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Micro-adaptivity: protecting immersion in didactically adaptive digital educational games

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Abstract

The idea of utilizing the rich potential of today's computer games for educational purposes excites educators, scientists and technicians. Despite the significant hype over digital game-based learning, the genre is currently at an early stage. One of the most significant challenges for research and development in this area is establishing intelligent mechanisms to support and guide the learner, and to realize a subtle balance between learning and gaming, and between challenge and ability on an individual basis. In contrast to traditional approaches of adaptive and intelligent tutoring, the key advantage of games is their immersive and motivational potential. Because of this, the psycho-pedagogical and didactic measures must not compromise gaming experience, immersion and flow. In the present paper, we introduce the concept of micro-adaptivity, an approach that enables an educational game to intelligently monitor and interpret the learner's behaviour in the game's virtual world in a non-invasive manner. On this basis, micro-adaptivity enables interventions, support, guidance or feedback in a meaningful, personalized way that is embedded in the game's flow. The presented approach was developed in the context of the European Enhanced Learning Experience and Knowledge TRAnsfer project. This project also realized a prototype game, demonstrating the capabilities, strengths and weaknesses of micro-adaptivity.

Keywords

digital educational games, game-based learning, micro-adaptivity, non-invasive assessment, personalization.

Introduction

The idea of using technology to support and facilitate teaching and learning has a long tradition. A famous (half) jocular metaphor is the *Nuremberg Funnel* (the phrase was coined by Georg Philipp Harsdörffer in the 17th century), which describes the wish for a mechanical way of teaching that allows each learner to acquire knowledge with minimal effort while allowing the educator to teach everything, even to the 'slowest' pupil. With the evolution of computer and Internet technologies, the number of educational applications and electronic learning contents has quickly risen. Technology-enhanced teaching and learning undoubtedly bear significant advantages, such as the rich potential of visualizations and animations that provide new insights and perspectives, the ubiquitous access to information, the possibilities for self-directed and self-regulated learning, or the possibilities for exchange and collaboration.

A rather new trend is to supplement the rich educational potential of learning technologies with the strong motivational potential adopted from entertainment technologies, in particular, computer games. The computer games genre is tremendously successful, popular and attractive. A significant number of young people spend many hours a week playing computer games, and these games are often preferred over others. Thus, using

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the motivational potential of computer games for educational purposes may open new horizons for educational technology. The nature of utilizing (computer) games for education is that playing games is one of the most natural forms of learning. Children learn to talk by playing with sounds, and they learn collaboration and strategic thinking when playing *Cowboys and Indians*. Immersive digital educational games (DEG) return to that origin and offer a highly promising approach that makes learning more engaging, satisfying, inspiring and maybe even more effective (see Mitchell & Savill-Smith 2004 or de Freitas 2006 for an in-depth overview). The major strengths of DEGs are generally observed in a high level of intrinsic motivation (Deci 1975) to play and proceed in the game, a meaningful yet rich and appealing learning context, immediate feedback and a high level of interactivity, challenge and competition. Some researchers even argue that the exposure to 'twitch speed' computer games, *MTV* and the Internet has altered cognitive processes, emphasizing specific cognitive aspects while de-emphasizing others (Prensky 2001). Thus, the so-called 'digital natives' may require different, possibly non-conventional, educational approaches. Although such theses are discussed controversially, it is clear that the young generation is familiar with computer games and their nature. More importantly, computer games are symbols of an entertaining, engaging and immersive medium. In addition to the intended and planned education, computer games are also a vehicle for meta-knowledge and skills (e.g. multitasking abilities or strategic thinking) and social aspects (e.g. collaboration or leadership). Thus, it is not surprising that there is currently a significant hype over game-based learning. According to many researchers in the field of game-based learning, however, DEGs are still in their infancy from a scientific and pedagogical perspective (e.g. Oblinger 2006). Major challenges for research, design and development are seen in, for example,

- finding an appropriate balance between gaming and learning activities (e.g. Van Eck 2006);
- finding an appropriate balance between challenges through the game and abilities of the learner (e.g. Kickmeier-Rust *et al*. 2007b);
- convincingly embedding educational objectives in a game scenario, particularly when declarative knowledge is concerned (cf. Kafai 2006); or
- managing the extensive costs of developing high-quality games (e.g. Van Eck 2006).

In conclusion, the attempt to utilize (at least part of) the time people spend on gaming for educational purposes and to utilize the educational potential of computer games that are very beneficial and desirable from a didactical perspective (e.g. giving learning a meaningful context and story) is a highly promising approach that may facilitate learning and make it a more pleasant task. Games, very naturally, can make learning important and meaningful to learners, and it can make knowledge an important asset (cf. Gee 2003). Moreover, games potentially reach children and adolescents who are not 'keen on learning' and who cannot be reached with conventional educational methods.

The focus of the present work is to address a major challenge for research, that is, finding a methodology/technology that allows for the tailoring of individual gaming/learning experiences by realizing an appropriate balance between game-related and educational challenges, and the learner's abilities, knowledge or learning progress. It is more important for DEGs than for any other educational genre to be tailored to an individual learning experience in order to reach educational effectiveness and maintain fun, immersion, flow experience[1] and the motivation to play, and therefore to learn. Thus, meeting individual preferences, interests, abilities and goals is key to successful game-based learning.

Intelligent adaptation and personalization

To meet the aforementioned claims, DEGs must autonomously adapt to the learner along a variety of axes, for example, prior knowledge, learning progress, motivational states, gaming preferences and psycho-pedagogical implications.[2] In current forms of technology-enhanced learning, concepts of adaptivity, adaptability and personalization have increasingly become important. Generally, adaptive approaches to e-learning contest the one-size-fits-all approach of traditional learning environments and the attempt to tailor the learning environment according to individual needs and preferences. The spectrum of approaches, methods, frameworks and applications is quite broad (cf. Kinshuk *et al*. 2006 or De Bra 2008). Essentially, adaptivity refers to three major concepts:

- *adaptive presentation*: adjusting the look and feel of a learning environment according to individual preferences or needs, for example, different colour schemes, layouts or amount of functionality;
- *adaptive curriculum sequencing*: providing the learner with learning tailored to individual preferences, goals, learning styles or prior knowledge; and
- *adaptive problem-solving support*: providing the learning with feedback, hints or solutions in the course of problem-solving processes.

The existing approaches, methods and frameworks for adaptation and personalization were developed in the context of conventional e-learning (e.g. designed for use with existing learning management systems), and therefore, they cannot be easily transferred to the context of DEGs. The underlying concepts and ideas must be extended and adjusted to the requirements of the rich virtual gaming worlds, particularly to maintain an immersive gaming experience and high levels of motivation, curiosity and flow experience (Kickmeier-Rust *et al*. 2007a).

In the present paper, we introduce an approach to non-invasive assessment of knowledge and learning progress in the open virtual worlds of computer games and a corresponding adaptation by personalized psycho-pedagogical interventions. The approach, labelled *micro-adaptivity*, was developed in the context of the Enhanced Learning Experience and Knowledge TRAnsfer (ELEKTRA) project (http://www.elektra-project.org), a multidisciplinary research and development project. The ELEKTRA project had the ambitious goal of utilizing the advantages of computer games and their design fundamentals for educational purposes and addressing specific disadvantages of game-based learning. Within the project, a methodology for the successful design of educational games was established, and a game demonstrator was developed based on a state-of-the-art three-dimensional (3-D) adventure game (see Figs 3 and 4 for some impressions of the game).

The concept of micro-adaptivity

The primary task for game-based adaptive educational mechanisms is to guide and support the learner in acquiring knowledge by, for example, informing the learner, intervening when misconceptions occur or when the learning progress is unsatisfactory, hinting or providing the learner with appropriate feedback. In addition, tasks are motivating, maintaining immersion and personalizing the game according to the preferences and needs of the learner.

Accomplishing this goal requires a theoretical and technological approach that enables the game to assess cognitive states (e.g. *competence states* or *motivational states*), learning progress, possible misconceptions or undirected/unsuccessful problem-solving strategies. In contrast to traditional forms of teaching (either in real or virtual environments), where the assessment occurs by test items, questions or tasks, DEGs require an assessment that does not destroy or impair motivation, immersion, flow experience or the game's storyline (Kickmeier-Rust *et al*. 2007b). This 'protection' is important from two perspectives. On the one hand, there is a large body of evidence concerning the negative impact of interruptions and attention splits on (problem solving) task performance and learning [e.g. Chandler & Sweller (1992) in the context of cognitive load theory; Foerde *et al*. (2007) in the context of cognitive neuroscience; or Gillie & Broadbent (1989) in the context of computer tasks]. On the other hand, from the perspective of fun and immersion, it is important not to compromise a fluent progress of game play and/or narrative (e.g. Freeman 2003 or Jennett *et al*. 2008).

The very basis of micro-adaptivity is a formal psychological model for interpreting a learner's behaviour within learning and assessment situations in an educational game. In contrast to traditional forms of electronic learning material, learning situations in DEGs generally have a large degree of freedom. We therefore interpret the learner's behaviour as a type of problem solving that is consistent with the idea of gaming.

Learner, domain and game

To realize the ambitious goal of non-invasive assessment and subsequent educational interventions, we combined the *Competence-based Knowledge Space Theory* (CbKST), which has been successfully utilized in conventional adaptive e-learning, with cognitive theories of problem solving. This theory provides a detailed domain model that includes a set of meaningful *competence states* as well as a set of possible *learning paths*. Problem-solving theories, in turn, provide a set of possible *problem-solving states* as well as possible problem-solving paths.

CbKST

Briefly, CbKST (cf. Korossy 1997; Albert & Lukas 1999) originated from the *Knowledge Space Theory* (KST) established by Doignon and Falmagne (1985, 1999), which is a well-elaborated set theoretic framework for addressing the relations among problems (e.g. tasks or test items). It provides a basis for structuring a domain of knowledge and for representing the knowledge based on prerequisite relations. While KST focuses only on performance/behaviour (e.g. solving a test item), CbKST introduces a separation of observable performance and latent, unobservable competencies, which determine the performance. Essentially, CbKST assumes a finite set of competencies and a prerequisite relation between those competencies. A *prerequisite relation* states that competency *a* (e.g. multiplying two positive integers) is a prerequisite to acquiring competency *b* (e.g. dividing two positive integers); if a person has *b*, we can assume that the person also has *a*. To account for the fact that more than one set of competencies can be a prerequisite for another competency (e.g. competency *a* or competency *b* are a prerequisite for acquiring competency *c*), *prerequisite functions* have been introduced (Fig 1a), relying on the type of relationships. Because of the prerequisite relations between the competencies, not all subsets of competencies are possible *competence states*. As an example, imagine four competencies from the domain of basic algebra, the abilities to add, subtract, multiply and divide numbers.

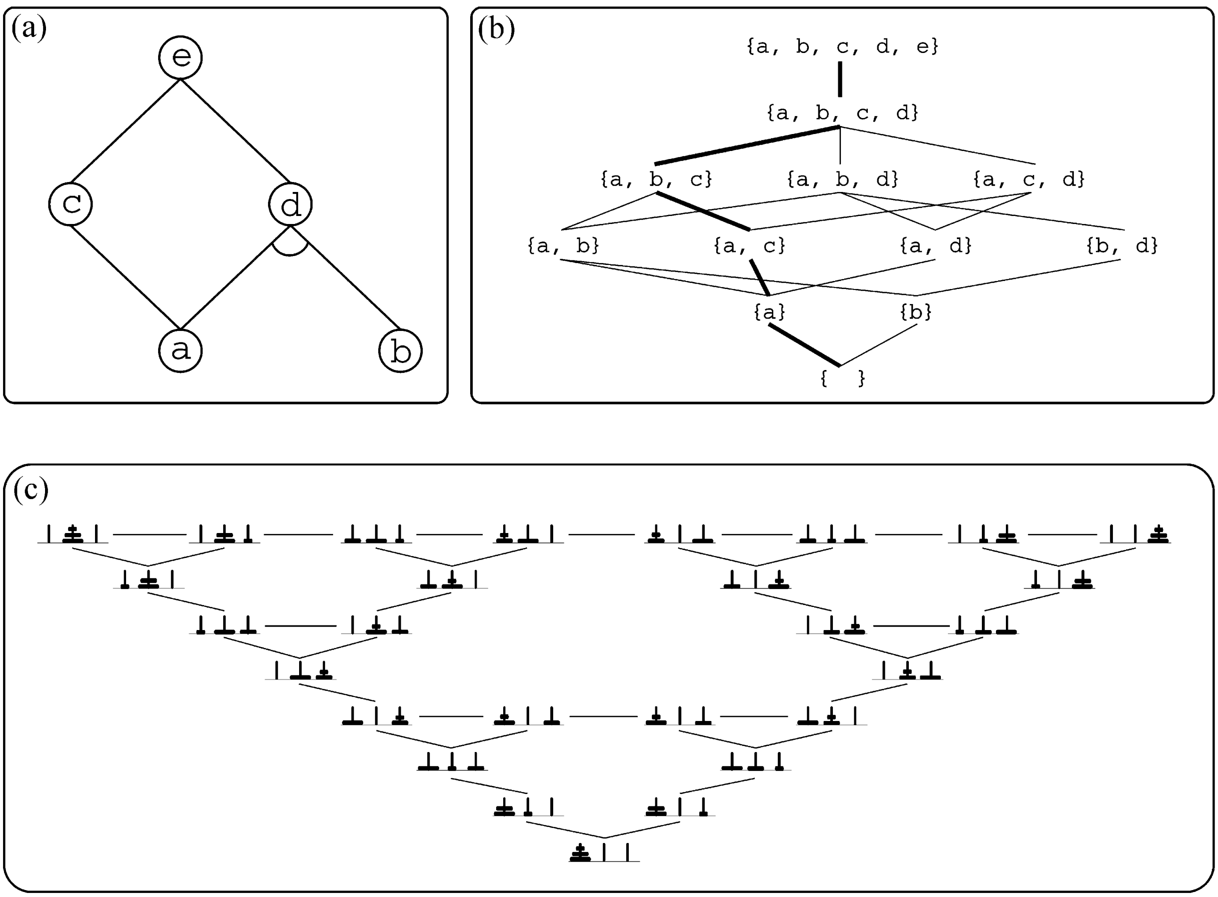


Fig 1 Panel (a) shows prerequisite functions (the bended line below competency *d* indicates an and/or-type relationship) between the competencies *a*–*e*. Panel (b) illustrates the resulting competence structure that includes 11 competence states. The bold lines indicate one of several admissable and meaningful learning paths. Panel (c) shows the problem space for the 'Tower of Hanoi' problem. The illustrations read from bottom to top.

Given four competencies, the set of all possible knowledge states is 2^4. If we assume that the competencies to add, subtract and multiply numbers are prerequisites for the competency to divide numbers, not all of the 16 *competence states* are plausible. For example, it is highly unlikely that a child has the competency to divide numbers but not to add numbers. The collection of possible competence states corresponding to a prerequisite relation is called *competence structure* (Fig 1b). Such a competence structure also defines different admissible and meaningful learning paths through a domain. Thus far, the structural model focuses on latent, unobservable competencies. By utilizing mapping functions, the latent competencies are assigned to a set of tasks/test items/actions relevant for a given domain, which induces a *performance structure*, the collection of all possible *performance states*. Learning or development is not seen as a linear course, equal for all learners; rather, learning follows one of a set of individual learning paths.

This approach has several advantages. The separation of performance and underlying latent competencies enables the modeling of a domain independent from concrete tasks. The tasks of different test instruments (e.g. different school tests or micro-adaptive conclusions in this particular case) can be mapped to a single competence structure, whereas no one-to-one mapping is required. This enables a continuous monitoring of learning, a comparison of performance across different instruments and experimental paradigms, and it supports educational measures. In the context of micro-adaptivity, an advantage of this approach is its strictly formal mathematical nature. This, in turn, enables integration with formal concepts of problem-solving processes.

A theory of human problem solving

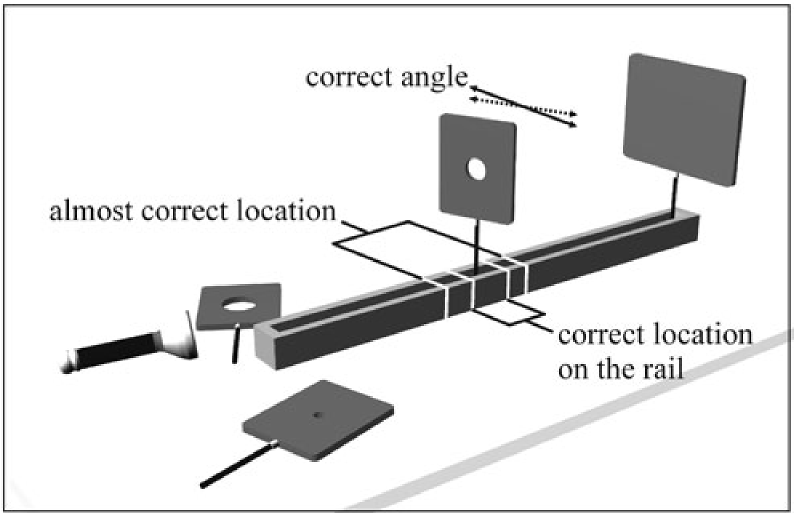
In this work, we rely on a formal theory of the human problem-solving process, the theory of Newell and Simon (1972; see also Newell 1990 for a conclusive overview). These authors considered problem solving as dynamic information processing and attempted to explain behaviour as a function of memory operations, control processes and rules. The very basis of this approach is to decompose a problem or situation (you may think about all possible states of the *Tower of Hanoi* problem) into a *problem space*, a collection of all possible and meaningful *problem solution states*, objects relevant for a problem and transition rules, which specify how admissible transitions from one problem-solving state to another can occur. For the *Tower of Hanoi*, the *problem space* would include all states where the rules 'a larger disk cannot top a smaller' and 'all disks must be on one of the pegs' are not violated (see Fig 1c). Based on the objects and the rules to each problem-solving state, a set of possible/admissible actions can be assigned. The selection from that set of actions is not only guided by the 'hard' rules, but also by heuristics, that is, strategies that might make the problem solving more effective than a random solution of actions (a common heuristic is to use that action that reduces the difference between the current problem-solving state and the goal state to the greatest degree).

Merging competence structures and problem spaces

To provide the game with holistic information about the knowledge domain (i.e. the competence structure) and the possible actions within the problem-solving processes (i.e. the problem spaces), both must be linked together. Unfortunately, typical learning situations are more complex than well-defined problems such as the *Tower of Hanoi* (Fig 1c). Most often, the degree of freedom within such situations is quite large, and the amount of possible actions a learner can perform is (as in the real world) infinite.

To reduce the complexity of our picture of the situation, we introduce the concept of *position categories*. A set of descriptions or specifications is assigned to each object of a learning or assessment situation within the game that has a certain meaning for the problem solution and learning process, and that can be manipulated (including the learner's avatar). A position category (Fig 2) describes an object within the game by its location (e.g. in the 3-D space), its properties (e.g. angle, alignment or slope) and its specific status (e.g. on or off). As an example, think about a torch that can be placed somewhere in a room with a certain angle, turned on and shining in a certain direction.

This classification is now a substrate of the problem space, which can be linked to the learner's available and unavailable competencies. Basically, there are two options to do so: first, a *deterministic linkage*, and second, a *probabilistic linkage*. Deterministic linkage means that each position category is associated with a specific set of competencies that the learner has and a




```
if x(blind) > 10 and x(blind) < 20 then
    if y(blind) = 0 then
        position_category = 1
    else
        position_category = 2
    end if
else if x(blind) <= 10 and x(blind) > 7 then
    if y(blind) = 0 then
        position_category = 3
    else
        position_category = 4
    end if
else if x(blind) >= 20 and x(blind) < 23 then
    if y(blind) = 0 then
        position_category = 3
    else
        position_category = 4
    end if
else
    position_category = 5
end if
```

Fig 2 The left panel illustrates the blind situation. There are a total of five position categories: *correct location on the rail and correct angle; correct location and incorrect angle; almost correct location and correct angle; almost correct location and incorrect angle; incorrect location on the rail independent of the angle*. The right panel shows the corresponding pseudo code to identify the position category for the blind (*x* indicates the location on the rail and *y* the angle). The blind on the rail is in position category 2.

specific set of competencies that the learner lacks. Of course, one or both sets can be empty. By the example shown in Fig 2, we can assume that the learner has the competency to position the blind correctly on the rail but does not have the competency to realize the right angle of the blind. However, probabilistic linkage means that a numeric value that describes the strength of belief that a specific set of competencies is available or lacking is assigned to each position category. Independent of the linkage type, a *utility value* is assigned to each category to provide the game with information about 'how correct' or 'how wrong' a position category is.

Updating competence state probabilities

As a next step, we must transfer our assumptions of available and lacking competencies to entire competence states and the likelihood of those states. To identify a learner's current competence state at the beginning of a gaming/learning episode, we assume an initial probability distribution over the competence structure. There exist an arbitrary number of possibilities for this initial probability distribution. The simplest form would be a uniform distribution in which each competence state has the same initial probability. A more reasonable approach would be to adjust the initial probability distribution to the learner's prior knowledge, for example, by conducting an entry test or by the extent of prior knowledge we can assume based on the learner's age, the school type, school grades or the gaming progress. The selection of the 'correct' method strongly depends on the given information about the learner's competencies and prior knowledge as well as the exact educational goals.

With each action the learner performs, the game updates the probability distribution over the competence states, where updating rules define the way in which the probabilities are updated in a specific situation (cf. Doignon & Falmagne 1999). A simple method is to increase the probabilities of all competence states that include competencies that are (either definitely or likely) available when realizing the corresponding position category. In turn, we can decrease the probabilities of those competence states that include competencies that are unavailable. On this basis, we are continuously approaching every action and every realized position category with a clearer interpretation of the learner's competence state. Although the single interpretations of available and lacking competencies may not be convincing, with an increasing number of actions, certain and, most often, similar competence states become increasingly clear. In the next step, on the basis of this monitoring and interpretation process, the game must respond in a psycho-pedagogically meaningful way.

Adaptive interventions

The basic idea of the micro-adaptivity concept is to provide the learner with appropriate educational support without corrupting immersion and the flow of the gaming experience. Both the assessment procedures and the system's responses to the learner must be educationally meaningful and suitable. As a consequence, the game can be equipped with a set of potential interventions (including feedback) that can be triggered in an intelligent manner. The conditions under which a certain adaptive intervention is given are developed on the basis of pedagogical and didactic rules while considering a strong integration in the game play context. The nature of this set of rules may vary depending on the nature of the learning situation, ranging from if–then clauses to alterations of interventions (e.g. varying the intensity of an intervention). Different learning situations and different types of rules may also induce different types of interventions. In the context of DEGs, we can classify the following intervention types:

- *Competence activation interventions* may be applied if a learner becomes stuck in some area of the problem space and some competencies are not used even though the system assumes that the learner possesses them.
- *Competence acquisition interventions* may be applied in situations when the system concludes that the learner lacks certain competencies.
- *Motivational interventions* may be applied, for example, if the learner unexpectedly fails to act for a certain long period of time.
- *Feedback* may be utilized to provide the learner with information about the learning progress or the game.
- *Assessment clarification interventions* may be applied, for example, in the form of a query, if the learner's actions provide contradicting support for the assumption of a certain competence state.

Pedagogical interventions and feedback guide the learning process and inform the learner about the learning progress and the possible deviations from a planned learning path. These interventions also aim to provide the learner with appropriate information and direct the learner's view on important information. In the context of computer-based learning, studies have demonstrated the effectiveness of interventions and feedback (cf. Azevedo & Bernard 1995). Moreno (2004), for example, used feedback to decrease the cognitive load of learners in discovery-based learning environments. In a recent study, Tan *et al*. (2006) showed that interventions could improve immediate goal achievement.

Technical realization: the ELEKTRA prototype

Architecture

The concept of micro-adaptive assessment and interventions has been developed in the context of the ELEKTRA project. In this project, a prototype game was developed to demonstrate and evaluate the concept of micro-adaptivity.

Basically, the architecture consists of four modules. The game itself, quite traditionally, is created using a high-end gaming engine. It provides the non-adaptive parts of the game, and as such, it is also the user interface to the system. A *skill assessment engine* updates the competence state probabilities, and the resulting information regarding the learner's competence state and its changes are then forwarded to an *educational reasoner*, the pedagogical part of micro-adaptivity. Based on a set of pedagogical rules and meta-rules as well as learning objectives, this engine provides recommendations on adaptive interventions to the adaptation realization module. This, in turn, maps the abstractly formulated educational recommendations onto more concrete game recommendations. In this mapping process, data on game elements and information on previously given recommendations are considered. The necessary information for the assessment-intervention loop is stored in machine-readable form in a Web Ontology Language (OWL) ontology (Kickmeier-Rust & Albert 2008), which allows the aforementioned engines to extract not only information, but also the relationships among the information from the ontology.

The game

The ELEKTRA prototype game is realized as a classical 3-D adventure game in first-person view, and it aims to teach eighth grade (i.e. 12-13 years of age) optics (Fig 3). Briefly, the aim is to save a girl, Lisa, and her uncle Leo who have been kidnapped by the evil Black Galileans. Moreover, the learner must stop the evil forces from taking over the entire world. During this journey, the learner must acquire specific, curriculum-related knowledge. The learning occurs in different

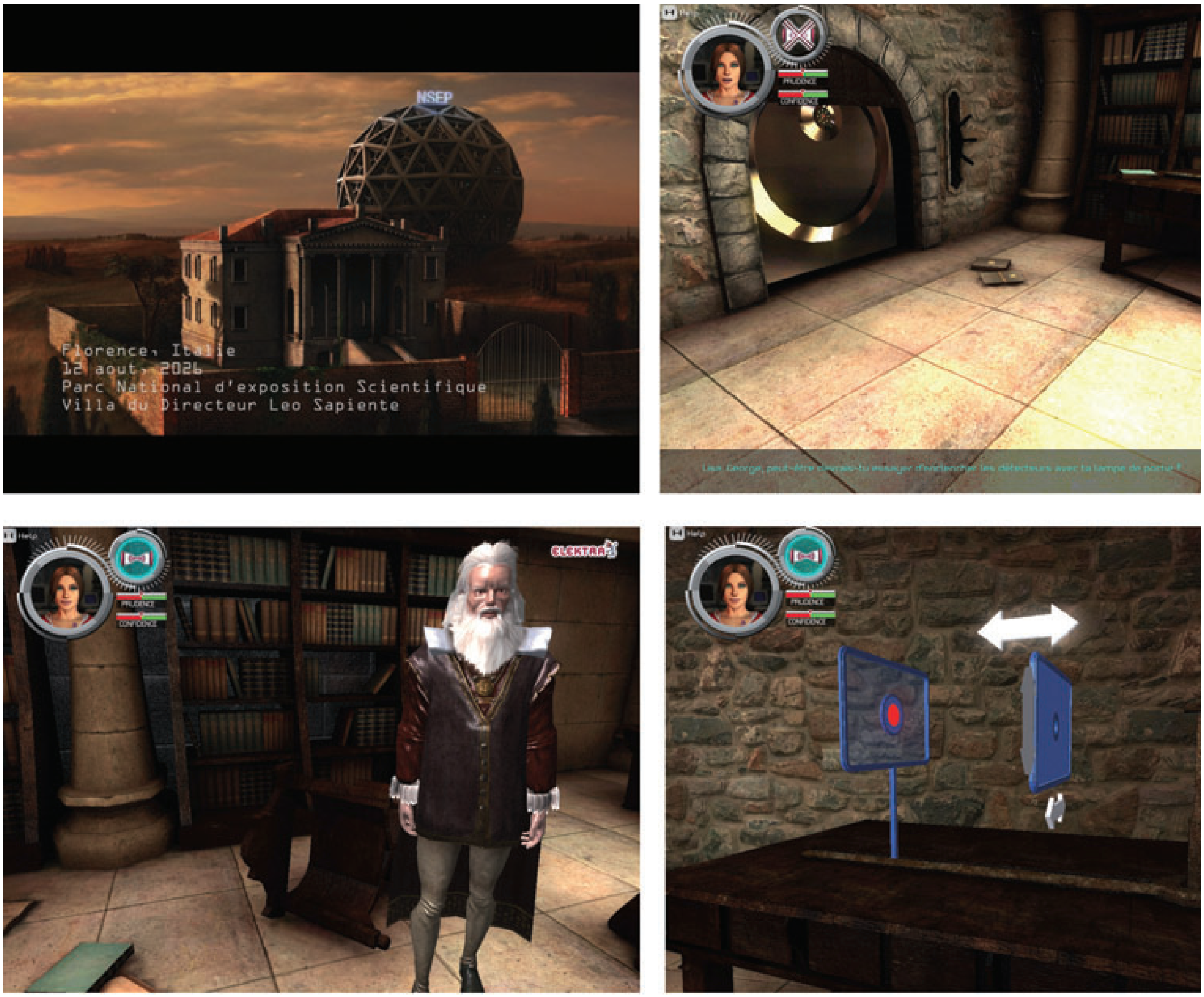


Fig 3 Screenshots of the ELEKTRA demonstrator game. The story starts outside a villa near a science park (upper left image). In the villa, the learner faces (among others) the task to open a solid metal door, which requires some knowledge about the propagation of light (upper right image). The ghost of Galileo Galilei is the learner's accompanying mentor and teacher (lower left image). To acquire knowledge and to proceed through the game, the learner conducts specific experiments, supported by Galileo and (via a headset indicated in the upper left corner of the screen) Lisa (lower right image).

ways, ranging from hearing or reading to freely experimenting. After finding a magic hourglass, the learner is in the company of the ghost of Galileo Galilei, who is the learner's (hidden) teacher. The non-playing characters play a significant role in intelligent, non-invasive educational and motivational interventions. For example, Galileo tells the learner specific facts that are needed for certain events in the game and intervenes by providing the learner with hints or feedback.

A concrete example for a learning situation is the so-called 'slope device' situation (Fig 4). In this situation, the students experiment with a machine in which several balls of different materials (solid and hollow iron, wood and plastic) are running down a slope along with a laser beam. This machine has a fan and a strong magnet. The learner's task is to make the balls fall into a hole by setting appropriate values for the fan and magnet. In addition, they should estimate the trajectory of the laser beam as influenced by the fan, gravity and a magnetic force. This experiment aims to visualize the effects of a fan, gravity and a magnet on different materials and, in the first instance, demonstrates that the laser beam is not influenced by such external forces and independently propagates in a straight line.

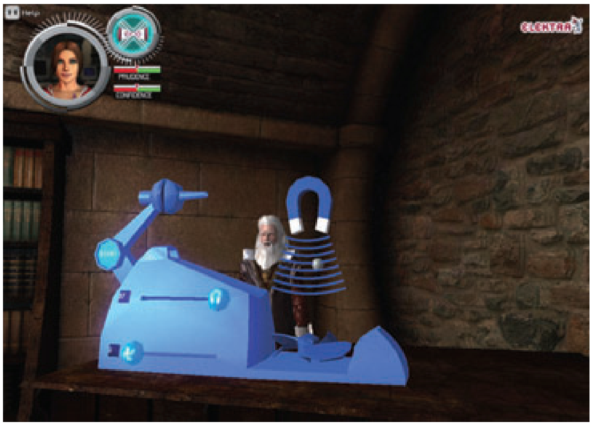


Fig 4 The 'slope device' teaching the straight propagation of light.

During the experiment, the system continuously monitors the learner's behaviour and updates the probability distribution of the competence states. As an example, if the learner constantly attempts to manipulate a wooden ball's trajectory with the magnet, the probabilities of competence states, including a competence 'knowing that magnets influence only metals', would be decreased. Depending on the given rule set, an intervention by Galileo might be triggered, for example, after certain competency probabilities had decreased below a certain threshold value. The concrete intervention would be selected from a set of possible interventions based on the probability distribution, in this example, an intervention that might say, 'Do you really think a magnet influences the trajectory of a wooden ball?'

Experiences with the game prototype

Evaluating and judging educational technology and media, for example, devising fair and meaningful comparisons with other educational measures, is not an easy task in general. It is even more complex when highly adaptive systems are in the focus of evaluations. Loosely speaking, adaptation means that each and every person receives, or at least should receive, a unique and individual learning experience. The biggest challenge, however, is to evaluate highly adaptive learning games, which add fun and gaming as another crucial dimension. This dimension oftentimes contradicts conventional metrics of success or efficiency (e.g. task completion time). From this perspective, gathering reliable, valid and robust data is difficult.

In different experimental evaluation studies with ELEKTRA's demonstrator game, we devised different questions, approaches and metrics. In the first instance, we investigated the utility of the micro-adaptive approach, essentially pursuing a yoked control approach. Yoked control (cf. Church 1964) refers to matching pairs of participants, wherein one receives appropriate adaptive support, while the other receives exactly the same interventions; however, in this case, the interventions are not presented contingent to the behaviour. The results showed that tailored interventions resulted in higher learning performance and stronger immersion in comparison to inappropriate interventions or no interventions. Another approach was, for example, to compare the immediate, direct effects of different types of interventions (we classified appropriate, inappropriate, neutral and no interventions) on the solution process in problem-solving tasks (as described above) in the game. In addition, for the effective approach to a solution, we found statically significant effects by appropriate micro-adaptive interventions (see Kickmeier-Rust *et al*. 2008 for details).

A specific behavioural pattern we occasionally observed was exploring the possibilities in the game and testing things out. This quite natural behaviour could lead to actions that are incorrect for solving a giving task; however, they are sensible from a gaming perspective. Unfortunately, this kind of exploratory behaviour, where things are deliberately done wrong, may lead to incorrect assessment results because the system interprets this behaviour in terms of lacking competencies. This is a significant problem for autonomous assessment systems in general, but may also be difficult for a human teacher. The presented approach has the advantage that the behaviour is reconciled with the cumulated learner model (i.e. the probability distribution over competence states). If the system detects a behaviour that (suddenly) is inconsistent with the learner model, for example, because the learners suddenly lack competencies they already had, it can trigger assessment clarification interventions (as described above). Of course, such a clarification query cannot assure correct assessment. The impact of incorrect assessments, however, can be reduced by an appropriate design. In the ELEKTRA prototype, the non-invasive assessment is primarily used for specific low-impact interventions such as hints or feedback. Important stages in the learning process are 'assessed' by a successful completion of complex tasks. Thus, progress in the game (e.g. opening a door to reach the next room) can only be made by demonstrating the necessary competencies.

In summary, the effects of the micro-adaptive approach were rather positive and beneficial for learning, as well as the gaming experience. Clear disadvantages of the approach are the high amount of necessary authoring efforts to feed the system with the required information and the high computational load of updating the competence state probabilities in huge competence spaces in real time with each gaming action.

Conclusion and outlook

Computer games with a primarily educational purpose and nature that can also compete with their non-educational, commercial counterparts in terms of immersion and motivational potential are a fascinating and desirable idea. To realize this vision, simply adding some learning to a computer game and adding some play to conventional learning materials is needed. Although the idea appears reasonable, competitive DEGs are the most challenging and demanding form of educational technology. Despite the hype over educational and 'serious' games, today's approaches (particularly those that have entered the market) are at an early stage in terms of psycho-pedagogical and didactic depth.

To converge to the realization of competitive DEGs, a psycho-pedagogical background must be developed, and the corresponding technology must be obtained. The immersive potential of DEGs is quite fragile; therefore, the most significant objectives are providing a subtle balance between challenge and ability on the one hand, and a personalized learning experience on the other hand. In the present paper, we have introduced an approach to micro-adaptive assessment and interventions in a non-invasive manner. Still, a number of open questions remain for psycho-pedagogical as well as technical research. From a technical perspective, the introduced approach to micro-adaptivity demands a significant computational load in processing assessment and probability updates. Future research must refine the theoretical and technical approaches to facilitate real-time computing. In addition, attention must be directed to generic rule sets for selecting suitable interventions. Finally, non-invasive methods of macro-adaptivity, for example, curriculum sequencing, must be developed in order to enrich the important possibilities for intelligent adaptation.

The European research project 80Days, inspired by Jules Verne's novel 'Around the World in Eighty Days', is a successor of ELEKTRA that aims to develop the necessary psycho-pedagogical and technological foundations for (also commercially) successful DEGs. 80Days leaves the well-structured domain of physics and will produce a demonstrator game that teaches geography for the age group of 12-14. The nature of the 80Days project melds adaptive educational technology with interactive and adaptive storytelling, and shifts non-invasive adaptation on a higher level. Through adaptive storytelling, we can realize a macro-adaptation, such as curriculum sequencing, without corrupting the narrative. Moreover, 80Days addresses the problems encountered with the ELEKTRA demonstrator game. For example, we attempt to reduce authoring efforts by developing a visual authoring tool. We also extend the theoretical approach with ideas of partitioning the huge competence spaces to reduce computational load.

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Notes

[1]According to Mihaly Csikszentmihalyi (1990), flow refers to a highly immersed experience when a person is engaged in a mental and/or physical activity to a level where this person loses track of time and the outside world, and when performance in this activity is optimal.

[2]Psycho-pedagogical implications refer to didactic and instructional principles. An example is the diversification of learning events (e.g. into transmitting information, experimenting, discussing or imitating), which is commonly considered beneficial to learning progress (cf. Merrill 2002).

References

Albert D. & Lukas J., eds (1999) *Knowledge Spaces: Theories, Empirical Research, and Applications*. Lawrence Erlbaum Associates, Mahwah, NJ.

Azevedo R. & Bernard R.M. (1995) A meta-analysis of the effects of feedback on computer-based instruction. *Journal of Educational Computing Research* **13**, 111–127.

Chandler P. & Sweller J. (1992) The split-attention effect as a factor in the design of instruction. *British Journal of Educational Psychology* **62**, 233–246.

Church R.M. (1964) Systematic effect of random error in the yoked control design. *Psychological Bulletin* **62**, 122–131.

Csikszentmihalyi M. (1990) *Flow: The Psychology of Optimal Experience*. Harper and Row, New York.

De Bra P.M.E. (2008) Adaptive hypermedia. In *Handbook on Information Technologies for Education and Training* (eds H.H. Adelsberger, P. Kinshuk, J.M. Pawlowski & D. Sampson), pp. 29–46. Springer, Berlin.

Deci E.L. (1975) *Intrinsic Motivation*. Plenum Press, New York.

de Freitas S. (2006) *Learning in immersive worlds. A review of game-based learning*. Available at: http://www.jisc.ac.uk/media/documents/programmes/elearning_innovation/gaming%20report_v3.3.pdf (last accessed 28 August 2007).

Doignon J.-P. & Falmagne J.-C. (1985) Spaces for the assessment of knowledge. *International Journal of Man-Machine Studies* **23**, 175–196.

Doignon J.-P. & Falmagne J.-C. (1999) *Knowledge Spaces*. Springer, Berlin.

Foerde K., Poldrack R.A. & Knowlton B.J. (2007) Secondary-task effects on classification learning. *Memory & Cognition* **35**, 864–874.

Freeman D. (2003) *Creating Emotion in Games: The Craft and Art of Emotioneering*. New Riders, Indianapolis, IN.

Gee J.P. (2003) *What Video Games Have to Teach Us about Learning and Literacy*. Palgrave/Macmillan, New York.

Gillie T. & Broadbent D. (1989) What makes interruptions disruptive? A study of length, similarity, and complexity. *Psychological Research* **50**, 243–250.

Jennett C., Cox A.L., Cairns P., Dhoparee S., Epps A., Tijs T. & Walton A. (2008) Measuring and defining the experience of immersion in games. *International Journal of Human Computer Studies* **66**, 641–661.

Kafai Y.B. (2006) Playing and making games for learning. *Games and Culture* **1**, 36–40.

Kickmeier-Rust M.D. & Albert D. (2008) The ELEKTRA ontology model: a learner-centered approach to resource description. In *Advances in Web Based Learning – ICWL 2007*, Lecture Notes in Computer Science, 4823/2008 (eds H. Leung, F. Li, R. Lau & Q. Li), pp. 78–89. Springer, Berlin.

Kickmeier-Rust M.D., Albert D., Hockemeyer C. & Augustin T. (2007a) Not breaking the narrative: individualized competence assessment in educational games. *Proceedings of the European Conference on Games-based Learning (ECGBL)*, 25–26 October 2007, Paisley, Scotland.

Kickmeier-Rust M.D., Peirce N., Conlan O., Schwarz D., Verpoorten D. & Albert D. (2007b) Immersive digital games: interfaces for next-generation e-learning. In *Universal Access in HCI, Part III, HCII 2007, LNCS 4556* (ed. C. Stephanidis), pp. 647–656. Springer, Berlin.

Kickmeier-Rust M.D., Marte B., Linek S.B., Lalonde T. & Albert D. (2008) The effects of individualized feedback in digital educational games. In *Proceedings of the 2nd European Conference on Games Based Learning*, 16–17 October 2008, Barcelona, Spain (eds T. Conolly & M. Stansfield), pp. 227–236. Academic Publishing Limited, Reading, UK.

Kinshuk, Lin T. & Patel A. (2006) User adaptation in supporting exploration tasks in virtual learning environments. In *The International Handbook of Virtual Learning Environments*, Vol. 1 (eds J. Weiss, J. Nolan, J. Hunsinger & P. Trifonas), pp. 395–425. Springer, Dordrecht, The Netherlands.

Korossy K. (1997) Extending the theory of knowledge spaces: a competence-performance-approach. *Zeitschrift für Psychologie* **205**, 53–82.

Merrill M.D. (2002) First principles of instruction. *Educational Technology, Research and Development* **50**, 43–59.

Mitchell A. & Savill-Smith C. (2004) *The Use of Computer and Video Games for Learning: A Review of the Literature*. Learning and Skills Development Agency, London.

Moreno R. (2004) Decreasing cognitive load for novice students: effects of explanatory versus corrective feedback in discovery-based multimedia. *Instructional Science* **32**, 99–113.

Newell A. (1990) *Unified Theories of Cognition*. Harvard University Press, Cambridge, MA.

Newell A. & Simon H. (1972) *Human Problem Solving*. Prentice-Hall, Englewood Cliffs, NJ.

Oblinger D. (2006) Games and learning. *Educause Quarterly Magazine* **29**, 5–7.

Prensky M. (2001) *Digital Game-Based Learning*. McGraw-Hill, New York.

Tan J., Biswas G. & Schwartz D. (2006) Feedback for metacognitive support in learning by teaching environments. In *Proceedings of the 28th Annual Meeting of the Cognitive Science Society* (eds R. Sun & N. Miyake), pp. 828–833. Mahwah, NJ: Lawrence Erlbaum.

Van Eck R. (2006) Digital game-based learning. It's not just the digital natives who are restless. *Educause Review* **March/April**, 17–30.