Robust student knowledge: Adapting to individual student needs as they explore the concepts and practice the procedures of fractions

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Abstract.
Robust knowledge consists of both conceptual *and* procedural knowledge. In order to address both types of knowledge, offering students opportunities to explore target concepts in an exploratory learning environment (ELE) is insufficient. Instead, we need to combine exploratory learning environments, to support students acquisition of conceptual knowledge, with more structured learning environments that allow students to practice problem-solving procedures step-by-step, to support students' acquisition of procedural knowledge. However, how best to combine both kinds of learning environments and thus both types of learning activities is an open question. We have developed a pedagogical intervention model that selects and sequences learning activities, exploratory learning activities and structured practice activities, that are appropriate for the individual learner. Technically, our intervention model is implemented as a rule-based system in a learning platform about fractions. The model's decision-making process relies on the detection of each individual student's level of challenge (i.e. whether they were under-, appropriately or over-challenged by the previous learning activity). Thus, our model adapts flexibly to each individual student's needs and provides them with a unique sequence of learning activities. Our formative evaluation trials suggest that single components of the intervention model, such as the ELE, mostly achieve their aims. The interplay between the different components of the intervention model (i.e. the outcomes of sequencing and selecting exploratory and structured practice activities) is currently being evaluated.

1 Introduction

Exploratory Learning Environments (ELEs), that include intelligent support, facilitate constructivist learning by offering opportunities for student self-determined exploration of a virtual environment [1]. The exploration of an ELE allows for sense-making activities which in turn promote the student's conceptual knowledge [2]. However, when integrating ELEs into the classroom, conceptual knowledge alone is insufficient. We need to move beyond this and enable students to achieve *robust* knowledge. Robust knowledge is deep, connected and comprehensive knowledge about a domain that lasts over time, accelerates future learning, transfers easily to new situations and is thus a very desirable learning goal [2–4]. It consists of both conceptual knowledge (understanding 'why') *and* procedural knowledge (knowing 'how') [5]. Thus, in addition to exploratory learning opportunities, we also need to provide students with learning opportunities that foster procedural knowledge [5] – opportunities for practicing problem-solving procedures, in structured learning environments such as that offered by some Intelligent Tutoring Systems (ITSs) [2] [6].

While prior work in the learning sciences and educational technology has mostly focused on fostering *either* procedural knowledge with structured practice activities (SPA) within ITSs *or* conceptual knowledge with exploratory learning activities (ELA) within ELEs, we aim to extend the existing literature by combining both types of learning activities – exploratory and structured – in order to help students acquire robust knowledge. This novel approach, combining both types of learning activities in one learning environment, also exploits the fact that conceptual and procedural knowledge evolve both iteratively and simultaneously [5].

Here, we report on a pedagogical intervention model (Figure 1), that specifies how to intelligently combine and sequence both ELA and SPA in order to promote complete robust knowledge. In doing so, we followed a theory and a data driven approach and thus iteratively improved our pedagogical model [7]. For example, our pedagogical intervention model builds on the cognitive psychology literature and, as such, is domain-neutral and thus transferable to other domains. However, as learning always depends on a target domain, the model also builds on previous work in the field of mathematics education, particularly fractions learning. The intervention model focuses on the individual student's level of challenge (categorized as either under-, appropriately or over-challenged) and selects the next learning activity accordingly. The model further specifies when students should receive cognitive support, so called task-dependent-support (TDS) , and emotional support, so called task-independent-support (TIS) [8]. The technical implementation of the intervention model is based on a rule-based system that, in order to determine each individual student's level of challenge, evaluates various input indicators (for example the student's response to the activity and the amount of feedback the system has provided).

A speech-enabled learning platform about fractions represents our intervention model and is embedded in the larger context of the 7th grant European research project "iTalk2Learn". In the following sections, we explain the rationale behind the intervention model in more detail, in particular describing how we determine each student's level of challenge, and we finish by discussing future steps.

2 The pedagogical intervention model

When combining ELA and SPA, the first question we have to address is which should come first? We argue that students should first start with an ELA rather than an SPA. The benefits of beginning with an ELA are evident in findings from Kapur [9]. He was able to show that students who started with an ill-structured task (*cf.* ELA) and continued with a well-structured task (*cf.* SPA) gained significantly more conceptual knowledge than students learning in the reverse order. This research was extended by Kapur in his work on Productive Failure [10] which replicated the finding that exploring concepts first fosters conceptual knowledge without hampering the acquisition of procedural knowledge. The choice to start with an ELA was also rooted in a domain-specific reason. From more than 20 years of research, the Rational Number Project [11] elicited four essential beliefs about how best to support students learning fractions [12]. One of these essential beliefs is that "teaching materials for fractions should focus on the development of conceptual knowledge prior to formal work with symbols and algorithms" [13].

The next question to be addressed when combining ELAs and SPAs is what activity comes after the initial ELA? The answer depends on the individual student's level of challenge. Students who are over-challenged with the initial ELA should continue with another less challenging ELA, in order to prevent them applying rules without prior reasoning [14]. On the other hand, students who are under-challenged should be given a more challenging ELA, in order to extend their learning. Finally, for students who are appropriately challenged by the ELA, switching from the exploratory to a structured activity is useful because the acquisition of conceptual and procedural knowledge mutually depend upon each other: changes in one type of knowledge lead to changes in the other type of knowledge which in turn lead to changes in the first type [5]. For example, when a student is appropriately challenged by an ELA, an SPA that is mapped to the ELA allows the student to elaborate and consolidate the conceptual knowledge that was acquired during the ELA.

A third question to be addressed is once a student has engaged with a SPA, what activity comes next? In light of ACT-R theory [15] and the power law of practice [16] students should be provided with more than a single SPA because they need sufficient practice in order to become fluent in the application of a problem-solving procedure. Accordingly, the student should engage with more than a single SPA. In addition to providing students with opportunities to become fluent with a given procedure, we also aim to facilitate students' flexible retrieval of different procedures by providing them with interleaved practice of SPAs, rather than simple blocked practice [17, 18]. However, once the student has become fluent with a given procedure, then additional practice does not lead to better learning [17]. Therefore, students are switched back to the ELE. In this way, the student starts a new learning cycle, which (in the context of our project) is embedded in a particular coarse grain goal of fractions learning (e.g. equivalence of fractions). Here again, depending on the student's level of challenge, the new learning cycle focuses either on the same coarse grain goal, and thus provides the student with additional learning opportunities for that goal, or moves to another coarse grain goal (e.g. adding fractions).

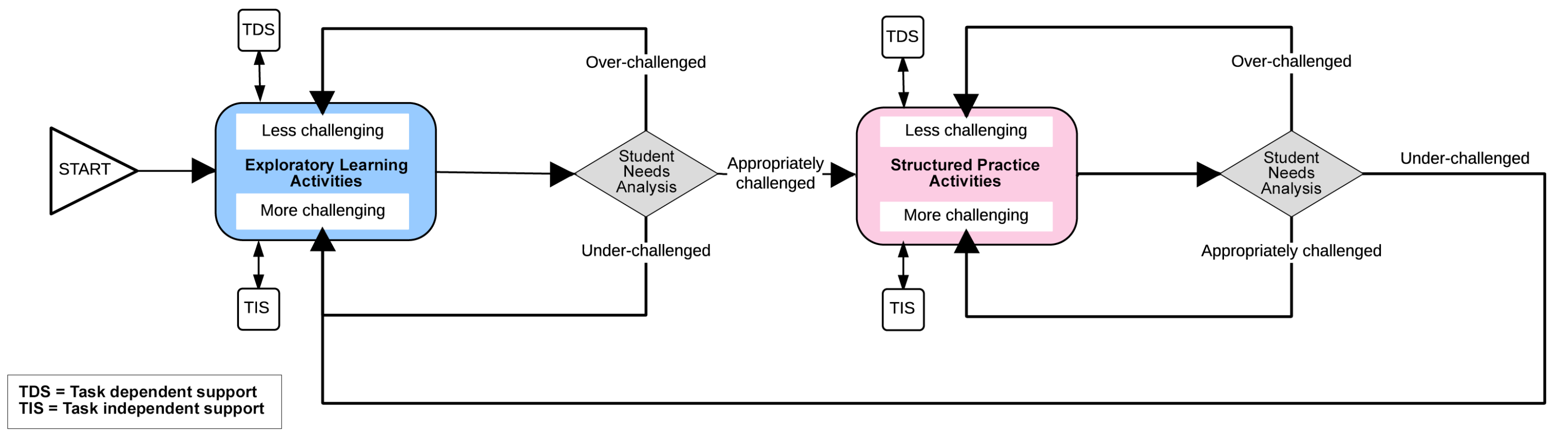

Figure 1: The pedagogical intervention model.

3 Determining a student's level of challenge

Determining a student's current level of challenge is a complex affair, because it is a function of characteristics both of the student *and* of the activity. For example, an ELA is likely to be less challenging for a student with high prior knowledge than for another student with low prior knowledge. Based on our pedagogical intervention model and a student model (i.e. considering the various input variables) the analytical engine (that we call the Students Needs Analysis or SNA) determines the student's level of challenge and thus the learner's appropriate next activity (i.e. output decision). For example, the SNA draws on the student's response to previous activities and to the current activity (using as a proxy the amount of task-dependent support, TDS [19], and the amount of task-independent support, TIS [8], delivered by the system), and the affective state inferred from the student's speech. Combining all these various inputs, each of which is assigned a weighting based on expert pedagogy, provides the SNA with a level of redundancy: a decision about the next appropriate activity can still be reached even if one of the inputs does not give any useful information or gives contradictory information.

3.1 Student Needs Analysis for exploratory learning activities

After each ELA, the SNA determines whether the student was under-, appropriately or over-challenged, based on the following input variables:

- the student's response to the current activity (using as a proxy the amount of TDS and TIS delivered by the system);
- the student's affect state inferred from prosodic cues in the student's speech;
- the student's affect state inferred from their screen and mouse behavior.

Based on these data, the SNA makes an output decision, selecting the next activity that is appropriate for the learner. If, for example, the system has had to deliver a large amount of TDS and the student's affective state has been calculated as *frustrated*, the SNA will determine that the student was over-challenged by the ELA and will sequence to a less challenging ELA. If, on the other hand, few TDS prompts have been delivered and the student's affect is inferred from speech to be *bored*, the SNA will determine that the student was under-challenged by the ELA and will sequence to a more challenging ELA.

Finally, if the SNA infers the student is appropriately challenged (for example, if there has been a minimal number of TDS and the affect has been categorized as *enjoyment*), the SNA switches to the structured practice environment. To ensure that students are provided opportunities to build upon and consolidate their conceptual knowledge, by applying it during structured practice, the SPA are mapped as closely as possible to the just-explored ELA. The close mapping of activities also aims to keep the individual student in their zone of proximal development, that is "the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult [or an Intelligent Tutor's] guidance, or in collaboration with more capable peers" [20].

3.2 Student Needs Analysis for structured practice activities

After students have completed a SPA, the SNA determines what the next activity should be based on the following input indicators (a future implementation will also take account of the number of SPAs the student has completed and the time taken):

- performance prediction, based on a machine-learning model that uses a student's past activity performance to predict future activity performance [21];
- the student's affect state inferred from prosodic cues;
- the TIS previously delivered.

Here, again, the SNA determines whether the student is under-, appropriately or over-challenged. If the SNA detects that a student was over-challenged by a SPA and the student's affect is categorized as *frustrated*, the SNA will deliver a less challenging SPA. By providing over-challenged students with a less challenging SPA we aim to enable the student to become fluent with a less challenging procedure, before re-exposing him to the more challenging procedure that they had not managed before. On the other hand, if the SNA detects that the student is appropriately challenged, he will be assigned a more challenging SPA. A machine-learning-based performance prediction model is used to determine how challenging activities are to the student. It takes into account data about the student's performance on previous tasks and data from other students working on these tasks from a historic dataset. Finally, if the SNA detects that the student is under-challenged, the SNA will switch back to the ELE and will assign a new ELA that is more challenging than the last ELA that they explored.

4 Summary and outlook

Our intervention model, currently implemented within the context of learning fractions, combines exploratory learning activities (ELA) with structured practice activities (SPA) according to each individual student's level of challenge, in order to achieve robust knowledge. In addition to the adaptive selection of the next activity, our intervention model also provides adaptive support in the form of TDS and TIS during each learning activity. Accordingly, students are provided with both cognitive and emotional support as they learn about fractions. Although our intervention model evolved within the domain of fractions learning, it is transferable to other domains as the rationale behind the intervention model is domain-neutral.

Repeated formative evaluation trials across the UK and Germany have tested the effectiveness of all the separate components of the intervention model. For example, various Wizard-of-Oz studies have delivered first empirical evidence that our ELE and its TDS supports students' exploratory behavior and fosters their conceptual understanding of fractions. Meanwhile, the interplay between different components of the intervention model is currently being evaluated. To test the effectiveness of the intervention model we have created different versions of our learning platform. For example, in two quasi-experimental studies in the UK and Germany, we are comparing a full version of the learning platform representing our intervention model with a version that is without the ELE (but has all the other components). We expect differential effects in terms of students' knowledge acquisition (full version, complete robust knowledge, vs. the version without the ELE, procedural knowledge only) and user experiences. The initial results of these evaluation studies will be presented during the AIED workshop.

Once the learning platform is evaluated we will intensify our effort to facilitate the use of the platform for teachers by providing guidelines about how best to prepare for students' interaction with the platform. Additionally, for when working with the platform in class, we aim to provide teachers with a tool (e.g., a teacher dashboard) which will allow them to monitor individual student's use of the learning platform [22]. A further promising approach would be to enable students to learn collaboratively with the platform, as collaborative learning might further support students exploratory behavior and hence additionally support students' learning. From a more technical perspective, our next step is to develop a Bayesian network that is able to predict more precisely the learner-appropriate next activity. However, this first requires the collection of training data for the network from our current rule-based implementation of the SNA.

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