Learning on Electrical Circuits While Playing 'E&E Electrical Endeavours'

Design Research on a Serious Game Optimizing for Conceptual Understanding

Ruurd Taconis[1], Mariette Dubois[2], Lesley de Putter[3,4] and Henry van Bergen[5]

[1]*Eindhoven School of Education, Eindhoven University of Technology, Den Dolech 2, Eindhoven, The Netherlands*
[2]*Sondervick College, Knegselseweg 30, Veldhoven, The Netherlands*
[3]*Heerbeeck College, Willem de Zwijgerweg 150, Best, The Netherlands*
[4]*Eindhoven University of Technology, Den Dolech 2, Eindhoven, The Netherlands*
[5]*Faculty of Electrical Engineering, Eindhoven University of Technology, Den Dolech 2, Eindhoven, The Netherlands*

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Abstract: A serious game was developed in a two year design research project by educational researchers, game-designers and secondary school teachers in close collaboration. In a first round, students played the game in class using an open-inquiry strategy. Although the game had a strong impact on the students' conceptual development, it provoked the construction of misconceptions. The game was adapted and partially redesigned on the basis of the evaluation outcomes and an additional expert-review. Also the instructions to the game were redesigned and written down in a teachers' guide. In a second round, a pedagogical approach of alternating open-inquiry type gaming-episodes with guided reflection and internalisation episodes was used in class. Again a strong impact on students' conceptual understanding of electrical circuits was found. Significantly fewer misconceptions occurred. The results indicate that the close collaboration of school teachers, educational experts and game designers was fruitful for improving the serious game and its use in school practice. Moreover it became clear that serious games have the potential to contribute to students' conceptual understanding, in particular when a suitable mental model is coherently represented in the game´s layout and structure.

1 INTRODUCTION

Serious games are an inviting new option in education. The game industry is growing spectacularly. However, the characteristics that make games adequate *serious* games and the pedagogical do's and don'ts of using them in education are still largely uncovered (Michael and Chen, 2006). This paper reports on a design research project conducted using the game 'E&E electrical endeavours'. The project's aim is to help students master the subject of electrical circuits in grade 9 of Dutch secondary education, develop a pedagogical approach to using serious games in secondary education, and to motivate students for science and electrical engineering.

The game was previously developed at the faculty of Electrical Engineering at Eindhoven University of Technology mainly for raising the interest of potential new students. Hence the main focus in the initial version 1.0 of the E&E electrical endeavours game was on student involvement and motivation, excellent graphics and challenging content on electrical circuits. The game can be typified as a simulation based game for individual use. It is not a role-playing game where players are set against each other. In version 1.0 no match with formal science curricula was pursued. A pilot evaluation (Dekker et al., 2010) showed the game was attractive and entertaining for students in secondary school.

Secondary schools were seeking ways to modernize education by implementing ICT, to enrich science education by e.g. serious games, and to bring a lively perspective on scientific practice and careers into the school.

Combining these, the joint conclusion was that both university and secondary school goals could be successfully supported if an attractive serious game

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could be constructed. The game should fit well into the formal curriculum, clearly contribute to student learning and should be brought into school as a sincere and attractive picture of scientific practice and careers.

To achieve this, a project group was formed comprising secondary school teachers, experts on science education and game-designers. Their task was to: "Construct and evaluate a serious game that is attractive and motivating on one hand and making an adequate contribution to formal learning in secondary education on the other". In line with this, a key research question addressed in this paper is: which characteristics of the game and of the way it is implemented in classroom make it adequate for learning about electrical circuits and dealing with misconceptions in particular? The approach taken to actually develop the game and answer the question was a design research project.

2 THEORY

2.1 Design Research

Design research is well known in both engineering and educational research (Gravemeijer & Cobb, 2006). In design research on education, education is being (re)designed and evaluated in various rounds. These comprise an alternating sequence of (re)design and evaluation leading to new or refined design criteria. The evaluation adds up to a picture that allows answering previously set research questions, as well as bringing forth new hypothesis and tentative answers. From a methodological point of view, it is a productive experimental design with both explorative and confirmative aspects. From a practitioner's point of view, it has the strong advantage of making a very close connection between research on one hand, and professional practice and professional development on the other.

2.2 Serious Games and Learning

Theory on the design and use of simulation-type serious games in education strongly emphasises the concepts of flow (Csikszentmihaly, 2009) and experiential learning. A key theory on experiential learning is developed by Kolb (1984), and adapted for the case of serious games by various authors (Ruben, 1999; Koops and Hoevenaar, 2012).

Using insights from general cognitive constructivist learning theories and the five stage model of skill acquisition by Dreyfus & Dreyfus (1980) (shown in Figure 1), Taconis (2011), developed a hypothetical model of experiential learning in serious games.

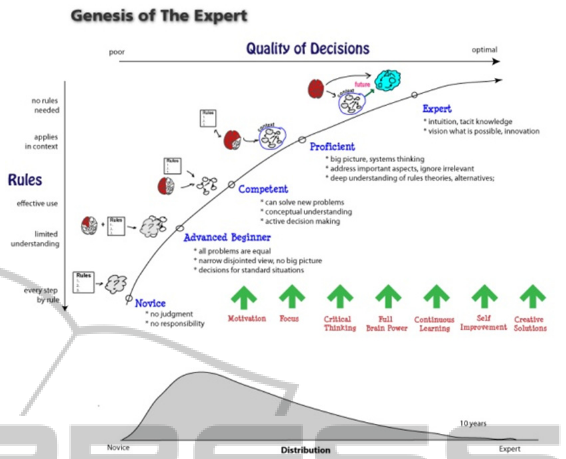

Figure 1: The Dreyfus & Dreyfus five stage model of the genesis of an expert (http://www.leanleadershipacademy.com/wp-content/uploads/2013/04/novice-expert1.jpg).

The 'Taconis model' explicitly pictures how the rules underlying and governing the game-engine, through producing the game's 'behaviour' and the regularities in the gaming environment, structure the learners experiences while gaming. It also pictures how skilled action by the learner, the acquisition of operational rules and ultimately a coherent reconstruction of the rules underlying the game-engine´s may result from the learners 'structured experiences'.

Figure 2: The hypothetical model of experiential learning in simulation-based serious games by Taconis (2011).

In the model 'skilled actions' (upper box in second column in Figure 2) are defined as those actions adequate within the gaming environment that do not imply or require conscious declarative knowledge.

These actions represent adequate behaviour in standard situations without being underpinned with knowledge. This corresponds to the *advanced beginner* position in the Dreyfus & Dreyfus five-stage-model.

'Operational rules' (middle box in second column in Figure 2) are – in line with the five- stage-model – considered a next step in development. The operational rules are typified by the involvement of conceptual understanding, though of an operational type, using concepts that are apparent within the experienced game environment. An example would be a learner that acts adequately within the game and is able to explain why and how he performs in terms of the game-world. This could be considered roughly equivalent to the stage of being *competent* within the five-stage-model though this concerns the game-environment only. Reaching this level requires the constructing (learning) of operational rules from experience, and it is presumed to require systematic and reflective thinking. Constructing these rules may be stimulated by asking the students questions, facilitating group discussions and adding tasks that require the construction and verbalization of such rules. Operational rules and skilled actions may transfer from the strict game-environment to other situations/environments, and this is more likely to occur the more akin these situations are (Vockell, 2013). For example, from a serious game that models projectile trajectories, skilled actions and operational rules may relatively easily transfer to projectile shooting experiments in classroom, but less easily to text-book questions on this subject or the context of satellite trajectories.

The (re)construction of 'theoretical insight' (lower box in second column in Figure 2), aligns with both '*competent* within the game-environment' towards '*competent* in real life'. This splitting-up of the 'competent stage' in the five-stage-model results from the fact that experiential learning from serious games involves two realities: the real world and the game world that simulates it. By its nature, theoretical insight will formally apply to real-life situations, since the rules a simulation based serious game is built upon apply to real world as well. Even though in many cases the rules underlying the game are in fact simplified versions of real life rules.

But this equivalence will not be automatically clear to the learner. Hence, theoretical insight only principally applies to both the game-world and the real world. In education, the learner should make considerable effort to understand and recognize this difference (transfer) and to achieve a 'competent in real-life' stage.

Constructing or reconstructing theoretical insight definitely requires systematic and reflective thinking as described above, but also making comparisons with contrasting and/or akin situations and theoretical points of view. The confrontation with situations other than the game-environment is needed; both to help constructing the theoretical ideas independently from the game-world and to facilitate transfer to other situations (Vockell, 2013).

The presumed necessity to implement in classthese reflective of theoretical components as well as exercises in other learning-environments than the game-environment, conflicts with the fundamental importance of flow for gaming and the use of serious games in education. Put in terms of a concrete design dilemma: how can we have students 'in the flow' while gaming within the game-environment as well as active as critical thinkers on a theoretical level transcending the game-environment. This seems to connect to a fundamental design dilemma in inquiry structured or open education aiming at conceptual development described by various authors such as Kirschner, Sweller and Clark (2006) and - for the case of education on electrical circuits - Kock et al. (2013).

Once attained, theoretical insight opens up an avenue to develop towards proficiency with respect to real-life situations and beyond.

2.3 Learning about Electrical Circuits

Learning problems in electricity have been widely documented: Over the years remedies have been suggested to overcome students' conceptual problems in electricity, but only with limited success (Mulhall et al. 2001). The topic is still receiving attention (for example Engelhardt and Beichner 2004; Hart 2008; Taber et al. 2006; Jaakkola, Nurmi & Veermans, 2010). Coming to grips with the scientific concepts in electricity requires an understanding of the physics involved, which is at least partly at odds with the everyday experiences and ways of speaking about electricity (Shipstone 1985; Duit and Schecker, 2007).

A key problem is the development of inadequate conceptual understanding of various aspects of electrical circuits and particular persistent 'misconceptions' that students tend to develop. In Duit's STCSE bibliography on students' 'misconceptions' and conceptual change (Duit, 2009) several hundreds of publications are listed on learning electricity.

Taconis (2010) has described a hierarchical building of concepts concerning electrical circuits based on a review of literature. Each addition to the concepts requires all concepts in the lower floors to be rightly understood.

1) Correct understanding of electrical circuits essentially being closed but not short circuited, and the electricity circling in the circuit, and the current not being consumed in the circuit,
2) Understanding that two distinct physical quantities are necessary to understand/describe the flow in electrical circuits (and such systems): electrical current and voltage,
3) Understanding of the topological types of electrical circuits; series and parallel and their implications for electrical current and voltage.
4) Understanding of particular electrical components and their properties.

Students may experience problems on either level of this hierarchy and students' alternative ideas often do not correspond to the scientific view and do not easily change through instruction (Shipstone 1985; Duit and Von Rhoeneck 1998; Engelhardt and Beichner 2004; Taber et al. 2006). Kock et al. (2013) conclude: when trying to solve problems or explain phenomena in circuits, students frequently (a) confuse important concepts such as current and voltage, (b) use the idea that current is consumed (or use unipolar, clashing or shared current models), (c) view power supplies as a source of constant current instead of constant potential difference, (d) have difficulties building and drawing circuits and (e) do not realize that a change of one element can have an impact on the current in the whole circuit.

A main obstacle here is that students may tend to understand electrical phenomena in terms of the so called 'experiential gestalt of causation' (Anderson, 1986). This basic misinterpretation may underlay many of the observed misconceptions.
In the 'experiential gestalt of causation' there is an *aim*, a *cause* or chain of causes that instigates a process, a *medium/vehicle*, and a *desired effect*. This mental model implies a number of intuitive qualitative rules such as:

- the effect is roughly in the direction of the cause / chain of causes,
- the stronger the initial cause / chain of causes, the stronger the effect – by default proportional,
- the cause / chain of causes costs 'effort', and is weakened in the long run (due to exhaustion) while the effect continues,
- there is a physical connection of the cause to the effect, possibly through the medium (or vehicle), which may damp the effect – by default proportional to its dimensions,
- the better the medium and / or the smaller the distance the stronger the effect,
- as the cause stops, of if the contact is ended or the medium is removed, the effect stops.

Figure 3 shows an example.

Figure 3: 'Electricity' effect as experienced in day to day life: when plugged in (cause) de 'electricity' from the socket is directed to the light bulb connected (aim) via the cord (medium/vehicle) to produce the desired effect. An example of cause - effect reasoning, from which students may derive interpretations such as: a wire twice as long will make the light bulb half as bright.

An attempt to counter the misinterpretation of electrical circuits from such a linear causal perspective often made is to explain that the electrical circuit is to be understood in terms of an analogy. Two such analogies are regularly used in science education (Hart, 2008) with their own strengths and weaknesses:

a) Fluid current analogies, that of the home heating system in particular,
b) Microscopic analogies in which the electrical current is modelled by a stream of electrons depicted as e.g. lorries carrying an electrical load travelling a closed path.

The E&E electrical endeavours game uses the water current analogy.

2.4 Research Questions

The research questions are:

1. Can we built and use for education a serious game that leads to adequate qualitative understanding of electrical circuits without particular misconceptions?
2. What characteristics of the game and the way it

is used in classroom facilitate adequate understanding of electrical circuits? In particular:

a. in dealing with misconceptions
b. keep a productive the balance between flow-based gaming and reflective and theoretical activities.

3 METHODS

The project was performed in two consecutive rounds each comprising a (re)design and a testing phase. It started with the game version 1.0 as previously build. On advice of the secondary school teachers version 1.0 was upgraded to version 1.1 before starting the project, in order to remove mistakes and smaller difficulties. Version 1.1 was tested by panels of experts in the pedagogy of science, school teachers and students and found adequate for classroom use.

3.1 Description of the Development Rounds

Version 1.1 was taken to the classroom in two Dutch grade 9 classes, one general secondary education and one pre university education. A third one, also pre university education, served as a control group. The lessons were structured to an open inquiry model. The students were allowed to play with version 1.1 during 1½ lesson (approximately 75 minutes). The lessons for the experimental and control groups were partly the same, but deviated in the experimental group playing the game and the control book following the textbook. This is shown in Table 1. Figure 4 a typical screen shot.

In round II, version 3.0 was taken to the classroom in three Dutch grade 9 classes, one general secondary education and two pre university

Table 1: The quality of the circuits built.

	Experimental groups	Control group
1	Introduction Activation of basic knowledge from grade 8	
	Inquiry learning playing with version 1.1 The teacher coaches; no additional teacher explanation of theory	Individual working from the textbook The teacher coaches; no additional teacher explanation of theory
2	Learning task: Build a parallel circuit of two light bulbs	
	Continuation like 1st lesson	Continuation like 1st lesson
3-6	Classical teaching using the textbook	
	Test	

Figure 4: Characteristic screen shot of E&E electrical endeavours version 1.1.

education. Version 3.0 has a renewed level structure that closely follows the regular Dutch grade 9 lesson plan. Also the layout of the game screen is renewed. First, in the left part of the screen the electrical circuit is continuously shown as a closed circuit providing an overview to the students which is much akin to the electrical schemes' usually found in textbooks. Second the working screen on the right is redesigned to more realistically depict voltage and current meters and the way they should be connected. Figure 5 gives an impression.

Figure 5: A characteristic screen shot of E&E electrical endeavours version 3.0.

In round II there was no control group. The lessons were structured according to the teacher guide that was written on the basis of the experiences in the first round and a review of literature. In the first lesson –again- the subject was introduced and the prior knowledge of the students was activated The students were then allowed to play freely with the game for approximately 40 minutes, in which they could take op the challenges built into the games level structure. The next lesson, a classroom discussion was organized evaluating the students various ideas and results, and drawing common conclusions on understanding electrical circuits. In both coaching the students and the classroom discussions, the teacher could make use of a set of questions in the teacher guide especially designed to stimulate the verbalization/construction of operational rules and theoretical knowledge and to stimulate transfer (see Figure 2). The whole experiment comprised 6 lessons (300 minutes).

3.2 Analysis of the Circuit Building Test

For both rounds, the learning results were obtained using the standard test results (grades). The same test was completed by all groups in that round. In addition an analysis was made of pictures taken from the circuits built in the learning tasks ‘build a parallel circuit of two light bulbs’. The analysis focussed on the correctness of the circuits and the presence of misconceptions. Four misconceptions were focussed on in particular: circuit not closed /incorrect, short circuit, a circuit lay-out depicting a ′linear causal ‘understanding’ of electrical circuits, and the type of meaning of ′parallel′ the students displayed in the circuit built. Concerning the latter: components may be placed ‘visually parallel’ though when analysing the circuit net ′electrically parallel′ – see figure 6.

A codebook was used to underpin the various judgements on the circuits and the apparent presence of misconceptions and two researchers cooperated in categorizing the various circuits.

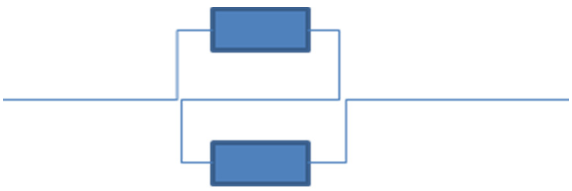

Figure 6: Optically parallel though not electrically.

4 RESULTS

In round I, the teacher reported a marked distinction between students that are experienced gamers and other students. The non-gamers experience difficulty in finding their way in the game, while the gamers seemingly effortless solve the problems presented.
The teacher also reported that all students had difficulty recognizing the electrical components in the game. Students in the experimental setting comment: *“it was fun, but I would have preferred an ordinary lesson since then I would have understood it much better”.*

The result of the analysis of the ‘parallel circuits’ built in the second lesson and their quality in general is shown in Table 2.

Table 2: The quality of the circuits built.

	Round I			Round II			t-test
	n*	**M**	**SD**	**n***	**M**	**SD**	
g.s.e. exp.	13	-0,54	0,75	11	1,68	1,03	5,94***
g.s.e. contr.	---	---	---	---	---	---	
p.u.e exp.	11	1,05	1,59	24	1,92	0,70	1,74*
p.u.e contr.	12	2,75	0,45	---	---	---	
TOTAL	**36**	**1,04**	**1,70**	**35**	**1,84**	**0,81**	**2.54****

Abbreviations: g.s.e. = general secondary education, p.u.e = pre university education. Sign. Levels: * = 5%, ** = 1%, *** = 0,1%
* duo’s of students

The control group that worked from the textbook clearly outperformed the two experimental groups. However it was observed that the average grades for the test at the end of the lessons did not significantly differ for the three groups. The teacher commented that she had to make an extra effort in the experimental groups to secure their progress.

An analysis of misconceptions in the circuits built after the second lesson is shown in Table 3, which shows that misconceptions occurred frequently in the experimental groups.

Table 3: The occurrence of misconceptions in the first and second round.

		Circuit not closed /incorrect	**Short circuit**	**Causal mental model**	**Visual view of ‘parallel’**
Round I	M	0,45	0,39	0,52	1,19
(n*=24)	SD	0,47	0,50	0,45	0,38
Round II	M	0,03	0,14	0,41	0,16
(n*=35)	SD	0,17	0,36	0,35	0,81
t-test		-4,19***	-2.10*	-1.0 (ns)	-6,55***

Sign. Levels: * = 5%, ** = 1%, *** = 0,1%
* duo’s of students

A qualitative analysis of the circuits built revealed a very interesting pattern.

It appeared that a majority of students (54%) built a circuit in a very particular manner. For general secondary education students this is even 77%. First they added a switch to the circuit - a component that was not at all mentioned in the assignment. Second they ordered the components in a linear fashion starting with the switch, followed by the ‘parallel part’ and ending with a light bulb. Figure 7 shows three examples (three left columns),

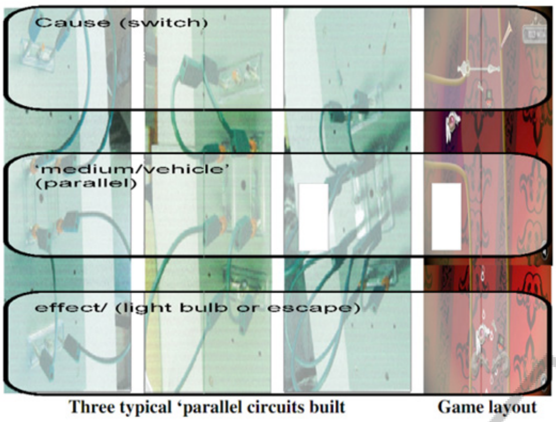

Figure 7: Student mimicking the games circuit lay-out and linear topology when building a parallel circuit.

as well as the game lay-out (right column). This typical lay-out by the students both resembles the game's screen lay-out and is in accordance with the 'experiential gestalt of causation'.

The disappointing learning result from the game as such, the lack of student and teacher enthusiasm, the frequent occurrence of misconceptions, and the apparent strong but unwanted learning effect arising from the games lay-out that effectively *encourages* students to understand electrical circuits in terms of 'the experiential gestalt of causation' formed a strong incentive to improve both the game, and the way it is used in classroom. First a panel of teachers was asked to comment on the game and the inquiry based classroom implementation. This resulted in redesigning specifications for the game, and the conclusion that the open-inquiry approach should be replaced by a carefully planned approach combining experiential learning on one hand and reflection, verbalisation en additional experience on the other. This criticism was theoretically underpinned by experimental work of Kock et al. (2013) and the theoretical insight by Kirschner, Sweller and Clark (2006). A review of literature led to the model by Taconis (2011) depicted in Figure 2, and a extend teacher guide comprising: a) background information on learning from serious games and understanding electrical circuits, b) an example time table, c) concrete questions the teachers could use to stimulate the verbalization/construction of operational rules, theoretical knowledge and their transfer (Figure 2).

In round II the changes were implemented. The teachers reported the students being enthusiastic about the game, and students reporting that 'it really helped them to understand electrical circuits'. One student for instance stated: *'the game really made me understand what I am doing, and helps me to explain what it is to my friends'*. This was supported by a very high mean score on the test concluding the lessons: 7.2 out of 10 (usually 6.3).

The quality of the 'parallel circuits' built is shown in Table 2. It reveals a significant increase with respect to the quality of the circuits built in the first round. Table 3 shows that also the occurrence of misconceptions significantly decreased, except for the occurrence of the 'experiential gestalt of causation'.

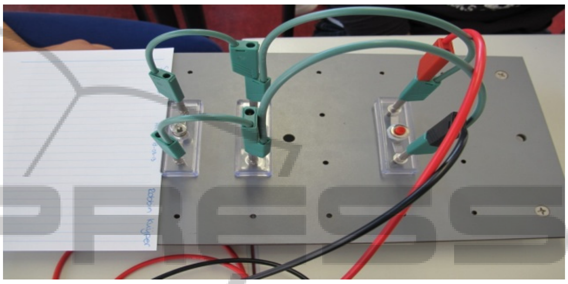

Figure 8: Typical wrong placement of the switch.

A qualitative analysis of the circuits built by the students revealed that in addition many students (54%) have difficulties with the correct placement of the switch (Figure 8). It effectively functions as an optional 'shortcut' directly at the entrance of the powering wires from the power unit. Again, this is in clear accordance with de games lay-out (Figure 5), were the switch has taken the form of a beam across and blocking the current at the top of the screen.

4 CONCLUSIONS & DISCUSSION

We conclude that the close cooperation between school teachers, experts on science education and game-designers was a successful way to a clear improvement in both the game and the way it is adequately used in classroom. Note that enhancing the games contributed to cognitive learning did not imply a decrease in student enthusiasm. The progress made is documented in the projects physical products: the game and guideline for its adequate use in education.

It is concluded that the game when used according to the guideline, probably contributes to improved student understanding. However, misconceptions still occur, those related to 'the experiential gestalt of causation' in particular. In terms of the model by Taconis (2011) learning effects seem to concentrate on the level of 'skilled action' (building an electrical circuit) and

´operational rules´. Students do not report on theoretical understanding or models they (re-)constructed.

Concerning the second research question, it is found that the games screen lay-out has a strong though undesired impact on students' mental model of electrical circuits and student learning. The way things are presented apparently strongly influences the students´ way of 'looking at things'. This 'topological mimicking' seems to be a very powerful learning mechanism. The games lay-out, and probably its structure as well, sends out a very strong message about 'how things are'. Though not entirely effective in the case of our project, the strength of this mechanism is potentially valuable for designing serious games.

Concerning the use of serious games in classroom, it became clear that 'open inquiry' alone is not the way to go. An approach balancing gaming and deep cognitive processing in alternating phases seems much more fruitful. In this a rule of thumb helping teacher in a practical way could be: "treat serious games as experiments or practical exercises".

Our research has been on a fairly small scale, and as such its outcomes may be easily over generalized. But they point toward two particular issues of importance for larger scale future research:

- developing a pedagogical approaches balancing between play and open inquiry on one hand and stimulating and structuring deep cognitive processing on the other. Put more generally: seeking a productive balance between flow and reflection.
- taking advantage of the strong modelling impact the lay-out and the structure of the game have on student learning.

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APPENDIX

The E&E game and its versions:

1.0 and 1.1 (http://www.eeee.tue.nl/)
2.0 (http://www.eeee.tue.nl/sloa/index.html)
3.0 (http://www.eeee.tue.nl/sloa/thebeginning/index.html)