ITS component. An application developed in Unity3D communicated with the tutoring engine by interfacing with the GIFT gateway using an Extensible Markup Language Remote Procedure Call (XML-RPC) compatible framework (Fig. 5).

ARWILD shows the potential of using ITSs in ill-defined domains beyond a traditional desktop-like User Interface (UI); the potential for integrating ITSs with third party AR applications and finally, the potential applications of AR for training, beyond structured maintenance and assembly training tasks. AR does not simply add richness to the experience, but is used to add context to the training environment, potentially enhancing learning.

However there were some noteworthy limitations [10]. First, using the Oculus Rift, the video feed introduced slight delays which could cause motion sickness. Second, the positions of the web cameras potentially reduces depth perception, impacting usability. Finally, no evaluation was done either on the usability of the ARWILD system, nor on its effectiveness of enhancing military-focused psychomotor skills.

2.4.3. Intelligent augmented reality radiology tutor

The Intelligent Augmented Reality Radiology tutor assists learners perform needle insertion tasks in radiology training [11]. The ITS component checks the alignment and angle of the inserted needle and uses AR annotations to guide the learner to perform the insertion correctly.

The system architecture consists of three components: (1) The ITS module; (2) The user interface module and (3) The AR module. However, the ITS module is a proof-of-concept module that merely issues feedback, calculates needle angle and precision, and aggregates data into a dashboard for later review. As such, even though, some personalisation of the tutoring experience occurs, it is significantly less than that offered in other common ITS systems like The Motherboard Assembly Tutor [12]. A preliminary evaluation showed that participants, who received personalised feedback from the prototype system, made fewer errors and had higher needle precision, compared to experts who had no such guidance [11].

2.5. Summary

In summary, AR overlays 3D graphics on the real world to create a more engaging learning experience in real-time [1,93]. AR enhances learning in hands-on assembly and repair tasks like machinery operation and repair by providing additional spatial cues [13,23,92]. Unfortunately, many existing AR training systems are designed specially for linear tasks and only provide limited individual learning support [9]. On the other hand, Intelligent Tutoring System (ITSs) use a variety of algorithms to provide personalised error detection, feedback and task sequencing [3], so combining them with AR is a promising solution for enhancing learning in hands-on tasks.

Only a few authors have addressed ITS/AR integration issues like feasibility, effectiveness and design [9–11]. Little research has been done on the user interface design. For example, AR has created a paradigm shift from desktop-based UIs to overlaid graphics on the real-world, but most ITSs are desktop-based systems, which have limited usability in a real environment [8,76].

Several promising systems exist: (1) The Motherboard Assembly Tutor (MAT) that overlays AR annotations on a computer motherboard to facilitate learning of computer part assembly [9]; (2) ARWILD facilitates inter-soldier communication using AR 3D avatars [10]. Finally, a proof-of-concept AR tutor that guides a learner through needle insertion in radiology tasks [11]. However, these systems lack discussion and integration of important design of user interfaces, and only [9] has evaluated the learning effectiveness of AR training systems combined with an ITS.

3. An ideal ARAT system

This section summarises the characteristics, design, and implementation of an ideal training system that combines ITS with AR. This is followed by a discussion of the implementation of such a system.

3.1. Design space

The Augmented Reality Adaptive Tutor (ARAT) design space classifies systems that combine ITS with AR. This is a combination of the existing reality-virtuality continuum [21] and a proposed ITS generation continuum.

3.1.1. Reality-virtuality continuum

The Reality-Virtuality continuum [21] classifies experiences that fall somewhere in between the real-world and a fully immersive virtual environment. Interfaces are arranged on this continuum depending on how much they replace the users view of the real world. For example, VR aims to completely immerse the user in a virtual world, so it is at the far-right end of the continuum. On the

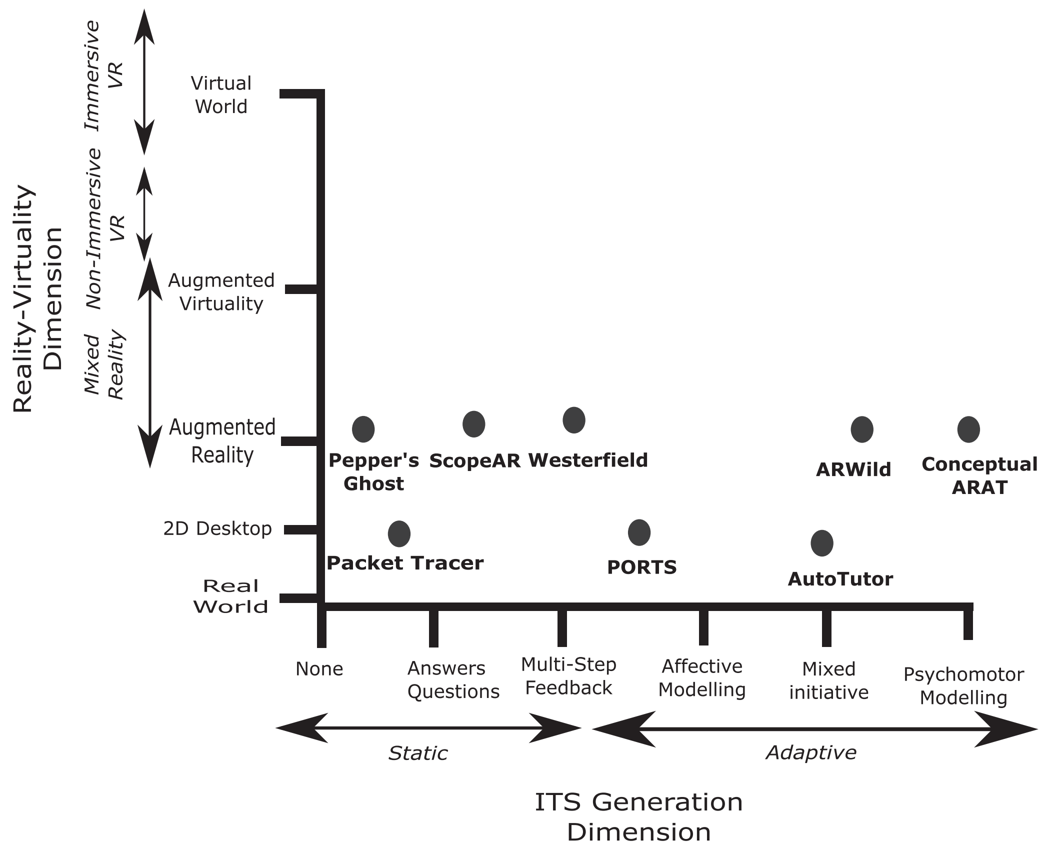

Fig. 9. ARAT design space.

other hand, AR falls somewhere in-between, by combining virtual content with reality.

3.1.2. ITS generation continuum

ITS have transitioned through various phases since their conception in the early 1970s. Each phase represents a paradigm shift in ITS research and development. First Generation ITS performed basic sequencing of information based on questions [51]. Second generation ITS incorporated an inner loop to provide feedback on a sub-step and is now considered an essential feature for any ITS [80]. Third generation ITSs incorporated affective state modelling, allowing it to understand and issue feedback based on a learners emotional states [71,74]. Fourth generation ITSs incorporated a mixed-initiative design so that they be interactive [75]. The user could issue questions and feedback to the ITS. Finally, fifth generation ITSs are combined with external applications and provides complex forms of modelling such as psychomotor modelling [60].

We propose a novel ITS generation continuum, which depicts the characteristics found in each generation. For example, psychomotor modelling is at the far right of the continuum because they depend on the other features. On the far left of the system is a training system that issues feedback but provides no personalisation.

3.1.3. Proposed design space

Many of the requirements for combining ITSs with AR are needed to combine ITS with either the real-world, or with virtual environments and as such, are not exclusive to AR. Due to this, such systems can be categorised on both the Reality-Virtuality continuum [21] and our proposed ITS Generation Continuum. We propose a novel design space that combines the two separate continuums together into the one space. Fig. 9 illustrates the design space and includes some example systems, including desktop training applications for comparative purposes. ITSs are loosely defined and some are closer to conventional training systems than to artificial intelligence. Due to this, a means of categorising the two paradigms: Reality-Virtuality and ITS capabilities are an essential motivation behind conceiving this design space. For example, although, we do not consider ScopeAR to be an ITS, it still employs some features of an ITS such as feedback. To provide clarity, ScopeAR would be placed in the design space to illustrate its capabilities. Similarly, combining an ITS with 3D desktop applications like FlightGear, an open-source flight simulator [100] would require many of the requirements of integrating with AR, even though, the display is not in the real-world.

3.2. Adaptive augmented reality tutor (ARAT) definition

An Augmented Reality Adaptive Tutor (ARAT) is a computer-based training system that: (1) Uses spatial information from the real-world to detect errors, provide feedback and/or sequence tasks using an ITS; (2) Uses Augmented Reality to enhance learning and (3) Creates context by using a combination of instructional cues and Augmented Reality. An ARAT is an AR training system that is integrated with an ITS. It facilitates the exchange and sharing of information about the user's real-world between an AR application and an external ITS.

An ARAT comprises of these characteristics:

1. *Dynamic spatial information sharing*: An AR front-end application dynamically exchanges its spatial information with an ITS, which uses it to perform psychomotor modelling.
2. *Dynamic augmented environment in real time*: ARATs provide a dynamic augmented environment that is updated in real time by using the modelling techniques of the ITS

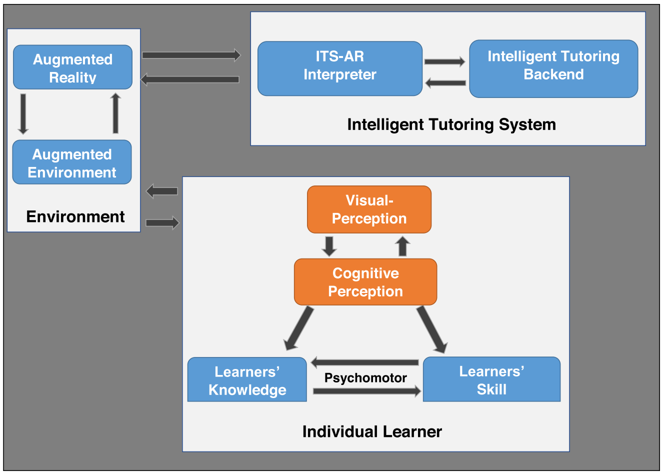

Fig. 10. ARAT conceptual architecture.

3. *AR-based instruction*: The ITS performs dynamic augmented environment to convey instruction using AR
4. *Environment context*: The instruction is combined with AR to create context that is used by the learner for mental model construction.

There are two fundamental principles to ARATs. First, the AR application works in unison with the ITS to convey a unified instructional aim. For example, using AR to show a virtual teacher in the real-world, or mixing unrelated AR content are not ARATs because the instructional aims are not integrated into AR. Furthermore, such design would likely be distracting [101,102]. Such information richness does not necessarily facilitate learning, even though, it mimics current real-world practice. Such examples mix AR and ITS technologies together in the sense that they are both used in the same learning experience, but they are not combined in an instructional sense. An example of appropriate ARAT design is an automative repair application [44]. In this example, AR is used to overlay annotations to illustrate how a completed automobile engine would appear, helping the learner create an accurate mental model of how the engine works, when completed correctly. The AR plays a direct role of enhancing the instruction.

ARATs differ from standalone AR training systems in the following ways:

1. *Uses ITS modelling:* ARATs use ITS modelling to provide learner support, rather than simple coded rules.
2. *Spatial sharing:* Shares spatial 3-Dimensional (3D) information with an ITS to provide psychomotor modelling support
3. *Combines AR with instruction:* AR is used to improve the understanding of any complementary instruction, such as using pointing arrows to clarify what needs to be done.

3.3. ARAT architecture

The ARAT conceptual architecture (Fig. 10) shows the individual components of an ARAT and the interaction between them. An ARAT consists of: (1) The individual learner; (2) The augmented environment and (3) the intelligent tutoring back end. The augmented environment consists of both the application used to facilitate AR experiences, as well as the resulting environment that is created by combining real and virtual together to create the mixed reality experience [21]. This architecture is based loosely on the diagram presented by [103], but adds a forth element, context. The intelligent tutoring back-end performs the modelling capabilities and provides an adapted AR experience.

In general, learners develop their mental models by interacting with the environment [95,96,104]. Human learners adapt their behaviour to conform to the social environment and this leads to a habitual mode of processing information [96]. This can lead to cognitive biases and errors in learning that must be relearned correctly [96]. The connection between the environment and instruction adds context that facilitates this relearning process [96]. For example, when assembling a motherboard, learners tend to relate it to their previous experiences. However, this perception may differ from reality due to gaps in knowledge [105]. The role of the ARAT is to correct learner errors using AR.

4. Designing ARAT systems

This section proposes a three-stage process for designing and implementing ARATs in a training and education context: (1) Identify challenges and limitations; (2) Identify system requirements and finally, (3) Detail feasible implementations.

4.1. Challenges and limitations identification

The first stage is to identify the challenges and limitations, so the system can be appropriately designed to mitigate them [106]. From the literature, the following challenges and limitations are noteworthy:

1. *Authoring support*: One of the significant limitations of ITS systems are their limited authoring capabilities [107,108]. This includes no authoring support for ITSs in AR learning tasks [8].
2. *Extensibility*: ITSs need to be extensible to support additional domains and changes to learning standards and procedures [61]. Currently, many ITSs are standalone systems that support a limited number of domains.
3. *System usability*: AR provides unique accordances compared to desktop-based user interfaces. This change in paradigm means that existing ITSs will have usability issues [41,109]
4. *Interoperability*: ITSs need to support necessary capabilities to be integrated into AR, such as support for a spatial 3D ontology and schema [9].

From these challenges and limitations, a series of design requirements can be inferred, as further described below:

4.1.1. Authoring support

Although ITSs have been shown to improve learner gains, their use in education is comparatively low, due to the limited resources in authoring such systems [107]. Some authoring tools have been developed to support ITS development including: (1) REDEEM [72]; (2) RIDES [85]; (3) Cognitive Tutor Authoring Tools (CTAT) [79]; (4) ASPIRE [83] and finally, (5) GIFT [110]. However, except for GIFT, these tools do not support authoring of psychomotor tasks that have a 3D component [9] and many of these authoring systems cannot interpret 3D ontologies.

4.1.2. Extensibility

Deploying an ITS is a time consuming and costly process [107] because many of them are designed only for a specific domain [61]. Consequently, many of the components of these systems cannot be reused, which results in a lot of wasted effort in developing these systems.

4.1.3. User interface

The user interface design of ITSs and ITS authoring tools tend to use a desktop design [76]. However, since AR uses different affordances than desktop user interfaces (UIs), a new design is necessary [109]. Current designs of AR training systems vary considerably due to lack of uniform standards [44]. This leads to inconsistency in their use and makes them difficult to compare and employ across domains.

4.1.4. Interoperability

Both AR and the ITS require a common framework to be able to communicate with each other, but existing ITSs are not designed for this. Consequently, ITSs may not be interoperable with other systems. For example, many ITSs lack a schema of the 3D world [8]. Since AR pertains to the real, 3D world, it follows that an ITS needs to have some level of spatial understanding of what the learner is doing in the real world. However, many existing ITSs are desktop systems, so lack this important feature. Modern authoring tools support communicating with third party applications over a computer network to provide integration. In this case, a server is used to provide a common framework. Some standards exist for communicating data of this kind over a network such as the JavaScript Object Notation (JSON) syntax for standardised exchange of messages.

4.2. System requirements

The second phase of design is to identify the system requirements for an ARAT system. The purpose of the design should be to create a modular ARAT system, that can be easily tailored to an individual educator's needs.

4.2.1. Extensibility

ARATs need to be interoperable to support an educator's requirements and the diverse application of Augmented Reality. To achieve this, we propose the following requirements:

1. *Leverage flexible modelling capabilities*: This supports the open-ended nature of AR domains.
2. *Flexible feedback presentation*: The system needs to be flexible in how the feedback can be presented, so that it can be integrated into a task that has been designed for use in an augmented environment.
3. *Modular architecture*: Support for and integrating a modular architecture to support extending the capabilities of the system.
4. *Content separation*: Separate content such as the spatial model from the programming logic [103].

4.2.1.1. Flexible modelling capabilities to support the open-ended nature of psychomotor domains. For psychomotor domains, the ITS modelling capabilities must allow the learner to complete the task step(s) in any order they like [8,90]. Constraint-Based Modelling (CBM) tutors are easier to adapt than cognitive tutors for this kind of problem [57,82]. In addition to implementing a suitable modelling algorithm, the ITS also needs to incorporate real-time, proactive modelling, which means to predict and respond to certain behaviours as they are happening, including constantly changing its pedagogy [111].

Assessments in the psychomotor domain necessitates the need for modelling psychomotor learning based on one's reaction time and precision in a given training activity [60,76]. This may include, for instance, understanding distances between objects in the real world and the learner's muscle position when performing a task. Currently, only few systems including GIFT has implemented support for psychomotor modelling.

4.2.1.2. Flexible feedback presentation. The system needs to be flexible in how the feedback can be presented, so that it can be integrated into a task that has been designed for use in an augmented environment. Ideally, feedback should avoid overwhelming the learner with redundant information [112].

4.2.1.3. Modular architecture. An architecture that is modular allows incorporation of various modules to support specific domains. Two reasons for the modular design include: (1) Psychomotor pedagogical strategies are not standardised and (2) AR is typically used in flexible and complex domains, which requires their own pedagogical strategies. First, psychomotor pedagogical strategies are not well understood, so educators need to develop and implement their own strategies. A modular architecture allows these strategies to be more easily integrated [61]. Second, AR is a flexible domain and as previously discussed, has broad application across many domains. However, even within domains, pedagogical strategies can vary depending on learner aims. A given strategy is not necessarily effective across all domains, so new pedagogical approaches will be needed. As such, a generalised architecture is suitable for addressing these concerns by allowing rapid authoring of generalised systems [60].

4.2.1.4. Separate content from logic. Programming or integrating the spatial model into the ITS logic should be avoided, since it limits the flexibility of the training experience. For example, this can be accomplished using a message bus that standardises data that is shared across subsystems [60]. Finally, Table 1 shows a comparison of the extensibility capabilities for some common authoring systems: GIFT, ASPIRE, Reusable Educational Design Environment and Engineering Methodology (REDEEM), RIDES, Extensible Problem Specific Tutor (xPST) and CTAT.

4.2.2. Interoperability

Interoperability is necessary to integrate AR and ITS technologies together. Since neither system uses the same standard, a common gateway, such as a server is necessary to exchange messages between the two systems.

1. *Support for 3D schemas*: The ITS back-end needs to be capable of supporting 3-Dimensional (3D) concepts used in AR environments [8].
2. *Networking*: The ITS needs to support interfacing with networked applications like a common gateway server [8,113].
3. *Abstraction library*: A common abstraction library for interpreting generic messages from remote applications. If support is lacking, this can be implemented in a common gateway server [113].
4. *Support for non-standard interfaces*: To facilitate use in AR, the ITS needs to be support decoupling from its standard interface for use with AR [8].

The AR side needs support for the following

1. *3D Schema*: Understanding of 3D concepts. This is implied in AR applications. [8].
2. *Abstraction Library*: Support for an abstraction library. Can be offloaded to a common gateway server if not supported [113].
3. *Networking*: Ability to communicate with a common gateway server and/or with an ITS system [8,103].

4.2.2.1. 3D schema support. Augmented Reality requires a schema, which represents 3D concepts [1]. For example, in assembly tasks, the ITS generally needs to understand the manipulation and rotation of components to provide appropriate remediation [12]. Systems, like ASPIRE, have limited support for authoring a spatial schema [8].

4.2.2.2. Networking and interfacing capabilities. Augmented reality requires a network communication layer to facilitate the exchange of spatial messages from an AR tracking Application Programming Interface (API) to a gateway service, or the ITS. Moreover, an abstraction library is needed to enable the AR and ITS to exchange data messages that are compatible with each other [60].

Table 1
Different authoring tools extensibility capabilities.

ITS authoring tool	Flexible modelling	Feedback presentation	Psychomotor modelling	Modular architecture
GIFT	Yes	Yes	Yes	Yes
ASPIRE	Yes	Yes	No	No
REDEEM	No	No	No	No
RIDES	No	No	No	No
xPST	No	Yes	No	No
CTAT	Yes	No	No	No

Table 2
Different authoring tools technical capabilities.

ITS authoring tool	Flexible modelling	Feedback presentation	Psychomotor modelling	Modular architecture	Custom interfaces	Mixed initiative
GIFT	Yes	Yes	Yes	Yes	Yes	Yes
ASPIRE	No	Yes	No	No	Yes	Yes
REDEEM	No	No	No	No	No	No
RIDES	No	No	No	No	No	Yes
xPST	No	No	No	Yes	Yes	No
CTAT	No	No	No	No	No	Yes

4.2.2.3. Spatial modelling. Storing of the spatial model is a complex problem, and one solution is for the front-end application to maintain the spatial model and send incremental updates to the ITS. Inclusion of such a spatial model in ITSs has previously been limited, in part because until recently, many ITSs did not model the psychomotor domain [76]. Even authoring systems like RIDES that have a simulator focus [85] did not implement a spatial model. This is because these systems only provided a 2-Dimensional (2D) representation of the real world being simulated. Table 2 shows a comparison of the technical requirements between several common ITS authoring systems: GIFT, RIDES, ASPIRE,REDEEM, xPST and CTAT.

4.2.3. System usability

Incorporating AR with ITS creates a unique set of usability requirements because AR has fundamentally changed the way systems are used, transitioning from a system centric focus to a user-centric focus [41,109]. For example, AR is described as a "next generation" interface that *'affords'* different interaction techniques from desktop-based interfaces [109].

An ARAT should have these usability requirements:

1. *Leverage AR accordances*: Leverage AR accordance such as touch and gesture-based input [109].
2. *Authoring system integration*: Integrate an authoring user interface to facilitate ITS authoring and development [8,72,85,107].
3. *Feedback presentation*: Present feedback in a manner to limit obstructiveness of the view space

4.2.3.1. AR accordances. Extensive work has shown that input devices like stylus pens, sensors and tangible user interfaces provides a more effective experience in AR than keyboard and mouse [41,42]. For example, stylus pen and pointing devices are used to show a cursor on the object in the real world. In other cases, AR tracking technology can be used to provide input, such as being used to detect position and orientation of objects and their distance from other markers tracked in the real-world [8]. As illustrated in PC-based Open-Architecture Reconfigurable Training System (PORTS) [112] and in TeachAR [48], speech recognition provides an intuitive way of interacting with the real world [48,112]. Another approach is eye tracking designed track the users' eye gaze and movements, for example, selecting real world objects by gazing at them for an extended period. These technologies could also be combined. For example, eye gaze with touch [114]. Head-Mounted Displays (HMDs) also have their own controls for input. For instance, the Microsoft HoloLens implements an air tap gesture that can be used to provide basic forms of input.

4.2.3.2. Authoring system integration. Providing an authoring tool is a necessary requirement for any widespread deployment of an ITS system [60,61,63,108]. The ITS used as the back-end component of an ARAT system should be capable of being authored using an authoring interface. For example, ASPIRE was used to author the ITS that formed the tutoring basis of the Motherboard Assembly Tutor (MAT) system [12]. This is of particular importance in an ARAT because the complexity of the spatial schema is very difficult to implement without an authoring tool [8]. However, many existing authoring systems such as ASPIRE lack support for authoring a spatial schema [8,12]. The GIFT Authoring System (GAS), which authors GIFT applications does have some support for spatial schema authoring but it is incomplete.

The ability to change the level of difficulty and provide for user control is important [19]. For example, REDEEM authoring tool allowed certain aspects of the tutoring experience to be disabled [72].

4.2.3.3. Feedback positioning. Text-based feedback should not be overlaid excessively, nor positioned where it could obscure the physical workspace. To alleviate this, feedback text can be combined with other forms of feedback, such as annotations, or with audio (such as pre-recorded instruction or synthesised speech). A bright colour should be used to minimise the affects of contrast between the real background and the text. The text should also be of a reasonable size to maximise readability, including dynamically resizing the text to a larger font when possible.

Table 3 compares these usability capabilities between various authoring systems: GIFT, ASPIRE, REDEEM, RIDES, xPST and CTAT.

4.3. ARAT implementations

The third phase of the design process is implementation. This paper describes two potential forms for implementing an ARAT:

1. *Non-intelligent client-based ARAT:* No logic in the AR application, which simply handles tracking, display, interaction and showing annotations when instructed.
2. *Intelligent client-based ARAT:* Partial logic in the AR application, which maintains its own spatial model and decides when/how to show AR content based on states, or messages sent to it from the ITS.

Table 3
Different authoring tools usability characteristics

ITS authoring tool	Separate content	Feedback presentation	Spatial schema authoring	Tweak interface	AR input supported
GIFT	Yes	Yes	No	No	Yes
ASPIRE	Yes	Yes	No	No	Yes
REDEEM	No	No	No	Yes	No
RIDES	No	No	No	Yes	No
xPST	No	Yes	No	No	Yes
CTAT	Yes	No	No	No	No

4.3.1. Non-intelligent client-based ARAT

A Non-Intelligent Client-Based ARAT consists of a front-end AR application, an optional server for message translation and a standalone ITS, which communicate with each other over a local area network. The AR application handles the tracking and shows AR content when it receives a message from an external server or ITS. An external server may provide a translation service that converts messages to/from the ITS to enable communication between the two applications. Spatial schemas are constructed and cached by the server, or by the ITS performing that role by using data it receives from the front-end AR application. An example of this kind of implementation is the MAT, which used an ITS to cache spatial information [12]. The downside of this approach is that either a server must be developed or the ITS domain model must be modified to add support for a 3D spatial model.

4.3.2. Intelligent client-based ARAT

An Intelligent Client-Based ARAT consists of a front-end AR application that communicates with a server, (or an ITS performing the server role) over a computer network, but instead of relying on the ITS constructing its own spatial model, the front-end AR application performs this role. In such a design, the ITS sends messages that the intelligent ARAT uses to adapt the spatial model, such as the display of annotations accordingly.

In this design, the ITS typically does not require a spatial model because the AR application is using AR mechanisms to determine spatial actions. For example, the ARAT would flag an object as not being correctly rotated and represent this to the ITS as some Boolean state. The ITS would then apply its pedagogical strategy, which may include providing feedback. The downside of this design is that the ITS may lack the ability to provide sufficient remediation because it does not include the full spatial model itself. For example, it would simply know that a student's solution is wrong, but not necessarily why. Additional development on the AR side might be necessary to provide effective learner support.

This design works well for ITSs that lack support for psychomotor modelling. For example, [12] noted limited spatial and psychomotor modelling in the ASPIRE authoring system. Such a design is implemented in ARWILD [10] where the Unity application performs the advanced detection techniques, but how this is represented to the ITS is not specified.

4.4. Summary

Integrating AR with ITSs is a challenging process because neither system is designed to be used together. However, modern ITSs and authoring tools have interoperable mechanisms that allow for such integration. For example, ASPIRE includes a network component that enables it to connect with external applications like AR [9]. Furthermore, many ITSs lack authoring support for spatial 3D concepts used by AR and many existing ITS are desktop focused, which are not usable in AR.

To overcome these limitations and challenges, we have identified three categories: (1) Extensibility; (2) Interoperability and (3) Usability. First, to support an extensible ITS, the ITS requires a modular architecture to enable use in a variety of educational domains, including AR. Second, to support interoperability, we recommend a system with networking support, where the ITS can communicate with a common gateway server over the network. This is because neither the AR application, nor the ITS implement a common framework for interpreting messages to/from the ITS. Finally, system usability is essential for widespread acceptance. This includes an authoring system that can support authoring of AR courses, including spatial 3D concepts. We also recommend support for AR-based interaction techniques like eye gaze and touch.

5. Opportunities for future work

This section describes opportunities for future work by identifying a series of unexplored research areas, which pertain to combining AR with ITSs. Overall, there are four major areas worthy of exploring: (1) Education theory; (2) Augmented Reality Adaptive Tutor (ARAT) design; (3) Learning effectiveness and finally, (4) Technical research.

5.1. Educational theory

Psychomotor training requires a different pedagogical approach than traditional forms of classroom-like learning. Some alternate pedagogies for psychomotor training have been proposed: (1) discovery-based learning; (2) inquiry learning and (3) active learning [115–117]. However, additional work is needed to understand the relationship between psychomotor skill and cognition [55].

It is unclear, to what extent, other dimensions of learning, such as motivation and engagement plays in the learning experience. For example, cognitive theories on education such as [55,118] do not include a mechanism that addresses issues like motivation and engagement. Understanding and integrating engagement and motivation can provide insight into ill-guided learning practices by students, such as shallow learning, which occurs when the learner blindly completes steps typically by guessing.

While AR and Human Computer Interaction (HCI) research has focused significantly on practical education, less work exists in the field of education that addresses learning that facilitates concrete knowledge transfer or the development of psychomotor skills [109]. In many cases, education literature has found that such methods do not assist with knowledge retention. This suggests underdevelopment of a pedagogy for psychomotor tasks.

5.2. Limited work on ARATdesign

The current state of the art for ARAT system design is [12]. While authors such as [10,11] have since designed their own ARATs systems, these authors neither discuss ARAT requirements, nor provide any design guidelines.

There is extensive research on the usability of AR systems in the field of HCI, but considerably less on the technical or pedagogical considerations. For example, one of the unexplored areas of pedagogical design is the integration of instruction with AR, so that both work in unison. AR training systems have inconsistent designs for displaying feedback in conjunction with AR, which suggests that the research is underdeveloped [8,44]. Even though mistakes are a necessary component of the learning experience, few systems in the literature contain mechanisms that follow this design [90].

5.2.1. System requirements

Additional work is necessary to understand the design requirements for ARATs. Only some papers explicitly discuss system requirements [9,12,12]. Areas lacking discussion include: (1) Design of a framework for integrating AR and ITS; (2) An enhanced authoring tool to support 3D spatial modelling and finally, (3) An adapted knowledge representation modelling algorithm to provide enhanced support for problem-based learning approaches.

Although, usability of AR systems has been extensively studied, little is known about the co-existence of ITS paradigms with AR. For example, reading text-based feedback on a head-mounted display (HMD) might be problematic. This suggests that alternate designs for user interfaces are needed to provide the feedback. Future research could explore the effectiveness of alternate approaches. Another potential area for research is accessibility of ITS interfaces for children and persons with disabilities [94]. This is because such persons may have different requirements pertaining to the design, which has not yet been explored significantly, in an ARAT context.

Users of Motherboard Assembly Tutor (MAT) self-reported high usability when using either variant of the system, but standardised instruments like System Usability Scale (SUS) [119] were not used and a full usability study was not performed.

5.3. More work needed on learning effectiveness

Currently, [8] has presented some work on evaluating the learning effectiveness of ARATs, but neither [10], nor [11] performed any evaluation of the learning effectiveness. There is potential to evaluate learning more broadly, such as concrete knowledge transfer and immersion in the experience.

Evaluating the learning effectiveness is difficult because of the ambiguous nature of learning. For example, the fundamental question of what it means to learn is not consistent due to underdeveloped and inconsistent theories of learning. Learning is often viewed as a cognitive process whereby long time memory is changed through integration of new information [55]. However, other researchers view learning has a holistic process that involves thinking, reflecting and acting [120]. Within the field of HCI, learning is viewed as development of hands-on skills, whereby the outcome is improved efficiency [121]. Attempts in HCI at evaluating learning effectiveness of AR training systems involves both usability and knowledge gains [8].

Additional work could look at applying other theories including: (1) Specialisation theory; (2) Experiential learning theory and (3) Theories of motivation and engagement. For example, research could look at how different learners adapt their own learning styles to solve the problem. There has been some work applying Experiential Learning Theory (ELT) to technology, such as [122,123]. Werrlich et al. [19] discusses the role of passive learning in education. However, more work is needed, with applying ELT for evaluating learning in ARAT systems. Motivation and engagement is another area of exploration, for the iSmart AR system in [93] provided an example of using AR for motivation. However, additional work should explore the specific role motivation plays in learning for ARATs systems and how ITS feedback might be used to provide more motivating learning experiences.

There are assumptions about what kind of domains both AR and ITSs should be used in. Typically, AR has focused on training tasks that have a psychomotor (or spatial) focus. However, there are untested assumptions as to what specialised domain an ARAT enhances learning. Future research could explore a series of different domains to compare the level of effectiveness across domains. For example, due to the lack of studies concerning ARATs, it has only been shown that AR and ITS are effective in domains with simple procedural tasks [44]. Ultimately, ITSs may lack the sophistication to support more complex domains. The task domain can also affect learner factors such as cognitive load, which may be less of an issue in simple procedural domains. Future research could explore how knowledge retention (cognitive load) is impacted with the use of ARATs across domains.

5.4. Technical research

Technical research, such as improved AR tracking methods; ARAT architectural design and, finally, development of spatial ontologies are potential areas for technical research. Additional work is necessary to improve interoperability between sub-systems. For example, a mechanism to integrate a 3D spatial ontology into an ITS [8]. The design and integration of the spatial schema is still not well understood. Most common authoring systems like Cognitive Tutor Authoring Tools (CTAT) and ASPIRE lack any support for schema modelling.

Systems that recognise real world spatial information is a key aim of AR training systems, such ARWILD [5,10,76], but this is only the first step. Additional work is necessary to enable ITSs to interpret the real-world more intuitively, for example, using depth sensing technology. Research into these areas would enable enhanced recognition of real world cues, the movement of objects in the environment and/or human emotion.

6. Conclusion

This paper shows that there are opportunities for additional research on the design and evaluation of ITSs integrated into AR training systems. However, implementation of such systems is challenging, in part, due to the lack of standardised APIs and schemas. To help overcome these challenges, we presented a series of design guidelines and recommendations for implementing these systems. These include: (1) A generalised, modular architecture to support a variety of domains and pedagogical approaches; (2) Improved authoring capabilities for authoring AR courses; (3) Sparingly use of annotations to avoid overwhelming the learner; (4) computer networking support and an abstraction library for sharing data between the ITS and AR.

We proposed two possible methods for implementation: The Non-Intelligent Client-Based ARAT and the Intelligent Client-Based ARAT. The Non-Intelligent Client-Based ARAT offloads most of the spatial processing to a third-party server or the ITS, whereas the Intelligent Client-Based ARAT undertakes some spatial processing. It is evident that both designs are less than ideal because the spatial schema needs to be designed on a per-course basis and this is not feasible without an authoring system, but currently, only Generalized Intelligent Framework for Tutoring (GIFT) provides some authoring support. We described existing ARAT systems using each of these methods. We also described possible areas for future research. Currently, user interface design of AR training systems in an ITS context is not well understood and additional work is needed in this space. Current user interface paradigms are designed around a desktop UI, which has limited usability in an AR context. Additional development of tracking algorithms and education theories are also advised to improve ITS practicality and deployment with AR training systems.

This paper aimed to show that combining AR with ITSs has the potential to create cognitive support tools that are better suited for the nature of psychomotor training than desktop-based ITSs.

Currently, only few niche systems are known to exist and their design and implementation is far from consistent. Within the last few years, more standardised architectures such as GIFT have begun to emerge, which has the potential to improve research and development of ARATs systems.

Acknowledgements

We acknowledge that the work presented in this paper is supported by an Australian Government research scholarship, The Australian Research Training Program (RTP) scheme, a research training scheme established by the government of Australia. We would also like to acknowledge the authors, who kindly provided permission to use their figures in this paper.

References

[1] Azuma RT. A survey of augmented reality. Presence: Teleoperators Virtual Environ 1997;6(4):355–85. doi:10.1162/pres.1997.6.4.355.

[2] Radu I. Augmented reality in education: a meta-review and cross-media analysis. Pers Ubiquitous Comput 2014;18(6):1533–43. doi:10.1007/s00779-013-0747-y.

[3] Latham A, Crockett K, McLean D, Edmonds B. A conversational intelligent tutoring system to automatically predict learning styles. Comput Educ 2012;59(1):95–109. doi:10.1016/j.compedu.2011.11.001.

[4] Ludwig J, Ramachandran S, Howse W. Developing an adaptive intelligent flight trainer. Tech. Rep. Fort Rucker, Al, 36362: U.S. Army Research Institute; 2005.

[5] Sottilare R, Hackett M, Pike W, LaViola J. Adaptive instruction for medical training in the psychomotor domain. J Def Model Simul 2017;14(4):331–43. doi:10.1177/1548512916668680.

[6] Sottilare RA, LaViola J. A process for adaptive instruction of tasks in the psychomotor domain. In: Design recommendations for intelligent tutoring systems, Volume 4 - Domain Modelling. US Army Research Laboratory; 2016. p. 185–94.

[7] Chen Y-C. A study of comparing the use of augmented reality and physical models in chemistry education. In: Proceedings of the 2006 ACM international conference on virtual reality continuum and its applications, VRCIA '06;. New York, NY, USA: ACM; 2006. p. 369–72. doi:10.1145/1128923.1128990. ISBN 1-59593-324-7.

[8] Westerfield G. Intelligent augmented reality training for assembly and maintenance. Computer Science and Software Engineering; 2012. Thesis.

[9] Westerfield G, Mitrovic A, Billinghurst M. Intelligent augmented reality training for assembly tasks. In: Artificial intelligence in education. Springer, Berlin, Heidelberg; 2013. p. 542–51. doi:10.1007/978-3-642-39112-5_55. Lecture Notes in Computer Science.

[10] LaViola J, Williamson B, Brooks C, Veazanchin S, Sottilare R, Garrity P. Using augmented reality to tutor military tasks in the wild. In: Proceedings of the interservice/industry training simulation and education conference, Orlando, FL, USA, 15050; 2015. p. 1–10.

[11] Almiyad MA, Oakden-Rayner L, Weerasinghe A, Billinghurst M. Intelligent augmented reality tutoring for physical tasks with medical professionals. In: Artificial intelligence in education. Springer, Cham; 2017. p. 450–4. doi:10.1007/978-3-319-61425-0_38. Lecture Notes in Computer Science.

[12] Westerfield G, Mitrovic A, Billinghurst M. Intelligent augmented reality training for motherboard assembly. Int J Artif Intell Educ 2015;25(1):157–72. doi:10.1007/s40593-014-0032-x.

[13] Tang A, Owen C, Biocca F, Mou W. Comparative effectiveness of augmented reality in object assembly. In: Proceedings of the SIGCHI conference on human factors in computing systems CHI '03. Fort Lauderdale, Florida, USA: Association for Computing Machinery; 2003. p. 73–80. doi:10.1145/642611.642626. ISBN 978-1-58113-630-2.

[14] Wiedenmaier S, Oehme O, Schmidt L, Luczak H. Augmented reality (AR) for assembly processes design and experimental evaluation. Int J HumanComput Interact 2003;16(3):497–514. doi:10.1207/S15327590IJHC1603_7.

[15] Henderson S, Feiner S. Exploring the benefits of augmented reality documentation for maintenance and repair. IEEE Trans Visual Comput Graphics 2011;17(10):1355–68. doi:10.1109/TVCG.2010.245.

[16] Nesbit JC, Adesope OO, Liu Q, Ma W. How effective are intelligent tutoring systems in computer science education?. In: Proceedings of the 2014 IEEE 14th international conference on advanced learning technologies; 2014. p. 99–103. doi:10.1109/ICALT.2014.38.

[17] Koedinger K, Anderson J, Hadley W, Mark M. Intelligent tutoring goes to school in the big city. Human-Comput Interact Inst 1997;8:30–43.

[18] VanLehn K. The relative effectiveness of human tutoring, intelligent tutoring systems, and other tutoring systems. Educ Psychol 2011;46(4):197–221. doi:10.1080/00461520.2011.611369.

[19] Werrlich S, Eichstetter E, Nitsche K, Notni G. An overview of evaluations using augmented reality for assembly training tasks. World Acad Sci Eng Technol Int J Comput Electr Automat Control Inf Eng 2017;11(10):1054–60.

[20] Wang X, Ong SK, Nee AYC. A comprehensive survey of augmented reality assembly research. Adv Manuf 2016;4(1):1–22. doi:10.1007/s40436-015-0131-4.

[21] Milgram P, Takemura H, Utsumi A, Kishino F. Augmented reality: a class of displays on the reality-virtuality continuum. In: Das H, editor. Proceedings of SPIE, 2351. The International Society for Optical Engineering; 1995. p. 282–92. doi:10.1117/12.197321.

[22] Caudell TP, Mizell DW. Augmented reality: an application of heads-up display technology to manual manufacturing processes. In: Proceedings of the twenty-fifth hawaii international conference on System Sciences, 1992, ii; 1992. p. 659–669 vol. 2. doi:10.1109/HICSS.1992.183317.

[23] Henderson SJ, Feiner S. Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret. In: Proceedings of the 2009 8th IEEE international symposium on mixed and augmented reality; 2009. p. 135–44. doi:10.1109/ISMAR.2009.5336486.

[24] Matsutomo S, Miyauchi T, Noguchi S, Yamashita H. Real-time visualization system of magnetic field utilizing augmented reality technology for education. IEEE Trans Magn 2012;48(2):531–4. doi:10.1109/TMAG.2011.2174208.

[25] Quarles J, Lampotang S, Fischler I, Fishwick P, Lok B. A mixed reality approach for merging abstract and concrete knowledge. In: Proceedings of the 2008 IEEE virtual reality conference; 2008. p. 27–34. doi:10.1109/VR.2008.4480746.

[26] ScopeAR. Worklink. Retrieved 19 April 2018; n.d. http://www.scopear.com/products/worklink/.

[27] Billinghurst M, Clark A, Lee G. A survey of augmented reality. Found Trends Hum-Comput Interact 2015;8(2–3):73–272. doi:10.1561/1100000049.

[28] Inc. P. Getting started. Retrieved 5 July 2016; n.d. https://developer.vuforia.com/library/getting-started.

[29] How to setup a simple unity project. Retrieved 15 Aug 2016; https://library.vuforia.com/articles/Solution/Compiling-a-Simple-Unity-Project.

[30] DAQRI. Artoolkit for unity. Retrieved 15 Aug 2016; n.d. https://artoolkit.org/documentation/doku.php?id=6_Unity:unity_about.

[31] Kato H, Billinghurst M. Marker tracking and hmd calibration for a video-based augmented reality conferencing system. In: Proceedings. 2nd IEEE and ACM international workshop on augmented reality, 1999. (IWAR '99); 1999. p. 85–94. doi:10.1109/IWAR.1999.803809.

[32] Apple Inc. ARKit. n.d. https://developer.apple.com/arkit/.

[33] Google Inc. ARCore overview | ARCore. 2018. https://developers.google.com/ar/discover/.

[34] Kim SL, Suk HJ, Kang JH, Jung JM, Laine TH, Westlin J. Using unity 3d to facilitate mobile augmented reality game development. In: Proceedings of the 2014 IEEE world forum on internet of things (WF-IoT); 2014. p. 21–6. doi:10.1109/WF-IoT.2014.6803110.

[35] Althoff T, White RW, Horvitz E. Influence of Pokmon go on physical activity: study and implications. J Med Internet Res 2016;18(12). doi:10.2196/jmir.6759.

[36] Poelman R, Krevelen van D. A survey of augmented reality technologies, applications and limitations. Int J Virtual Real 2010;9(2):1–20.

[37] Evans G, Miller J, Pena MI, MacAllister A, Winer E. Evaluating the Microsoft HoloLens through an augmented reality assembly application. In: Proceedings of the Degraded Environments: Sensing, Processing, and Display 2017, 10197. International Society for Optics and Photonics; 2017. p. 101970V. doi:10.1117/12.2262626.

[38] Marner MR, Irlitti A, Thomas BH. Improving procedural task performance with augmented reality annotations. In: Proceedings of the 2013 IEEE international symposium on mixed and augmented reality (ISMAR). Adelaide, SA, Australia: IEEE; 2013. p. 39–48. doi:10.1109/ISMAR.2013.6671762.

[39] Irlitti A, Von Itzstein S. Validating constraint driven design techniques in spatial augmented reality. In: Proceedings of the fourteenth Australasian user interface conference. In: AUIC '13, 139. Darlinghurst, Australia, Australia: Australian Computer Society, Inc.; 2013. p. 63–72. ISBN 978-1-921770-24-1.

[40] Tan CSS, Luyten K, Van Den Bergh J, Schöning J, Coninx K. The role of physiological cues during remote collaboration. Presence: Teleoperators Virtual Environ 2014;23(1):90–107.

[41] Billinghurst M. Hands and speech in space: multimodal interaction with augmented reality interfaces. In: Proceedings of the 15th ACM on international conference on multimodal interaction ICMI '13;. New York, NY, USA: ACM; 2013. p. 379–80. doi:10.1145/2522848.2532202. ISBN 978-1-4503-2129-7.

[42] Ha T, Feiner S, Woo W. Wearhand: Head-worn, rgb-d camera-based, bare-hand user interface with visually enhanced depth perception. In: Proceedings of the 2014 IEEE international symposium on mixed and augmented reality (ISMAR); 2014. p. 219–28. doi:10.1109/ISMAR.2014.6948431.

[43] Kaufmann H, Dnser A. Summary of usability evaluations of an educational augmented reality application. In: Virtual reality. Springer, Berlin, Heidelberg; 2007. p. 660–9. doi:10.1007/978-3-540-73335-5_71.

[44] Yin X, Gu Y, Qiu S, Fan X. VR amp;amp;AR combined manual operation instruction system on industry products: a case study. In: Proceedings of the 2014 international conference on virtual reality and visualization; 2014. p. 65–72. doi:10.1109/ICVRV.2014.55.

[45] Adas HA, Shetty S, Hargrove SK. Virtual and augmented reality based assembly design system for personalized learning. In: Proceedings of the 2013 science and information conference; 2013. p. 696–702.

[46] Kaufmann H, Meyer B. Simulating educational physical experiments in augmented reality. In: ACM SIGGRAPH ASIA 2008 educators programme SIGGRAPH Asia '08;. New York, NY, USA: ACM; 2008. p. 3:1–3:8. doi:10.1145/1507713.1507717. ISBN 978-1-60558-388-4.

[47] Singhal S, Bagga S, Goyal P, Saxena V. Augmented chemistry: interactive education system. Int J Comput Appl 2012;49(15):1–5.

[48] Dalim CSC, Dey A, Piumsomboon T, Billinghurst M, Sunar S. TeachAR: an inter augmented reality tool for teaching basic english to non-native children. In: Proceedings of the 2016 IEEE international symposium on mixed and augmented reality (ISMAR-Adjunct); 2016. p. 82–6. doi:10.1109/ISMAR-Adjunct.2016.0046.

[49] Hadar E, Shtok J, Cohen B, Tzur Y, Karlinsky L. Hybrid remote expert - an emerging pattern of industrial remote support. In: Proceedings of the forum and doctoral consortium papers, 1848. Essen, Germany: CEUR Workshop Proceedings; 2017. p. 33–40.

[50] Chandler P, Sweller J. Cognitive load while learning to use a computer program. Appl Cognit Psychol 1996;10(2):151–70. doi:10.1002/(SICI)1099-0720(199604)10:2<151::AID-ACP380>3.0.CO;2-U.

[51] Corbett A, Anderson J, Graesser A, Koedinger K, VanLehn K. Third generation computer tutors: learn from or ignore human tutors?. In: Proceedings of the CHI '99 extended abstracts on human factors in computing systems CHI EA '99;. New York, NY, USA: ACM; 1999. p. 85–6. doi:10.1145/632716.632769. ISBN 978-1-58113-158-1.

[52] Syberfeldt A, Danielsson O, Holm M, Wang L. Visual assembling guidance using augmented reality. Procedia Manuf 2015;1:98–109. doi:10.1016/j.promfg.2015.09.068.

[53] Merrill MD, Li Z, Jones MK. Second generation instructional design (ID2). Educ Technol 1990;30(1):7–11.

[54] Tsuruzoe H, Odera S, Shigeno H, Okada K. MR work supporting system using Pepper's ghost. In: Proceedings of the 26th international conference on artificial reality and telexistence and the 21st eurographics symposium on virtual environments ICAT-EGVE '16;. Goslar Germany, Germany: Eurographics Association; 2016. p. 61–8. doi:10.2312/egve.20161436. ISBN 978-3-03868-012-3.

[55] Kirschner PA, Sweller J, Clark RE. Why minimal guidance during instruction does not work: an analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. Educ Psychol 2006;41(2):75–86. doi:10.1207/s15326985ep4102_1.

[56] Hsu T-C. Learning english with augmented reality: do learning styles matter? Comput Educ 2017;106:137–49. doi:10.1016/j.compedu.2016.12.007.

[57] Mitrovic A, Weerasinghe A. Revisiting Ill-definedness and the consequences for ITSs. Front Artif Intell Appl 2009;200(1):375–82. doi:10.3233/978-1-60750-028-5-375.

[58] Roll I, Aleven V, Koedinger KR. The invention lab: using a hybrid of model tracing and constraint-based modeling to offer intelligent support in inquiry environments. In: Intelligent tutoring systems. Springer, Berlin, Heidelberg; 2010. p. 115–24. doi:10.1007/978-3-642-13388-6_16. Lecture notes in computer science.

[59] Latham AM, Crockett KA, McLean DA, Edmonds B, O'Shea K. Oscar: an intelligent conversational agent tutor to estimate learning styles. In: Proceedings of the international conference on fuzzy systems; 2010. p. 1–8. doi:10.1109/FUZZY.2010.5584064.

[60] Sottilare RA, Goldberg BS, Brawner KW, Holden HK. A modular framework to support the authoring and assessment of adaptive computer-based tutoring systems (CBTS). In: Proceedings of the interservice/industry training, simulation, and education conference; 2012. p. 1–13.

[61] Sottilare RA, Holden HK. Motivations for a generalized intelligent framework for tutoring (gift) for authoring, instruction and analysis. In: Proceedings of the AIED 2013 workshops proceedings, 7; 2013. p. 1.

[62] Dennis M, Masthoff J, Mellish C. Adapting progress feedback and emotional support to learner personality. Int J Artif Intell Educ 2016;26(3):877–931. doi:10.1007/s40593-015-0059-7.

[63] Brawner K, Holden H, Goldberg B, Sottilare R. Recommendations for modern tools to author tutoring systems. In: Proceedings of the interservice/industry training, simulation & education conference (I/ITSEC); 2012. p. 1–10.

[64] Bloom BS. The 2 sigma problem: the search for methods of group instruction as effective as one-to-one tutoring. Educ Res 1984;13(6):4–16. doi:10.2307/1175554.

[65] Ritter S, Anderson J, Koedinger K, Corbett A. Cognitive tutor: applied research in mathematics education. Psychonomic Bull Rev 2007;14(2):249–55.

[66] Mitrovic A. Learning SQL with a computerized tutor. In: Proceedings of the twenty-ninth SIGCSE technical symposium on computer science education SIGCSE '98;. New York, NY, USA: ACM; 1998. p. 307–11. doi:10.1145/273133.274318. ISBN 978-0-89791-994-4.

[67] VanLehn K, Lynch C, Schulze K, Shapiro J, Shelby R, Taylor L, et al. The andes physics tutoring system: Lessons learned. Int J Artif Intell Educ 2005;15(3):147–204.

[68] Baker SJ, Corbett AT, Gowda SM. Generalizing automated detection of the robustness of student learning in an intelligent tutor for genetics. J Educ Psychol 2013;105(4):946–56. doi:10.1037/a0033216.

[69] Lesgold A, Katz S, Greenberg L, Hughes E, Eggan G. Extensions of intelligent tutoring paradigms to support collaborative learning. In: Proceedings of the instructional models in computer-based learning environments NATO ASI Series;. Springer, Berlin, Heidelberg; 1992. p. 291–311. doi:10.1007/978-3-662-02840-7_18. ISBN 978-3-642-08148-4 978-3-662-02840-7.

[70] Hall J, Ko K. Enhancing decision sciences education through intelligent tutors. Inf Syst Educ J 2009;25(5):3–9.

[71] D'mello S, Graesser A. AutoTutor and affective autotutor: learning by talking with cognitively and emotionally intelligent computers that talk back. ACM Trans Interact Intell Syst 2013;2(4):23:1–23:39. doi:10.1145/2395123.2395128.

[72] Major N, Ainsworth S, Wood D. REDEEM: exploiting symbiosis between psychology and authoring environments. Int J Artif Intell Educ 1997:317–340.

[73] Goldberg B, Cannon-Bowers J. Experimentation with the generalized intelligent framework for tutoring (gift): a testbed use case. In: Proceedings of the AIED 2013 workshops proceedings volume, 7; 2013. p. 27–36.

[74] Heffernan NT, Koedinger KR. An intelligent tutoring system incorporating a model of an experienced human tutor. In: Intelligent tutoring systems. Springer, Berlin, Heidelberg; 2002. p. 596–608. doi:10.1007/3-540-47987-2_61. Lecture Notes in Computer Science.

[75] Graesser AC, VanLehn K, Rose CP, Jordan PW, Harter D. Intelligent tutoring systems with conversational dialogue. AI Mag 2001;22(4):39. doi:10.1609/aimag.v22i4.1591.

[76] Sottilare R, LaViola J. Extending intelligent tutoring beyond the desktop to the psychomotor domain: a Survey of smart glass technologies. In: Proceedings of the 2015 inter-service/industry training, simulation and education conference. Arlington, VA: National Training and Simulation Association; 2015. p. 1–11.

[77] De Jong CJ. Embedding an intelligent tutor into existing business software to provide on-the-job training. Christchurch, New Zealand: University of Canterbury; 2016.

[78] Kodaganallur V, Weitz RR, Rosenthal D. A comparison of model-tracing and constraint-based intelligent tutoring paradigms. Int J Artif Intell Educ 2005;15(2):117–44.

[79] Aleven V. Rule-based cognitive modeling for intelligent tutoring systems. In: Advances in intelligent tutoring systems. Springer, Berlin, Heidelberg; 2010. p. 33–62. doi:10.1007/978-3-642-14363-2_3. Studies in Computational Intelligence.

[80] Aleven V, McLaren BM, Sewall J, Koedinger KR. A new paradigm for intelligent tutoring systems: example-tracing tutors. Int J Artif Intell Educ 2009;19(2):105–54.

[81] Mitrovic A, Ohlsson S. A critique of Kodaganallur, Weitz and Rosenthal, "a comparison of model-tracing and constraint-based intelligent tutoring paradigms". Int J Artif Intell Educ 2006;16(3):277–89.

[82] Amalathas S, Mitrovic A, Saravanan R, Evison D. Developing an intelligent tutoring system for palm oil with ASPIRE. In: Proceedings of the 18th international conference on computers in education. Putrajaya, Malaysia: Asia-Pacific Society for Computers in Education; 2010. p. 101–3.

[83] Mitrovic A, Martin B, Suraweera P, Zakharov K, Milik N, Holland J, et al. ASPIRE: an authoring system and deployment environment for constraint-based tutors. Int J Artif Intell Educ (IOS Press) 2009;19(2):155–88.

[84] Mitrovic A, Martin B, Suraweera P, Milik N, Holland J, Zakharov K. ASPIRE - user manual. Intelligetn Computer Tutoring Group; Christchurch, New Zealand; 2007.

[85] Munro A, Johnson MC, Pizzini QA, Surmon DS, Towne DM, Wogulis JL. Authoring simulation-centered tutors with rides. Int J Artif Intell Educ 1997;8(3–4):284–316.

[86] Blessing SB, Devasani S, Gilbert S. Evaluation of webxpst: a browser-based authoring tool for problem-specific tutors. In: Proceedings of the international conference on artificial intelligence in education. Springer; 2011. p. 423–5.

[87] Olney AM. Gnututor: an open source intelligent tutoring system. In: Proceedings of the 2009 conference on artificial intelligence in education: building learning systems that care: from knowledge representation to affective modelling. Amsterdam, The Netherlands, The Netherlands: IOS Press; 2009. ISBN 978-1-60750-028-5.

[88] Holvikivi J. From theory to practice: adapting the engineering approach. In: Proceedings of the international conference on engineering education 2012 Proceedings ICEE, Turku, Finland; 2012. p. 273–80. ISBN 978-952-216-295-3.

[89] Hwang G-J, Sung H-Y, Hung C-M, Huang I, Tsai C-C. Development of a personalized educational computer game based on students learning styles. Educ Technol Res Dev 2012;60(4):623–38. doi:10.1007/s11423-012-9241-x.

[90] Ohlsson S. Learning from error and the design of task environments. Int J Educ Res 1996;25(5):419–48. doi:10.1016/S0883-0355(97)81236-0.

[91] ScopeAR. About scopear. Retrieved 23 June 2016; n.d. http://www.scopear.com/about/.

[92] Henderson SJ, Feiner SK. Augmented reality in the psychomotor phase of a procedural task. In: Proceedings of the 2011 10th IEEE international symposium on mixed and augmented reality; 2011. p. 191–200. doi:10.1109/ISMAR.2011.6092386.

[93] Freitas R, Campos P. Smart: a system of augmented reality for teaching 2nd grade students. In: Proceedings of the 22Nd British HCI group annual conference on people and computers: culture, creativity, interaction - Volume 2 BCS-HCI '08;. Swinton, UK, UK: British Computer Society; 2008. p. 27–30. ISBN 978-1-906124-06-9.

[94] Radu I, MacIntyre B. Using children's developmental psychology to guide augmented-reality design and usability. In: Proceedings of the IEEE international symposium on mixed and augmented reality (ISMAR); 2012. p. 227–36. doi:10.1109/ISMAR.2012.6402561.

[95] Joy S, Kolb DA. Are there cultural differences in learning style? Int J Intercult Relat 2009;33(1):69–85. doi:10.1016/j.ijintrel.2008.11.002.

[96] Kolb DA. Experiential learning : experience as the source of learning and development. Second edition. Upper Saddle River, New Jersey Pearson Education, Inc; 2015. ISBN 978-0-13-389240-6.

[97] Duffy TM, Cunningham DJ. Constructivism: implications for the design and delivery of Instruction. In: Jonassen D, editor. Handbook of research for educational communications and technology, New York, NY, USA; 1996. p. 170–98.

[98] Radkowski R, Herrema J, Oliver J. Augmented reality-based manual assembly support with visual features for different degrees of difficulty. Int J Human-Comput Interact 2015;31(5):337–49. doi:10.1080/10447318.2014.994194.

[99] Occipital Inc. Official structure sensor store - Give Your iPad 3d Vision. n.d. https://structure.io/.
[100] Huang H, Xu Y-P, Deng Z-W. Real-time visual flight simulation system based on flightgear simulator. J Syst Simul 2007;19(19):72–4.
[101] Nickerson JV, Corter JE, Esche SK, Chassapis C. A model for evaluating the effectiveness of remote engineering laboratories and simulations in education. Comput Educ 2007;49(3):708–25. doi:10.1016/j.compedu.2005.11.019.
[102] Adams DM, Mayer RE, MacNamara A, Koenig A, Wainess R. Narrative games for learning: testing the discovery and narrative hypotheses. J Educ Psychol 2012;104(1):235–49. doi:10.1037/a0025595.
[103] Sottilare R, Brawner K, Sinatra A, Johnston J. An Updated Concept for a Generalized Intelligent Framework for Tutoring (GIFT). Orlando, FL: US Army Research Laboratory; 2017. doi:10.13140/RG.2.2.12941.54244.
[104] Fosnot CT, Perry RS. Constructivism: a psychological theory of learning. Constr: Theory Perspect Pract 1996;2:8–33.
[105] Frezzo DC, Behrens JT, Mislevy RJ. Design patterns for learning and assessment: facilitating the introduction of a complex simulation-based learning environment into a community of instructors. J Sci Educ Technol 2010;19(2):105–14. doi:10.1007/s10956-009-9192-0.
[106] Rogers Y, Sharp H, Preece J, Tepper M. Interaction design: beyond human–computer interaction. netWorker: Craft Netw Comput 2007;11(4):34.
[107] Murray T. Authoring intelligent tutoring systems: an analysis of the state of the art. Int J Artif Intell Educ (IJAIED) 1999;10:98–129.
[108] Murray T. An overview of intelligent tutoring system authoring tools: updated analysis of the state of the art. In: Authoring tools for advanced technology learning environments. Springer, Dordrecht; 2003. p. 491–544. doi:10.1007/978-94-017-0819-7_17. ISBN 978-90-481-6499-8 978-94-017-0819-7.
[109] Santos MEC, Chen A, Taketomi T, Yamamoto G, Miyazaki J, Kato H. Augmented reality learning experiences: survey of prototype design and evaluation. IEEE Trans Learn Technol 2014;7(1):38–56. doi:10.1109/TLT.2013.37.
[110] Sinatra AM. A personalized gift: recommendations for authoring personalization in the generalized intelligent framework for tutoring. In: Proceedings of the international conference on augmented cognition. Springer; 2015. p. 675–82.
[111] Brawner KW, Holden HK, Goldberg BS, Sottilare R. Understanding the impact of intelligent tutoring agents on real-time training simulations. Tech. Rep. DTIC Document; 2011.
[112] Stottler R, Davis A, Panichas S, Treadwell M. Designing and implementing intelligent Tutoring instruction for tactical action officers. In: Maintainingt the Edge... Transforming The Force, 2007. San Mateo, CA: Stottler Henke Associates Inc.; 2007. p. 11.
[113] Shute V, Ventura M, Small M, Goldberg B. Modeling student competencies in video games using stealth assessment. In: Design recommendations for intelligent tutoring systems, Volume 1: Learner Modeling. Orlando, FL, USA: U.S Army Research Laboratory; 2013. p. 165–76. ISBN 978-0-9893923-0-3.
[114] Pfeuffer K, Gellersen H. Gaze and touch interaction on tablets. In: Proceedings of the 29th annual symposium on user interface software and technology UIST '16;. New York, NY, USA: ACM; 2016. p. 301–11. doi:10.1145/2984511.2984514. ISBN 978-1-4503-4189-9.
[115] Goldstein C, Leisten S, Stark K, Tickle A. Using a network simulation tool to engage students in active learning enhances their understanding of complex data communications concepts. In: Proceedings of the 7th Australasian conference on computing education - Volume 42 ACE '05;. Darlinghurst, Australia, Australia: Australian Computer Society, Inc.; 2005. p. 223–8. ISBN 1-920682-24-4.
[116] De Jong T, Joolingen WRV. Scientific discovery learning with computer simulations of conceptual domains. Rev Educ Res 1998;68(2):179–201. doi:10.3102/00346543068002179.
[117] Hmelo-Silver CE, Duncan RG, Chinn CA. Scaffolding and achievement in problem-based and inquiry learning: a response to Kirschner, Sweller, and. Educ Psychol 2007;42(2):99–107. doi:10.1080/00461520701263368.
[118] Schmidt HG, Loyens SMM, Gog TV, Paas F. Problem-based learning is compatible with human cognitive architecture: commentary on Kirschner, Sweller, and. Educ Psychol 2007;42(2):91–7. doi:10.1080/00461520701263350.
[119] Brooke J. SUS: a "quick and dirty" usability scale. In: Jordan PW, Thomas B, Weerdmeester BA, McClelland IL, editors. Usability evaluation in industry. London: Taylor and Francis; 1996. p. 189–227. ISBN 978-0-7484-0460-5.
[120] Kolb AY, Kolb DA. The Kolb learning style inventory - version 3.1 2005 technical specifications, 4. HayGroup; 2005.
[121] Gilbert A. Augmented reality for the US Air Force. In: Virtual, augmented and mixed reality. Springer, Cham; 2016. p. 375–85. doi:10.1007/978-3-319-39907-2_36.
[122] Dinita RI, Wilson G, Winckles A, Cirstea M, Jones A. A cloud-based virtual computing laboratory for teaching computer networks. In: Proceedings of the 2012 13th international conference on optimization of electrical and electronic equipment (OPTIM); 2012. p. 1314–18. doi:10.1109/OPTIM.2012.6231992.
[123] Konak A, Clark TK, Nasereddin M. Using Kolb's experiential learning cycle to improve student learning in virtual computer laboratories. Comput Educ 2014;72(Supplement C):11–22.