iTalk2Learn

2014-11-19

Deliverable 1.3

Report on intervention model

19th November 2014

Project acronym: iTalk2Learn

Project full title: Talk, Tutor, Explore, Learn: Intelligent Tutoring and Exploration for Robust Learning

Work Package: WP 1

Document title: D1.3 Report on intervention model

Version: 2.0

Official delivery date: 19.11.2014
Actual publication date: 19.11.2014

Type of document: Report

Nature: Public

Main Authors: Claudia Mazziotti (RUB), Michael Wiedmann (RUB), Wayne Holmes (IOE), Nikol Rummel (RUB), Katharina Loibl (RUB), Manolis Mavrikis (IOE), Alice Hansen (IOE), Beate Grawemeyer (BBK), Ruth Janning (UHI), Carlotta Schatten (UHI)

Reviewers: Wayne Holmes (IOE), Manolis Mavrikis (IOE), Alice Hansen (IOE), Beate Grawemeyer (BBK)

Version	Date	Sections Affected
1.0	28/04/2014	Final M18 version: Refinement after internal review
1.1	01/10/2014	First conceptual changes made to the intervention model with IOE
1.2	24/10/2014	Added Students Needs Analysis Section
1.3	04/11/2014	Added contributions from IOE, UHi & BBK: coherent fractions system from D1.2, performance prediction, TIS, case studies
1.6	11/11/2014	Submitted for internal review (IOE, BBK)
1.7	12/11/2014	Integration of feedback from IOE's review
1.8	13/11/2014	Integration of feedback from BBK's review
1.9	14/11/2014	Refinement on TIS by BBK & discussion with IOE about D1.3 structure
2.0	17/11/2014	Submitted to Project Coordinator

Executive Summary

A learning platform that intelligently supports the acquisition of robust knowledge about fractions requires an intervention model that describes the pedagogical decisions the platform makes to flexibly adapt to each individual learner. We have developed a novel intervention model detailing how the various components of the iTalk2Learn platform come together to enable and support students' learning activities towards the acquisition of robust knowledge.

In order to develop what is called robust knowledge, students need to gain procedural and conceptual knowledge, which evolve differently and thus require different types of instructional support (cf. D1.1). For instance, procedural knowledge is acquired through repeated structured practice activities and deepening of problem-solving procedures. In contrast, conceptual knowledge acquisition can be facilitated by providing students with exploratory learning activities and by encouraging reflection. The iTalk2Learn platform is the first of its kind that combines both types of activities. One of the main innovations within the iTalk2Learn project is thus to combine in our platform Intelligent Tutoring Systems (suited for structured activities) with exploratory learning environments (suited for exploratory learning activities). While Intelligent Tutoring Systems for fractions exist and are incorporated in the platform, we developed a new Exploratory Learning Environment as a second innovation of our project. D3.4.1 provides the technical details of the developed exploratory learning environment; D1.2 describes the tasks provided in the exploratory learning environment and the principled design approach taken to design them. For our exploratory learning environment (Fractions Lab) we developed task-dependent support helping students to explore the underlying concepts. For the Intelligent Tutoring Systems (Maths-Whizz for UK students and Fractions Tutor for German students) we relied on their existing task-dependent support functionalities). As a further innovation of the project we integrated task-independent support which aims to optimize cognitive processes by addressing students' affect during the learning process (cf. D2.2.1).

At its core, our intervention model details the pedagogical decisions for how to combine structured practice (within Intelligent Tutoring Systems) with exploratory learning activities (within an exploratory learning environment). It starts students with an exploratory learning activity, and switches to structured practice once the underlying concept is acquired. The intervention model describes how the iTalk2Learn platform can best adapt to the individual student's needs by providing task-dependent and task-independent support while students work on exploratory or structured tasks, and by sequencing tasks that are appropriate for the students' current cognitive and affective state. This adaptive functionality is enabled by a Student Needs Analysis which relies on multiple student data such as performance prediction, students' speech, prosodic cues, and logs from students' interaction with the platform.

The intervention model represents a nodal point of the iTalk2Learn project as it unifies pedagogical innovations with state-of-the art technologies of the other WPs of the project (cf. D2.2.1 for sequencing and support, D3.1 for speech recognition, and D4.2.1 for the platform development), and thus accomplishes milestone MS4 (pedagogical interventions). The technical implementation of the pedagogical decisions described by the intervention model will be presented in D2.2.2.

List of Figures

List of Abbreviations

ELE - Exploratory Learning Environment

FL - Fractions Lab

FT - Fractions Tutor

ITS - Intelligent Tutoring Systems

RNP - Rational Number Project

SNA - Student Needs Analysis

TDC - Task Difficulty Classifier

TDS - Task-dependent Support

TIS - Task-independent Support

WoZ - Wizard-of-Oz

Table of Contents

1. General Introduction

In iTalk2Learn the student interacts with a web-based learning environment to develop robust fraction knowledge, which consists of procedural and conceptual knowledge. These two types of knowledge evolve differently and require different forms of instructional support (cf. D1.1). Within the iTalk2Learn environment students are asked to solve structured tasks that focus on teaching procedural knowledge and to solve exploratory tasks that focus on teaching conceptual knowledge. This deliverable presents an intervention model that describes how to sequence tasks, switch between exploratory and structured tasks, and support students while they work on tasks. For offering the exploratory tasks within the iTalk2Learn platform we have developed the Exploratory Learning Environment (ELE) within the iTalk2Learn project, and for offering the structured tasks we incorporate existing Intelligent Tutoring Systems (ITSs). For German students, the structured tasks are provided by Fractions Tutor (FT), and for English students they are provided by Maths-Whizz. The two ITSs also come with built-in help functionalities (e.g. error feedback, hints) that are integrated into the iTalk2Learn platform. The built-in help functionalities form one part of the task-dependent support (TDS). The help functionalities within the ELE, called FL which we developed within the project, constitute the other part of the TDS. While the combination of exploratory tasks and structured tasks (including their TDS functionalities) focuses on students' cognitive processes, with the implementation of the so called task-independent support (TIS) we additionally consider students' affective state during their learning progress. The TIS is based on students' speech and interaction behaviour and supports students while working on both exploratory and structured tasks. Figure 1 shows the different components which form the architecture of the iTalk2Learn project.

Since prior work in the learning sciences and educational technology has focused on fostering *either* procedural knowledge with structured activities (within ITSs) *or* conceptual knowledge with exploratory activities (within ELEs), our pedagogical intervention model that will be presented in this deliverable below, aims to extend the existing literature by proposing to combine both learning activities by sequencing tasks within and switching between structured and exploratory activities. In doing so, the intervention model aims to facilitate both types of knowledge iteratively which then become, when adequately integrated, robust student knowledge (as presented in Mazziotti et al., 2014). Robust knowledge is knowledge that lasts over time, transfers to new situations, and accelerates future learning and is thus a desirable outcome of students' learning process (cf. Koedinger & Aleven, 2007; Koedinger, Corbett & Perfetti, 2012). Apart from providing the basis for combining both types of activities, the intervention model also addresses the question of how to adapt support in such a combined setting. For this, the intervention model takes into account both findings from our various formative evaluation trials and the literature on instructional design and mathematics education. This interdisciplinary approach offers a new perspective on supporting robust knowledge acquisition which strongly contributes to theory development in education.

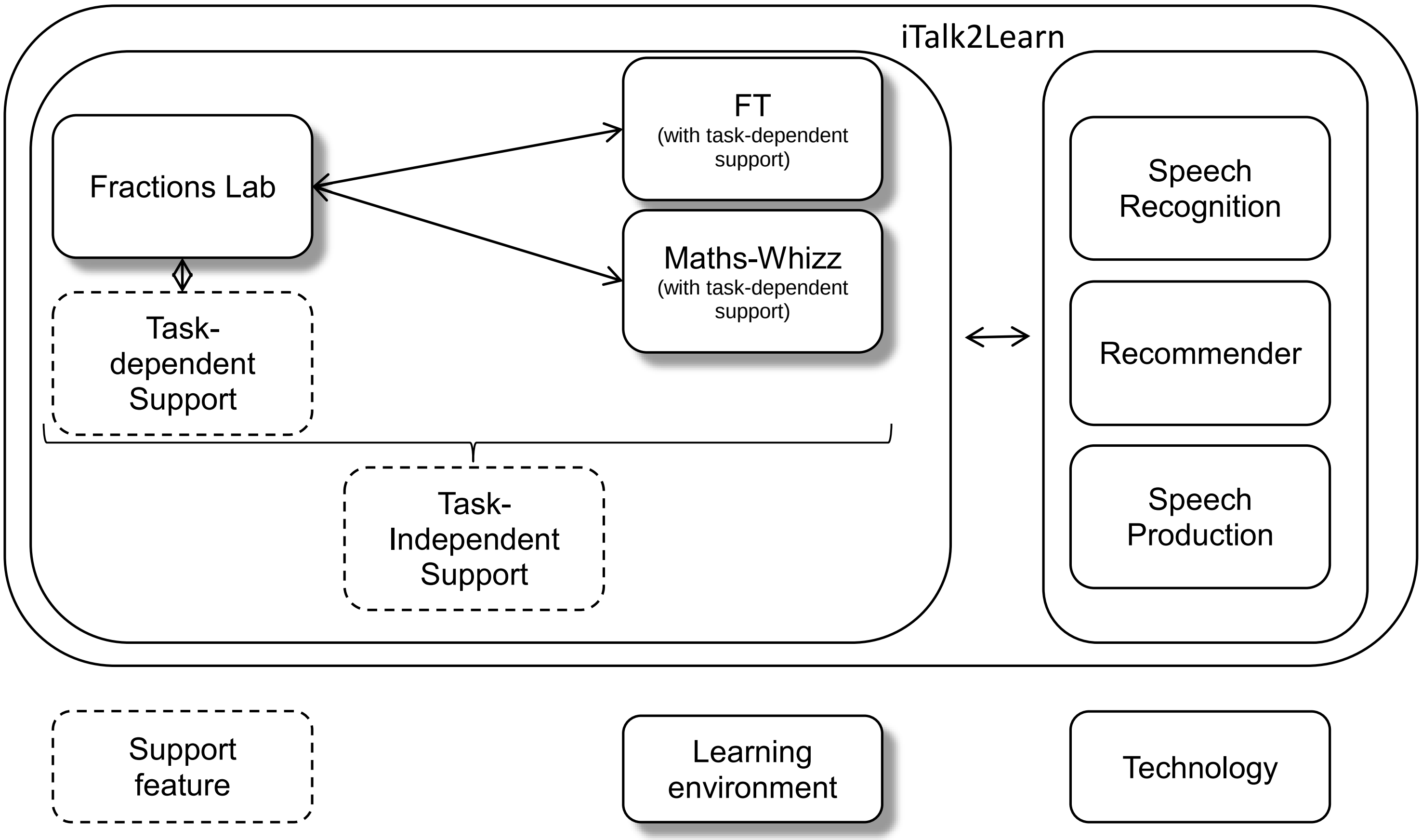


Figure 2: Architecture of the iTalk2Learn platform

At the same time, this deliverable forms the pedagogical foundation for the technical developments within the iTalk2Learn project. Therefore, it forms a nodal point of the project where the work from all different consortium members and in consequence from all different strands interact with each other (e.g., learning environments and support functions on, and speech recognition, speech production, and recommender based performance prediction, technical integration into the iTalk2Learn platform, pedagogy behind the platform). For example, the pedagogically-driven concept to select a (next) learning task which keeps the student in his or her zone of proximal development (Vygotsky, 1978) and thus flexibly adapts to his or her needs is technically implemented by the recommender shown in Figure 1 (D2.2.2 will describe the technical implementation). In this way, the project puts educational research and theory development at its core and aims to go beyond showing proofs of concept that the components of the developed platform work from a technical perspective.

In the following subsection we discuss the relationship of our pedagogical intervention model to the project in more detail. In Section 2, we describe how robust fraction learning can be fostered in computer-based learning environments to provide a background for Section 3 in which this is specified for the iTalk2Learn platform. This section describes the iTalk2Learn intervention model and details the pedagogical decisions behind the sequence of learning activities and the adaptive support. Section 4 presents case studies that illustrate how the intervention model adapts the iTalk2Learn platform to individual students. In concluding, Section 5 summarizes the key innovations and indicates the next steps in the project that this deliverable enables to tackle.

1.1. Relationship to the project and innovations

As the focus of existing ITSs is more on fostering procedural knowledge rather than both conceptual *and* procedural knowledge which are required for robust students' knowledge, one of iTalk2Learn's key innovations is the combination of structured activities (focusing on procedural knowledge development) with exploratory activities (focusing on conceptual knowledge development.) The question of how best to combine both types of activities is addressed in the pedagogical intervention model, aspects of which were introduced in D1.2 and which are now described in more detail in this deliverable. However, this pedagogical question is just one side of the iTalk2Learn project's coin. The other side is the technological question of how to technically integrate both structured and exploratory tasks and provide the intelligent functionalities that support learners. The technical integration was successfully managed by BBK in context of WP4. In WP2, intelligent functionalities were created. For example, the development of a machine-learning based performance prediction paved the way for sequencing the structured tasks within the iTalk2Learn platform. Last but not least, the possibility of detecting students' affects particularly from speech data (e.g. prosodic cues, key words) paved the way for the pedagogical innovation to support both students' cognitive state and students' affective state to promote learning. TIS based on the recognized speech data (cf. WP 3) supports students' affect by providing encouraging prompts when needed. In Appendix 2 the intervention model is displayed together with an overview of the contributions individual iTalk2Learn partners made in order to put the iTalk2Learn intervention model into practice.

2. Robust fractions learning in computer-based learning environments

From a theoretical perspective the two types of knowledge aforementioned, procedural knowledge and conceptual knowledge, form the basis of robust knowledge (e.g., Rittle-Johnson, Siegler, & Alibali, 2001; see D1.1). Both types of knowledge develop over the same period of time (e.g., LeFevre et al., 2006). They develop iteratively: increases in one type of knowledge lead to gains in the other type of knowledge, which in turn lead to increases in the first type of knowledge (cf. Rittle-Johnson et al., 2001). Because the development of the two types of knowledge relies on different types of activities and therefore requires different kinds of instructional support (Koedinger, Corbett, & Perfetti, 2012), we enable students to learn with different computer-supported learning environments (i.e. ITSs, ELE) suited for the different required activities. In the following sections we describe how ITSs and ELE can help students gain robust knowledge.

2.1. Procedural knowledge acquisition

As described in detail in D1.1, procedural knowledge can be acquired through repeated structured practice and deepening of problem-solving procedures (Anderson, Boyle, Corbett, & Lewis, 1990). ITSs offer students efficient instructional support for practicing problem-solving procedures because students solve problems step-by-step, and receive immediate feedback. This way they can automatize the problem-solving procedure bit by bit (e.g., Anderson & Lebiere, 1998). In the context of the iTalk2Learn project we integrate Maths-Whizz for UK students and FT for German students to foster procedural knowledge. Both ITSs, their structured tasks, and their built-in functionalities (e.g., feedback, hints), are described in detail in D1.1 and D 1.2.

In light of the ACT-R theory (Anderson & Lebiere, 1998) and the power-law-of-practice (Newell & Rosenbloom, 1981), students should be provided with more than a single structured task because they need practice to become fluent in the application of a problem-solving procedure. However, once the student has become fluent with a given procedure, then additional practice does not lead to better learning as Rohrer and Taylor (2006) could show. Normally, structured practice should interleave tasks that focus on different procedures (e.g., Rau, Aleven, & Rummel, 2013). However, when students learn for the very first time about fractions, they may not be familiar with even one procedure. In this special case, the three structured tasks should be isomorphic (i.e. differing only in terms of the used numbers; blocked practice) in order to facilitate becoming fluent with the to-be-learned procedure in a short period of time (cf. power-law-of practice).

2.2. Conceptual knowledge acquisition

D1.1 and D3.2 describe how by providing students with exploratory tasks and by encouraging reflection and self-explanation, students are supported to abstract information, construct schemata, and hence develop conceptual knowledge (e.g., Koedinger et al., 2012). The iTalk2learn project has developed FL with this in mind. The main objective of FL is to enable students to inspect and manipulate various fractions representations, investigate their relationships, explore the concept of equivalence and challenge their misconceptions on addition and subtraction (see also coarse grain goals in D1.2).

For FL, we iteratively developed a number of exploratory tasks (see D 1.2 section 4.2). Because we want to foster primarily conceptual knowledge by providing students with exploratory tasks, we paid particular attention to the various dimensions which determine students' understanding of the underlying concept of the fraction task at hand that are described in D1.2. These dimensions are the fine-grain goal(s) the task is intending the student to meet, the interpretation of fractions, the representation(s) of fractions, the fraction types used in the task (i.e. unit fractions, proper fractions, improper fractions), and finally the task type (i.e. structured, or exploratory: classify, analyse, interpret, justify, construct). In terms of the exploratory tasks, these five task dimensions paved the way for the selection of an appropriate next learning task

2.3. Supporting knowledge acquisition

D1.1 briefly summarises that the richness of ELEs often comes at the cost of the necessary pedagogical support. As research on open-ended learning environments shows (e.g., de Jong & van Joolingen, 1998; Leutner, 1993) students' exploration needs to be supported in order to ensure students' fruitful interaction within FL. Therefore, we developed TDS for FL. The TDS for FL was developed in iterative design and test cycles as described in D5.1 and in D5.2. The major outcome of these iterative design cycles (forms of TDS and rules when to provide which TDS) will be explained in the section on the intervention model. As already mentioned also the structured environments, Maths-Whizz and FT, come with TDS. The TDS of both structured environments will also be explained in the section on the intervention model.

So far, we have described how the acquisition of robust fraction knowledge can be supported on a cognitive level by highlighting the potential of ITSs, ELEs, and TDS of both kinds of learning environments. TIS in iTalk2Learn provides one more form of support on the cognitive level but mainly focuses on support on the affective level. Regarding cognitive support, TIS prompts students to talk aloud and use mathematics vocabulary while interacting with the iTalk2Learn platform. It has been suggested that learning mathematics is often like learning a foreign language, and that focusing on using mathematical vocabulary helps students to make connections and revise their interpretations (cf. Borasi et al. 1998). Reminding students to use vocabulary might help them to think through the problem and resolve confusion.

Regarding affective support, research on learning and emotions within computer-supported learning environments (e.g., Baker, D'Mello, Rodrigo & Graesser, 2010; Woolf et al., 2009) has shown that students' affective state influences learning. For example, when students feel excited or happy they tend to perform more successfully (Boekaerts, 1993; Kort et al, 2001; Oatly & Nundy, 1996). Also our formative evaluation studies reported in D5.2 showed that TDS in the form of problem-solving feedback was not effective when students were confused or frustrated. Against this background it becomes evident that support on a cognitive level alone is not sufficient but that additional support on an affective level is needed. This becomes particularly true when we consider that students will learn with iTalk2Learn not only for a short but for a longer period of time. The TIS in iTalk2learn therefore addresses activity emotions that arise during learning (Pekrun, 2006) such as enjoyment, anger, frustration, boredom, surprise, or confusion. The design of TIS will be explained in the section on the intervention model.

2.4. Combining conceptual and procedural knowledge acquisition

When combining exploratory and structured tasks, the first question is which should come first. We argue that students should first start with an exploratory task and not a structured task. This decision was based on over 20 years of research of the Rational Number Project (RNP; e.g., Cramer, Behr & Lesh, 1997), a research project about learning and teaching fractions. The RNP elicited four essential beliefs about how to best support students' learning fractions (e.g., Cramer, Post & del Mas, 2002). 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 (Cramer et al., 1997)" (Cramer & Henry, 2002, p. 41). Since our exploratory tasks are designed to foster conceptual knowledge, and the formal work with symbols and algorithms is comparable with structured tasks in Maths-Whizz or FT, we argue that students should start with an exploratory task that facilitates acquisition of conceptual knowledge. The benefits of beginning with an exploratory task, not a structured task are also evident in findings from Kapur (2008). He was able to show that students who started with an ill-structured task (cf. exploratory learning task) and continued with a well-structured task (cf. structured practice) gained significantly more conceptual knowledge than students learning in the reverse order (i.e. well-structured task prior to ill-structured task). This research was extended by Kapur in his work on Productive Failure (e.g., Kapur, 2012) which replicated the finding that exploring concepts first fosters conceptual knowledge without hampering the acquisition of procedural knowledge.

The next question when combining exploratory and structured tasks is what task comes after the initial exploratory learning task? Students should continue with an exploratory task when they are over challenged with the initial exploratory tasks, because we aim to prevent that they apply rules without prior reasoning (Skemp, 1976). However, when students are appropriately challenged, switching from the initial exploratory to a structured task is necessary because the acquisitions of conceptual and procedural knowledge mutually depend on each other (Rittle-Johnson et al., 2001). We therefore aim to foster both types of knowledge iteratively (cf. Rittle-Johnson et al., 2001). Students should switch back to exploratory tasks once they become fluent with to-be-practiced procedures because additional structured tasks will not lead to better learning as shown by Rohrer and Taylor (2006). This way, the student restarts a new learning cycle. The goal of this new cycle should closely align to the goal of the previous cycle so that the students can continue to build on and elaborate their knowledge. The goals therefore are not ordered in a linear sequence but in a spiral (cf. Elaboration Theory; Reigeluth, Merril, Wilson, & Spiller, 1980) by keeping the coarse grain goal the same and only varying the fine grain goals between learning cycles. In addition, this approach facilitates representational flexibility - a core facet of conceptual knowledge (e.g., Lesh, 1999), because multiple fractions representations (and interpretations) are used to work towards the same coarse grain goal. Only when students demonstrate an appropriate level of attainment within the coarse grain goal at hand, they should be moved to the next coarse grain goal.The intervention model discussed in the next section will show how this theoretical reasoning can be applied in practice by the iTalk2Learn platform.

3. Intervention Model

The development of our pedagogical intervention model combined a theory-driven with a data-driven approach. We developed an initial intervention model based upon literature reviews and discussions with domain experts about instructional design, pedagogical psychology, mathematics education and educational technologies (for instance, RUB met Prof. Vincent Aleven, see also D7.3.1). We then refined our intervention model in line with the results from the various formative evaluation trials reported in D5.2. Additionally, we improved our pedagogical model based on feedback we received at the EARLI SIG 6 & 7 Meeting (Instructional Design & Learning and Instruction with Computers) 2014. The previous Section 2 described the theoretical reasoning behind the intervention model. This section will now detail the pedagogical decisions the intervention model makes.

The intervention model describes how learning with iTalk2learn fosters robust fractions knowledge through combining exploratory and structured tasks. Specifically, it prescribes strategies for sequencing within and switching between exploratory and structured tasks. These strategies are based on student needs analyses that determine how the system can best adapt to individual students. Apart from the sequencing and switching of tasks, the intervention model further prescribes how students are supported while working on tasks with TDS and TIS. By delivering these kinds of support, we increase the degree of guidance at crucial points for students and hence flexibly react to students' current challenges.

The intervention model is depicted in Figure 2. As a brief introduction to the model, we will now provide an overview of a fictitious student's journey through iTalk2Learn, Pam. After being familiarized with the platform and its tools (Coarse-grain goal 0, see D1.2) Pam will begin with an exploratory task in FL that is related to Coarse-grain Goal 1. This initial exploratory learning task encourages her to consider how fractions are part of a whole. Although she will have met this notion previously, either through personal experience or teacher-led tasks, the task is designed to challenge potential misconceptions and to introduce interpretations and representations of fractions she may not have been exposed to before in a formal setting. In FL, she will be able to manipulate fractions representations in order to solve the task and receive help when she gets stuck. Once the Student Needs Analysis (SNA) determines that Pam has successfully solved the exploratory task, she will receive a structured task (delivered within an ITS: Maths-Whizz in UK and FT in Germany) in which she can consolidate the newly acquired conceptual knowledge through practicing procedures that closely map onto the just completed exploratory task. Within the ITS, Pam will receive help from TDS and TIS when she gets stuck. Based on the SNA, the system will assign Pam subsequent structured or exploratory tasks as it determines to be best for her. The subsequent task may be within the same coarse-grain goal or the next, depending on the student's performance and the tasks completed.

The following sub-sections explain the intervention model step by step (see Figure 2). Section 4 will then describe several cases of possible student paths through the system that illustrate the way iTalk2Learn adapts to individual students.

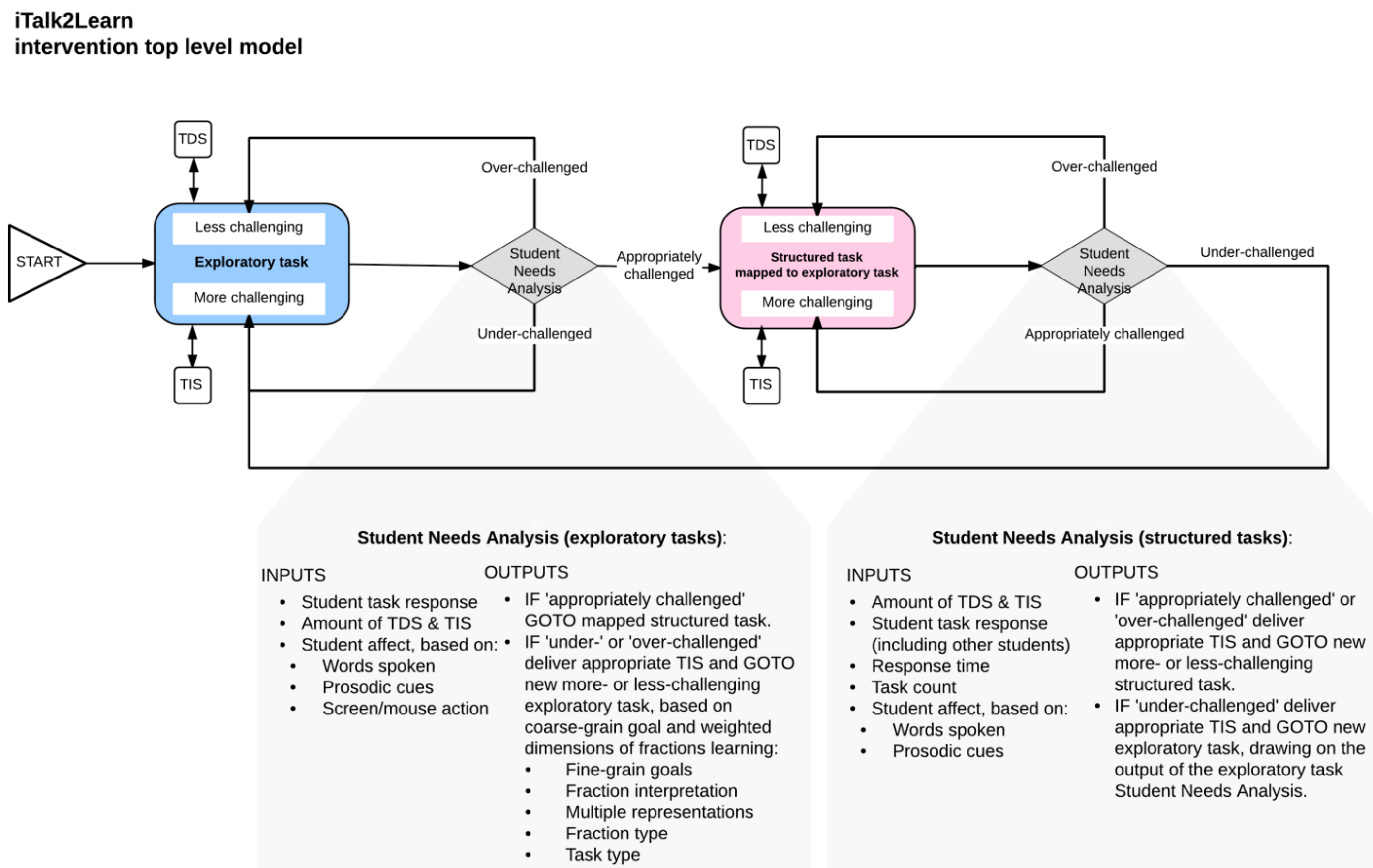


Figure2: Pedagogical Intervention Model.

3.1. Exploratory learning with FL

Exploratory learning activities are primarily meant to build conceptual knowledge that enables students to solve a wide variety of fractions tasks. FL prompts students to manipulate various fractions representations, investigate their relationships, explore the concept of equivalence and challenges their misconceptions on addition and subtraction. This allows students to abstract information presented in the ELE and construct fractions schemata. As we have explained in Section 2, when students learn with iTalk2Learn they start with an exploratory learning task.

While students carry out the exploratory tasks, the system deploys TDS and TIS as needed to adapt to the individual student. The following sections describe in detail how these support components look like while students work on exploratory tasks. In the section on structured practice (Section 3.2), we will give additional information on how TDS is implemented for structured practice.

3.1.1. *Task-dependent Support within FL*

While students solve exploratory tasks, the system responds dynamically to the changing needs of the students by providing them with TDS. For FL a large amount of work had to be undertaken to develop and refine TDS rules and feedback in order to flexibly adapt to students' needs. This work built on the outcomes of the formative evaluations, and in particular of the Wizard-of-Oz (WoZ) studies that are reported in detail in D5.2. The TDS rules are categorized according to the approximate time of feedback delivery (i.e. at the *start*, *middle* or *end* of a student's engagement with the ELE); and the feedback's purpose:

- relating to Polya Steps 1 and 2: understand problem, formulate goals, devise a plan (Polya 1945), for example: *"Read the task again, and explain how you are going to tackle it."*;
- instruction (next step), for example: "You can use the arrow buttons to change the fraction.";
- instruction (problem solving), for example: "Remember that the denominator is the bottom part of the fraction.";
- instruction (opportunity), for example: "You could now copy the fraction and use the partition tool to make an equivalent fraction.";
- affirmation, for example: "The way that you worked that out was excellent. Well done.";
- reflection, for example: "Please explain why you made the denominator 12.".

Drawing on the feedback literature in general (cf. Goldin et al. 2013; Fyfe 2012; Hattie & Timperley, 2007) and on the outcomes of previous research by project partners on feedback types (Mavrikis et al. 2013) in particular, TDS feedback was written for each TDS rule to operationalise four levels of complementary feedback:

Level 1: guidance (supportive information, for example: *"Did you know that you can click..."*, which has the aim of prompting the student to move forwards);

Level 2: Socratic (questions, for example: *"How are you going to...?"*, which has the aim of encouraging the student to think about and verbalise what they need to do next);

Level 3: didactic: conceptual (instructional feedback focused on conceptual issues, for example: *"You have changed the numerator. You need to change the denominator"*, which has the aim of giving the student specific instruction to address a conceptual issue);

Level 4: didactic: procedural (instructional feedback focused on procedural issues, for example: *"You have changed the numerator to 12. You need to change the denominator to 12"*, which has the aim of giving the student specific instruction to enable them to move forward).

These levels of complementary TDS feedback are designed to be delivered in order. In other words:

- if a student's action triggers a TDS rule, they are first given 'guidance';
- if their subsequent action again triggers the same TDS rule, they are given 'Socratic' feedback, and so on, up through 'didactic conceptual' and 'didactic procedural';
- if, after having triggered one TDS rule, the student's action triggers a different TDS rule, the second TDS rule takes precedence;
- if later the student triggers a TDS rule previously triggered, they are given the next level of feedback.

If (after having received the task description, 'guidance', 'Socratic' feedback and 'didactic conceptual' feedback) the student is still unable to proceed with the task, the system delivers 'didactic procedural' feedback which gives the student the specific procedural step that they need to complete in order to move forward. Their experience can be further enhanced if they are then encouraged to reflect both on the feedback that they received and on their task response.

3.1.2. *Task-independent Support*

While students solve exploratory tasks, the system also provides them with TIS to respond dynamically to the changing needs of the students. TIS is also provided during structured practice after the same fashion as will be described now. TIS was developed and refined based on the outcomes of the formative evaluations, in particular of the WoZ-studies that are reported in detail in D5.2. The TIS rules are categorized according to the purpose of the feedback:

- prompting students to talk aloud, for example: "Please describe what you are doing";
- prompting students to use mathematical vocabulary, for example: "Can you explain that again using the terms denominator, numerator?";
- giving students emotional boosts depending on their affective state, that is, for
    - frustration, for example: "It may be hard, but keep going.";
    - boredom, for example: "Please answer the task. You are doing great! ";
    - enjoyment, for example: "Great! Excellent work!";
    - surprise, for example: "You seem to be surprised. What surprised you just now?"
    - confusion, for example: "You are doing well! Keep going."

Affective states, use of mathematical vocabulary, and talking aloud are detected from students' speech input (see D5.2 for an overview). Speech is processed by the speech recognition system developed by SAIL (see D3.3.1), and by a perceived task difficulty classifier (TDC) developed by UHi (see D3.4.1). The TDC extracts information about speech pauses from raw speech data, and information about numbers and lengths of vowels and consonants from speech data that is preprocessed by the speech recognition system. These data are then used to classify perceived task difficulty as appropriately challenging, over challenging, or under challenging the student. For example,

- frustration is detected when
    - The student says: "This is really hard"; and the
    - TDC recognizes sighing
- boredom is detected when
    - The student says: "This is so boring"; and the
    - TDC recognizes student pauses
- enjoyment is detected when
    - The student says: "This is fun"; and the
    - TDC recognizes no student pauses
- surprise is detected when

  - The student says: “This is easy”; and the
  - TDC recognizes gasping
- confusion is detected when
  - The student says: “I don’t get it”; and the
  - TDC recognizes student pauses

The TIS can also modify the delivery of TDS. For example, as the WoZ-studies reported in D5.2 revealed, providing TDS in the form of problem-solving instruction alone does not seem to be a very effective strategy when students are frustrated. In contrast, asking students to talk aloud when frustrated might help them to express their problems, which might move them out of their negative affective state. When TIS detects frustration, it therefore supersedes TDS by giving an emotional boost.

3.1.3. *Students Needs Analysis for sequencing in FL*

After students have completed an exploratory task and may have received TDS and TIS, a SNA determines what the next task should be. Should students continue with more exploratory tasks? If so, how challenging should these tasks be? Or should students switch to structured tasks? For this, the SNA collects INPUT indicators about the student needs and translates them into pedagogical OUTPUT decisions. During exploratory learning, the following INPUT indicators are available:

- the student’s response to the current task (their ‘move’),
- the student’s affect state inferred from prosodic cues in the student’s speech,
- the student’s affect state inferred from key words in their speech,
- the student’s affect state inferred from their screen/mouse behaviour (and if they followed the feedback in FL)
- amount of the TDS feedback previously delivered to the student
- amount of the TIS feedback previously delivered to the student

These data are combined by the SNA to determine whether the student is over challenged, under challenged, or appropriately challenged. The system can then make output decisions to adapt to the student’s needs: deliver TIS as needed and select a new task that is appropriate for the learner.

The level of challenge a student experiences is a function of the student and the task. To select appropriate tasks, the SNA therefore needs to consider how specific students experience specific tasks. To describe the tasks, we rely on our coherent system of fractions learning discussed in detail in D1.2. The system comprises nine coarse-grain goals (e.g., fraction equivalence, addition of fractions with like denominators) and five dimensions of fractions learning within these coarse-grain goals: fine grain goals (e.g. recognise the whole, interpret the size of a fractional part), fraction interpretation (part-whole, ratio, operator, quotient, measure), fraction representation (area, number line, sets of objects, liquid measures), fraction type (unit, proper, improper fractions), and task type (e.g. construct, analyse). The extensive analysis of fractions tasks that was undertaken to construct this system extends the current literature on fractions significantly and has begun to be disseminated and published (see D1.2). For instance, while existing research on fractions learning focuses only one or two dimensions (e.g., Charalambous & Pitta-Pantazi, 2007; Charalambous, Delaney, Hsu, & Mesa, 2010; Hanula, 2003), we have identified a total of five dimensions of fractions tasks and will be able to extend the research literature as a result of this.

All iTalk2Learn structured and exploratory tasks have been categorized according to these five dimensions and the coarse grain goals using the task template introduced in D1.2. The SNA also uses these dimensions when analysing students' performance on tasks. It builds and continuously updates a detailed student model (this will be reported in D2.2.2). This model includes which tasks present which level of challenge for the individual student. For example, for one student it may not matter much whether a task uses the area or the number line representation of fraction. For another student, this may change the level of challenge significantly. The SNA uses this information about the student when drawing on the database of tasks to assign an appropriately challenging task for each individual student.

The SNA determines that a student is *over challenged* with the exploratory task at hand when it, for example, identifies the student's previous task response as incorrect and classifies the affective state as frustrated. The SNA will then sequence to a less challenging exploratory learning task to address the students' difficulties (see map key SNA OUTPUTS in Figure 2). On top of that the student will receive TIS to reduce feelings of frustration (see also Section 3.1.2).

The SNA determines that the student is *under challenged* with the exploratory task at hand when it, for example, sees that the student is solving the current task very quickly and the student's affect is categorized as bored. The SNA will then in a first step provide TIS to the student in a form of an emotional boost. In a second step, the SNA will sequence to a more challenging exploratory learning task (see map key SNA OUTPUTS in Figure 2).

Finally, if the student is *appropriately challenged*, he or she will proceed to the structured practice component. To ensure that students are prepared to succeed on the structured tasks, and also to provide opportunities to consolidate their conceptual knowledge by applying it during structured practice, the structured tasks are closely mapped to the just-solved exploratory task on the five dimensions and the respective coarse grain goal. However, our goal is not a full mapping of tasks, but to find tasks that overlap on most of the task dimensions. This way students are constantly exposed to new task features that are within 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 Intelligent Tutor's] guidance, or in collaboration with more capable peers" (Vygotsky, 1978, p. 86). For example, exploratory tasks and structured tasks contribute not only towards one but to several fine-grain goals, so that tasks can overlap on multiple fine-grain goals. Similarly, other task dimensions will only partially overlap.

Even though tasks are thus closely mapped between exploratory learning and structured tasks, the learning activities triggered by these tasks are very different. Exploratory tasks prompt students to manipulate different representations and to explore the underlying fine grain goal on their own. In contrary, structured tasks prompt students to solve the task step-by-step and offer direct feedback, while limiting the variety of representations.

3.2.Structured practice with Maths-Whizz and FT

Structured practice is intended to build procedural knowledge that enables students to solve a variety of fraction tasks. The ITSs built into the iTalk2Learn platform help students solve problems step-by-step, and deliver immediate feedback. This allows students to learn new procedures and deepen familiar procedures through repeated practice.

Support during structured practice is provided on the one hand by the TDS which was already built into the ITSs. On the other hand, it is provided by the TIS which was newly developed for the iTalk2Learn platform and which has already been described in Section **Fehler! Verweisquelle konnte nicht gefunden werden.**. We will now briefly describe the TDS functionalities that were already built into Maths-Whizz and FT, respectively.

3.2.1. *Task-dependent support within Maths-Whizz and FT*

The modular approach of the iTalk2Learn platform allows the integration of components that were not developed within the iTalk2Learn platform. The ITSs that are plugged into iTalk2Learn to provide structured practice come with their own TDS as discussed in D1.1 and D1.2

In Maths-Whizz, as students work through the structured tasks, they receive feedback according to their answers. When an incorrect answer is entered, Maths-Whizz provides feedback in the form of a *help*, encouraging students to elaborate and reflect about problem-solving strategies before having another attempt. Up to three helps are offered per question, at which point a student receives the correct answer. Correct answers are rewarded with a celebratory response.

In FT, students also receive immediate feedback while solving structured tasks step by step. Additionally, students can ask for hints on up to three different levels: abstract, concrete and solution.

3.2.2. *Students Needs Analysis for sequencing after structured tasks*

After students have completed a structured task, the SNA determines what the next task should be. Should students continue with more structured tasks (sequencing)? If so, how challenging should these tasks be? Or should students switch to exploratory tasks? For this, the SNA translates INPUT indicators into pedagogical OUTPUT decisions. During structured practice, the following INPUT indicators are available:

- the student's response to the current task (including additionally other students' task response)
- task count as the number of tasks students are challenged with,
- response time taken for a single task or sub-task, and
- the student's affect state inferred from prosodic cues in the student's speech,
- the student's affect state inferred from key words in their speech,
- amount of the TDS feedback previously delivered to the student
- amount of the TIS feedback previously delivered to the student

Based on this information, the SNA determines whether the student is over challenged, under challenged, or appropriately challenged. As previously mentioned, the level of challenge students experience is a function of the student and the task. To select appropriate tasks, the SNA therefore needs to consider how specific students experience specific tasks. For structured tasks, the SNA includes performance prediction. This is based on a machine-learning model that uses students' past task performance to predict future task performance and thus intelligently adapts to students' needs (for more details see D2.2.1 and D5.2). It takes advantage of the indicators listed above. Because formative trials showed that the time students need to solve a structured task is much lower than the time needed for an exploratory task, the SNA also gives special consideration to student task count and time taken. This ensures that the student has enough time and thus sufficient opportunity to practice the procedures addressed in the structured tasks.

The SNA detects that the student is *over challenged* when it, for example, identifies that the student made a high number of errors and that the affect is classified as frustrated. He or she will then receive TIS and a new structured task that is less challenging. Here the performance prediction can provide additional information. If the system predicts a high performance on the same procedure, then the new task will be on a procedure that has not been practiced recently. Otherwise, the new task will be on the same procedure.

When the SNA detects that the student is *appropriately challenged*, the student will be provided with appropriate TIS, and then the SNA will assign a more challenging structured task, as determined by performance prediction.

Last but not least, if the student is *under challenged* by the structured task, the student will receive appropriate TIS and a new exploratory learning task will be assigned that is more challenging than the last exploratory task. This will generally be a task within the same coarse grain goal. In order to move to the next coarse grain goal, students need to demonstrate an appropriate level of attainment within the coarse grain goal at hand. The appropriate level of attainment can be demonstrated when the SNA detects that a particular student is still under challenged when re-starting the learning cycle with a new exploratory task with the same coarse grain goal as the previous exploratory task. The SNA then provides the student with an exploratory learning task addressing another coarse grain goal.

4. Case studies

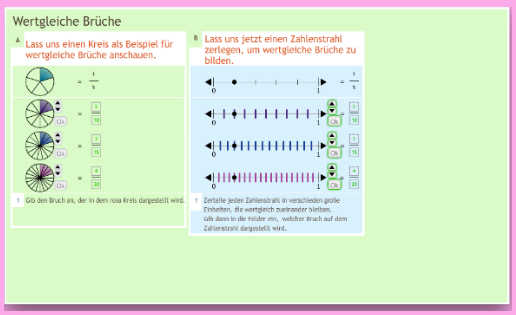
Two case studies provide a lens upon a small section of two fictional students' potential learning paths through the iTalk2Learn platform as they learn equivalent fractions (coarse grain goal 2) and the addition of fractions with unlike denominators (coarse grain goal 3c). Case Study 1 illustrates a German student's learning path through FL and FT and Case study 2 study illustrates a UK student's learning path through FL and Maths-Whizz. Of course, both case studies reflect simplified examples of the complexity of the iTalk2Learn platform.

Case study 1 Coarse-grain goal 2 Equivalent fractions (Germany)

	Exploratory and structured task	**Student actions during task and support given**	**SNA(simplified)**	**Pedagogical decision**
1	Task 2.2 "Make a fraction that is equivalent to x/y."	student first does not know what to do student uses different representations but does not change denominator *and* numerator	Student task response: No interaction with the system Student affect: confusion Student task response: interaction with the system, generic misconception Student affect: confusion	→ provide TDS "How are you going to tackle this task?" → provide TIS e.g., "You can use the arrow buttons to change the fraction." → provide a further exploratory task, i.e. sequencing within ELE keeping the same coarse grain goal, but: 1. Same fine grain goals (8: Generate a common denominator; 11: partition to find equivalents)

	Exploratory and structured task	Student actions during task and support given	SNA(simplified)	Pedagogical decision
				2. Same fraction interpretation (part/whole) 3. Different fraction representation (use area representation only) 4. Same fraction type (Set B: proper fractions) 5. Different task type (Construct)
2	Task 2.8 "Make a fraction that equals x/y and has c as denominator."	Student uses area representation.	<u>Student task response:</u> use of representations and comparison check box, correct answer <u>Student affect:</u> enjoyment	→ switch to structured task on equivalence using dimensions: 1. Same fine grain goal (8: Generate a common denominator) 2. Same fraction interpretation (part/whole) 3. Same fraction representation (area representation)

	Exploratory and structured task	Student actions during task and support given	SNA(simplified)	Pedagogical decision
				4. Same fraction type (Set B: proper fractions) 5. Different task type (Structured)
3	Structured task on equivalence (task set II, see D 1.2 Appendix III) 	Student is on task. Asks for all available levels of hints at each sub-step. Types in incorrect answers. Student is still over challenged	<u>Student task response</u>: incorrect, <u>Amount of TDS:</u> high <u>Response time:</u> 4 minutes <u>Task count:</u>1 <u>Student performance prediction:</u> will not master the next task <u>Student affect:</u> frustration	→ provide TDS → TIS (e.g., It may be hard, but keep going) → Sequence within structured tasks on equivalence with worked example (instruction)

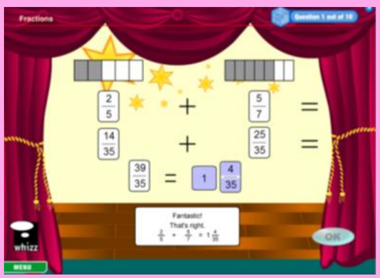
	Exploratory and structured task	Student actions during task and support given	SNA(simplified)	Pedagogical decision
4	Similar structured tasks which the student has previously successfully accomplished (task set IV, see D 1.2 Appendix III) 	is now successful	<u>Student task response:</u> correct <u>Response time:</u> 2 times 3 minutes <u>Task count:</u> 2 <u>Student performance prediction</u>: next task will be correct <u>Student affect</u>: enjoyment	→ Switch to exploratory task
5	Task2.6 Michael says "x/y = a/b because x times y equals b. Show why you agree or disagree."	Student is on-task	<u>Student task response:</u> move <u>Student affect:</u> enjoyment	Exploratory task on equivalence (SAME COARSE-GRAIN GOAL) using dimensions:

	Exploratory and structured task	Student actions during task and support given	SNA(simplified)	Pedagogical decision
			Amount of TDS: low	1. Different fine grain goal (9: Multiply numerator and denominator to find equivalents) 2. Same fraction interpretation (part/whole) 3. Different fraction representation (number line, liquid measures or sets representation) 4. Same fraction type (Set B: proper fractions) 5. Same task type (Construct)

Case study 2 Coarse-grain goal 3c addition of fraction with unlike denominators (UK)

	Exploratory and structured task	Student actions during task and support given	SNA(simplified)	Pedagogical decision
1	Task 3b+.2 "Show how you could make this fraction [7/12] by adding two fractions with different denominators."	student first does not know what to do student makes two fractions using number line but with the same denominator student makes two fractions with different denominators using number line and uses	<u>Student task response:</u> No interaction with the system <u>Student affect:</u> confusion <u>Student task response:</u> interaction with the system, error detected <u>Student affect:</u> enjoyment <u>Student task response:</u> interaction with the system, <u>Student affect:</u> enjoyment	→ provide TDS "Make a fraction that can be added to another to make 7/12" → provide TIS "Re-read the task aloud" → provide TDS "Check your two fractions. The denominators should be different" → provide a further exploratory task, i.e. sequencing within ELE keeping the same coarse grain goal, but: 6. Same fine grain goals (8: Expand fractions to find equivalent; 11: partition to

	Exploratory and structured task	Student actions during task and support given	SNA(simplified)	Pedagogical decision
		the addition box to check their answer		find equivalents; 14: Produce the sum of two fractions) 7. Same fraction interpretation (part/whole) 8. Same number line representation (use number line representation only) 9. Different fraction type (Set B: proper fractions) 10. Same task type (Construct)
2	Task 3b+.1 "[Clara] used [number lines] to add a/b [2/3] and x/y [2/9]. Can you find out what her answer was?"	Student uses number line representation	Student task response: use of representations and comparison check box, correct answer Student affect: enjoyment	→ switch to structured task on equivalence using dimensions: 6. Same fine grain goal (8: Expand fractions to find equivalent; 11: partition to find equivalents; 14: Produce the sum of two fractions) 7. Same fraction interpretation (part/whole) 8. Same fraction representation (area representation)

	Exploratory and structured task	**Student actions during task and support given**	**SNA(simplified)**	**Pedagogical decision**
				9. Same fraction type (Set B: proper fractions) 10. Different task type (Structured)
3	Structured task MA_GBR_1350CAx0200 	Student is on task. Student is under-challenged.	Student task response: correct Amount of TDS: low Response time: 2 minutes Task count:1 Student performance prediction: will master the next task Student affect: enjoyment	→ provide TDS → TIS (e.g., “Great! Excellent work!” → Switch to exploratory task
4	Task 3b-.1 [John] poured a/b [4/8] out. He had x/y [1/4] left. How much was in the jug before he began?	Student is on-task	Student task response: move Student affect: enjoyment Amount of TDS: low	Exploratory task on equivalence (SAME COARSE-GRAIN GOAL) using dimensions:

	Exploratory and structured task	Student actions during task and support given	SNA(simplified)	Pedagogical decision
				6. Different fine grain goal (15: Produce the solution of subtracting two fractions) 7. Same fraction interpretation (part/whole) 8. Different fraction representation (liquid measures) 9. Same fraction type (Set B: proper fractions) 10. Same task type (Construct)

5. General conclusion and outlook for iTalk2Learn

iTalk2Learn's intervention model describes how students acquire robust knowledge about fractions by combining exploratory with structured tasks. More specifically, our intervention model enables us to adapt to students' individual needs on several levels. First of all, based on our SNA we are able to select a task that is appropriate to student's current level of challenge. Thus, each individual student is provided with a unique sequence of learning tasks. This unique sequence implies both sequencing within and switching between structured and exploratory tasks and builds upon the iterative development of conceptual knowledge (facilitated by the exploratory task) and procedural knowledge (facilitated by the structured tasks; Rittle-Johnson et al., 2001). Apart from combining both kinds of tasks and the selection of a learner-appropriate task, our intervention model further provides adaptive support within each task. For instance, students are provided with TDS in order to help them to overcome their cognitive difficulties when needed. By additionally providing students with iTalk2Learn's on-top support feature TIS we go beyond providing students only with cognitive support but also provide emotional support. The TIS builds upon students' verbal and non-verbal utterances and identifies students' different affective states such as excitement, boredom and frustration which have an impact on learning (Boekaerts, 1993; Kort et al, 2001; Oatly & Nundy, 1996). Once students' affective states are identified the TIS flexibly reacts to students' affects as they solve both types of tasks. Additionally, the TIS also prompts students to integrate mathematical vocabulary in their explanations and prompts them to think-aloud when they do not talk.

In sum, the intervention model reflects a nodal point of the entire iTalk2Learn project, because it unifies not only all pedagogical components (i.e. FL, FT or Maths-Whizz, TDS and TIS) but also integrates technical components such as the recommender system developed in WP2, the TDC and the speech recognition developed in WP3. How exactly the different pedagogical and technical components of the iTalk2Learn project are unified in our intervention model and how different project partners contributed can be seen in Appendix 1.

In the future we will focus on three different strands, namely continuing the technical implementation of the pedagogical model, evaluating the platform including the intervention model, and working on joint publications.

As a next step of the development of the intervention model, we will discuss with the technical partners (UHI, BBK) how to optimally translate the pedagogical innovations described in the intervention model into technical practice. For instance, the SNA is implemented technically in the form of an analytic engine that takes into account INPUT indicators to update a model of the student's knowledge and that creates OUTPUT decisions by drawing on the student model, a domain model of fractions, and the pedagogical strategies described in the intervention model. As another example, the selection of a new task that is more or less challenging for a specific student requires that the student model includes a representation of the level of challenge tied to each dimension of fractions task for that student. This can be implemented technically by adding weights to each dimension in the student model. In addition, following feedback from Prof. Vincent Aleven (a leading researcher of educational technologies at the Human-Computer-

Interaction Institute, Carnegie Mellon University), we will explore the efficacy and feasibility of implementing additional INPUT indicators in the student model (specifically, fixed variables such as the student's gender, age or digital literacy). This work has already started and D2.2.2 will describe the technical implementation of the intervention model in its final form.

Of course parts of the intervention model have already been implemented and tested in the formative evaluation. For example, we have evidence both for the efficacy of TDS and for the added benefit that TIS can provide: TDS within FL is only productive under certain affective states which the TIS can influence (see D5.2). The full technical integration of the intervention model paves the way for the summative trials in which the effectiveness of the platform, including the model, for learning will be investigated.

Last but not least, we will work out different publication strategies in order to present our innovative intervention models on conferences and within different journals of various fields.

References

Anderson, J. R., Boyle, C. F., Corbett, A. T., & Lewis, M. W. (1990). Cognitive modeling and intelligent tutoring. *Artificial Intelligence, 42*, 7-49. doi:10.1016/0004-3702(90)90093-F

Anderson, J. R., & Lebiere, C. (1998). *The atomic components of thought*. Mahwah, NJ: Lawrence Erlbaum Associates.

Baker, R. S. J. d., D'Mello, S. K., Rodrigo, M. T., & Graesser, A.C. (2010). Better to be frustrated than bored: The incidence, persistence, and impact of learners' cognitive-affective states during interactions with three different computer-based learning environments. *International Journal of Human-Computer Studies, 68* (4), 223–241. doi:10.1016/j.ijhcs.2009.12.003

Boekaerts, M. (1993). Being concerned with well-being and with learning. *Educational Psychologist, 28*(2), 149-167. doi:10.1207/s15326985ep2802_4

Boekaerts, M. (2007). Understanding students' affective processes in the classroom. In P. A. Schutz, & R. Pekrun (Eds.), *Emotion in education* (pp. 37-56). San Diego, CA US: Elsevier Academic Press. doi:10.1016/B978-012372545-5/50004-6

Borasi, R., Siegel, M., Fonzi, J., & Smith, C.F. (1998). Using transactional reading strategies to support sense-making and discussion in mathematics classrooms: An Exploratory Study. *Journal for Research in Mathematics Education, 29*(3), 275-305. doi:10.2307/749791

Charalambous, C., & Pitta-Pantazi, D. (2007). Drawing on a theoretical model to study students' understandings of fraction. *Educational Studies in Mathematics, 64*, 293–316. doi:10.1007/s10649-006-9036-2

Charalambous, C., Delaney, S., Hsu, H.-Y., & Mesa, V. (2010). A comparative analysis of the addition and subtraction of fractions in textbooks from three countries. *Mathematical Thinking and Learning, 12(2)*, 117-151. doi:10.1080/10986060903460070

Cramer, K., Behr, M., T., P., & Lesh, R. (1997). *Rational Number Project: Fraction lessons for the middle grades - Level 1*. Dubuque Iowa: Kendall/Hunt Publishing Co.

Cramer, K., Post, T., & delMas, R. (2002). Initial fraction learning by fourth- and fifth-grade students: A comparison of the effects of using commercial curricula with the effects of using the Rational Number Project curriculum. *Journal for Research in Mathematics Educations, 33*(2), 111-144. doi:10.2307/749646

Cramer, K., & Henry, A. (2002). Using manipulative models to build number sense for addition of fractions. In B.H. Littwiller & G.W. Bright (Eds.), *Making sense of fractions, ratios and proportions: 2002 Yearbook* (pp. 41-48). Reston, VA: National Council of Teachers of Mathematics.

de Jong, T., & van Joolingen, W. R. (1998). Scientific discovery learning with computer simulations of conceptual domains. *Review of Educational Research, 68,* 179–202. doi:10.3102/00346543068002179

Fyfe, E.R., Rittle-Johnson, B., & DeCaro, M.S., (2012). The effects of feedback during exploratory mathematics problem solving: Prior knowledge matters. *Journal of Educational Psychology,* 1094-1108. doi:10.1037/a0028389

Goldin, I. M., Martin, T., Baker, R., Aleven, V., & Barnes, T., (2013). Formative feedback in interactive learning environments. In H. C. Lane, K. Yacef, J. Mostow, & P. Pavlik (Eds.), *Artificial intelligence in education. Lecture notes in computer science* (pp. 94-946). Berlin, Heidelberg: Springer. doi:10.1007/978-3-642-39112-5_158

Hannula, M. S. (2003). Locating fractions on a number line. In N. A. Pateman, B. J. Dougherty, & J. T. Zilliox (Eds.). *Proceedings of the 27th International Group for the Psychology of Mathematics Education Conference Held Jointly with the 25th PME-NA Conference Volume 3* (pp-17-24). Retrieved from ERIC database. (ED500858)

Hattie, J., & Timperley, H. (2007). The power of feedback. *Review of Educational Research, 77*(1), 81-112. doi:10.3102/003465430298487

Kapur, M. (2008). Productive Failure. *Cognition and Instruction*, 26, 379–424. doi:10.1080/ 07370000802212669

Kapur, M. (2012). Productive Failure in learning the concept of variance. *Instructional Science, 40,* 651-672. doi:10.1007/s11251-012-9209-6

Koedinger, K. R., & Aleven, V. (2007). Exploring the assistance dilemma in experiments with cognitive tutors. *Educational Psychology Review, 19*, 239-264. doi:10.1007/s10648-007-9049-0

Koedinger, K. R., Corbett, A. C., & Perfetti, C. (2012). The Knowledge-Learning-Instruction (KLI) framework: Bridging the science-practice chasm to enhance robust student learning. *Cognitive Science, 36*(5), 757-798. doi:10.1111/j.1551-6709.2012.01245.x

Kort, B., Reilly, R., Picard, R. (2001). An affective model of the interplay between emotions and learning. In: *Proceedings of the IEEE International Conference on Advanced Learning Technologies* (pp. 43-46). New York, USA: IEEE Press. doi:10.1109/ICALT.2001.943850

LeFevre, J. A., Smith-Chant, B. L., Fast, L., Skwarchuk, S. L., Sargla, E., & Arnup, J. S. (2006). What counts as knowing? The Development of conceptual and procedural knowledge of counting from kindergarten through grade 2. *Journal of Experimental Child Psychology, 93*(4), 285–303. doi:10.1016/j.jecp.2005.11.002

Lesh, R. (1999). The development of representational abilities in middle school mathematics. In I. E. Sigel & K. Tyner (Ed.), *Development of mental representation: Theories and applications* (pp. 323–349). Hillsdale, NJ: Erlbaum.

Leutner, D. (1993). Guided discovery learning with computer-based simulation games: Effects of adaptive and non-adaptive instructional support. *Learning and Instruction, 3,* 113–132. doi:10.1016/0959-4752(93)90011-N

Mazziotti, C., Loibl, K., & Rummel, N. (August, 2014). *Towards combining structured practice and exploratory learning activities to foster robust knowledge.* Paper presented at the EARLI SIG 6 & 7 Meeting (Instructional Design & Learning and Instruction with Computers), Rotterdam.

Mavrikis, M., Gutierrez-Santos, S., Geraniou, E., & Noss, R., (2013). Design requirements, student perception indicators and validation metrics for intelligent exploratory learning environments. *Personal and Ubiquitous Computing, 17*(8), 1605–1620. doi:10.1007/s00779-012-0524-3

Newell, A., & Rosenbloom, P. S. (1981). Mechanisms of skill acquisition and the law of practice. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 1-55). Hillsdale, NJ: Erlbaum.

Oatley, K., & Nundy, S. (1996). Rethinking the role of emotions in education. In D. R. Olson & N. Torrance (Eds.), *The handbook of education and human development: New models of learning, teaching and schooling* (pp. 257-274). Cambridge, MA: Blackwell.

Pekrun, R. (2006). The control-value theory of achievement emotions: Assumptions, corollaries, and implications for educational research and practice. *Educational Psychology Review, 18,* 315-341. doi:10.1007/s10648-006-9029-9

Pólya, G. (1945). *How to solve it*. Madrid: Ed. Tecnos.

Rau, M. A., Aleven, V., & Rummel, N. (2013). Interleaved practice in multi-dimensional learning tasks: which dimension should we interleave? *Learning and Instruction, 23*, 98-114. doi:10.1016/j.learninstruc.2012.07.003

Reigeluth, C., Merril, M.D., Wilson, B., & Spiller, R. (1980). The elaboration theory of instruction: A model for sequencing and synthesizing instruction. *Instructional Science, 9*, 195-2019. doi:10.1007/BF00177327

Rittle-Johnson, B., Siegler, R. S., & Alibali, M. W. (2001). Developing conceptual understanding and procedural skill in mathematics: An iterative process. *Journal of Educational Psychology, 93*(2), 346–362. doi:10.1037/0022-0663.93.2.346

Rohrer, D. (2009). The effects of spacing and mixing practice problems. *Journal for Research in Mathematics Education*, *40*, 4-17. doi:10.1002/acp.1266

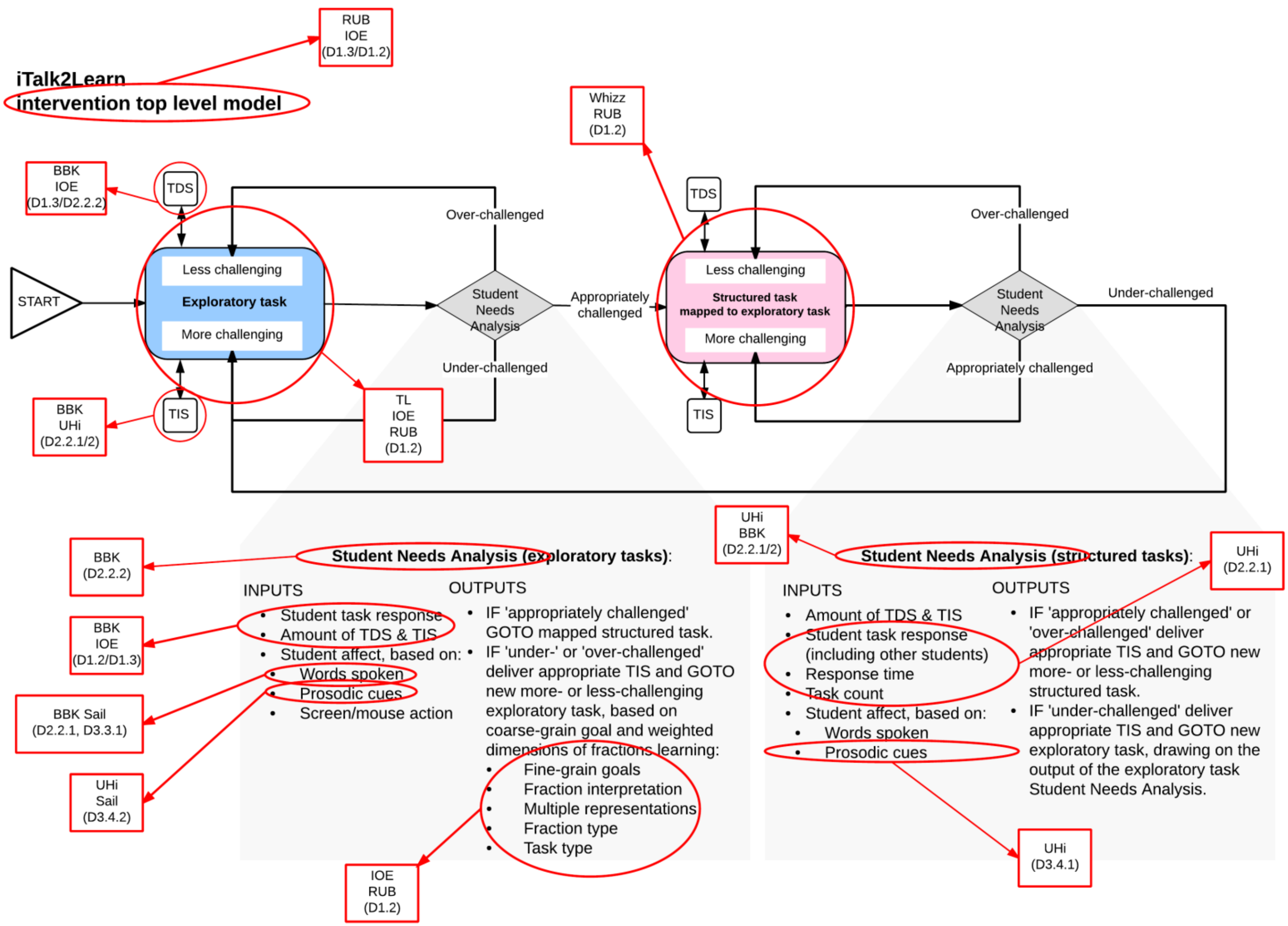
Rohrer, D., & Taylor, K. (2006). The effects of overlearning and distributed practice on the retention of mathematical knowledge. *Applied Cognitive Psychology, 20,* 1209-1224.

Skemp, R. (1976). Relational understanding and instrumental understanding. *Mathematics Teaching, 77*, 20–26.

Vygotsky, L. S. (1978). *Mind in society. The development of higher psychological processes*. Cambridge, MA: Harvard University Press.

Woolf, B., Burleson, W., Arroyo, I., Dragon, T., Cooper, D., & Picard, R. (2009). Affect-aware tutors: recognising and responding to student affect. *International Journal of Learning Technology 4*(3), 129–164. doi:10.1504/IJLT.2009.028804

Appendix 1: Intervention Model with project partners' contributions



Appendix 2: Examples for the task-dependent support rules within Fractions Lab

	TOP LEVEL RULES[1]			**TASK LEVEL EXEMPLIFICATIONS**[2] (i.e. <u>examples</u> only, based on Task 2.X)					
		IF…	THEN	IF…	THEN (guidance)[3]	THEN (Socratic)[4]	THEN (didactic: conceptual)[5]	THEN (didactic: procedural)[6]	THEN (highlight)[7]
1. Start	S1	student does nothing for 5 seconds	Polya Steps 1 and 2 (understand problem, formulate goals, devise a plan)	student does nothing for 5 seconds	*n/a*	*"How are you going to tackle this task?"*	*"Read the task again, and explain how you are going to tackle it."*	n/a	
2. Start	S2	student does nothing after feedback S1	Instruction (next step)	student does not make any representation	*"You can click one of the buttons on the representations toolbox to create a fraction."*	*"What do you need to do in this task?"*	*[Repeat task instructions]*	n/a	Representations toolbox

---

[1] Each 'top level rule' might appear once, more than once or not at all in any particular task.

[2] Although it is necessary to specify in advance all the potential feedback, it is anticipated that during a session a student might be presented with only a small number of feedback prompts. The choice of task level 'THEN' that the system delivers and how it delivers it (interruptive or non-interruptive) will also depend on voice/emotion recognition.

[3] Help, supportive information, feedback (e.g. "Did you know that…?")

[4] Socratic, questioning, feedback (e.g. "How are you going to…?")

[5] Didactic: conceptual, conceptual instructional feedback (e.g. "You have changed the numerator. You need to change the denominator.")

[6] Didactic: procedural, procedural instructional feedback (e.g. "You have changed the numerator to 12. You need to change the denominator to 12."). It is anticipated that 'didactic: procedural' would be the feedback of last resort.

[7] Part of screen highlighted

	TOP LEVEL RULES[1]			TASK LEVEL EXEMPLIFICATIONS[2] (i.e. examples only, based on Task 2.X)					
		IF...	THEN	IF...	THEN (guidance)[3]	THEN (Socratic)[4]	THEN (didactic: conceptual)[5]	THEN (didactic: procedural)[6]	THEN (highlight)[7]
3. Start	S3	student starts the task but stops[8]	Affirmation and instruction (next step)	student selects a representation but does not change it	*"You can use the arrow buttons to change the fraction."*	*"Good. What do you need to do now, to change the fraction?"*	*"Now click the up arrow next to the empty fraction, to make the denominator."*	*"Click the up arrow next to the empty fraction, to make the denominator (the bottom part of the fraction) 12."*	Arrow buttons
4. Mid	M1	student makes a procedural error	Instruction (problem solving)	student makes a representation but the denominator is not 12 and is NOT 4	*"You can click the up arrow next to your fraction to change it."*	*"Is the denominator in your fraction correct?"*	*"Check that the denominator in your fraction is correct."*	*"Check that the denominator (the bottom part of your fraction) is 12."*	Arrow buttons
5. Mid	M2	student starts the task but makes a conceptual error	Instruction (problem solving)	student makes a representation with the numerator 12 or 4	*"Remember that the denominator is the bottom part of the fraction."*	*"Have you changed the numerator or denominator?"*	*"Check that you have changed the denominator, not the numerator."*	*"Check that the denominator in your fraction, not the numerator, is 12 [or 4]."*	

[8] Feedback is typically triggered after a pause of 4 seconds. Therefore, in this document, 'stops' = 'pauses for more than 8 (tbc) seconds'.

	TOP LEVEL RULES[1]			**TASK LEVEL EXEMPLIFICATIONS**[2] (i.e. examples only, based on Task 2.X)					
		IF...	THEN	IF...	THEN (guidance)[3]	THEN (Socratic)[4]	THEN (didactic: conceptual)[5]	THEN (didactic: procedural)[6]	THEN (highlight)[7]
6. Mid	M3	student makes a fraction that does not relate to the task	Instruction (problem solving)	student makes a fraction that is NOT 3/4 or 9/12	*“Please read the task again carefully.”*	*“Is this the fraction you were planning to make?”*	*“Re-read the task then check your fraction.”*	n/a	
7. Mid	M4	student responds to (procedural or conceptual) feedback (M1 or M2) correctly	Reflective (feedback follow-up)	student receives feedback (M1 or M2) and changes the denominator to 12	n/a	n/a	*“Excellent. Please explain what the 'numerator' and ‘denominator’ are”*	n/a	
8. Mid	M5	student responds to feedback (M1 or M2) incorrectly	Instruction (feedback follow-up) (problem solving)	student receives feedback (M1) and changes the numerator to 12	*“The denominator is the bottom part of the fraction.”*	*“Have you changed the denominator or the numerator?”*	*“You changed the numerator. You need to change the denominator.”*	*“You changed the numerator. You need to change the denominator to 12.”*	

	TOP LEVEL RULES[1]			TASK LEVEL EXEMPLIFICATIONS[2] (i.e. examples only, based on Task 2.X)					
		IF…	THEN	IF…	THEN (guidance)[3]	THEN (Socratic)[4]	THEN (didactic: conceptual)[5]	THEN (didactic: procedural)[6]	THEN (highlight)[7]
9. Mid	M6	student completes a procedural step but stops[8]	Affirmation and instruction (next step)	student makes a fraction with 4 or 12 as the denominator but stops[2]	*"If you click near the top of your fraction, and click the up arrow, you can change the numerator (the top part of the fraction).*	*"Excellent. Now, how are you going to change the numerator?"*	*"You changed the denominator. Now, change the numerator."*	*" Now, change the numerator. Remember, you need to make the fraction equivalent to 3/4."*	Arrow buttons
10. Mid	M7	student completes a procedural step but stops8	Instruction (opportunity)	student makes 3/4 but stops	*"You could now copy the fraction and use the partition tool to make an equivalent fraction. To open the partition tool, right-click the fraction."*	*"Excellent. How about copying this and using the partition tool to make the equivalent fraction?"*	*"Excellent. Now copy this fraction and use the partition tool to change it"*	*"Excellent. Now copy the fraction use the partition tool to change it to a fraction with a denominator of 12"*	?

	TOP LEVEL RULES[1]			**TASK LEVEL EXEMPLIFICATIONS**[2] (i.e. examples only, based on Task 2.X)					
		IF...	THEN	IF...	THEN (guidance)[3]	THEN (Socratic)[4]	THEN (didactic: conceptual)[5]	THEN (didactic: procedural)[6]	THEN (highlight)[7]
11. Mid	M8	student completes a procedural step but makes a conceptual error	Instruction (problem solving)	student makes a fraction with 12 as the denominator, but numerator is not 9	*"Think about the denominators in the two fractions. What is the relationship between them? What do you need to do to* [3][9] *to work out the correct numerator for your fraction?"*	*"How could you compare your fraction with 3/4*[10]*?"*	*"Compare your fraction with 3/4*[11] *by using the comparison box."*	n/a	Comparison box.
12. Mid	M9	student receives feedback M8 but stops	Instruction (next step)	student receives feedback M8 but stops	*"In equivalent fractions, the two numerators must be the same multiple of each other as the two denominators."*	*"What are you going to compare your fraction with?"*	*"First create another fraction, this time 3/4. Then compare your two fractions."*	n/a	Representations toolbox

[9] Using '3' here is legitimate because this number is given in the task itself.
[10] Same as footnote above.
[11] Same as footnote above.

	TOP LEVEL RULES[1]			TASK LEVEL EXEMPLIFICATIONS[2] (i.e. <u>examples</u> only, based on Task 2.X)					
		IF...	THEN	IF...	THEN (guidance)[3]	THEN (Socratic)[4]	THEN (didactic: conceptual)[5]	THEN (didactic: procedural)[6]	THEN (highlight)[7]
13. Mid	M10	student completes a procedural step correctly (which implies they have not made a conceptual error at this step either)	Reflective (mid-task)	student makes a representation with the denominator 12	n/a	n/a	*"Excellent. Please explain why you made the denominator 12."*	n/a	
14. Mid	M11	student completes a full set of procedural steps but does not use an FL menu (to add, subtract or compare)	Instruction (next step)	student correctly makes 9/12 and 3/4	*"You could use the comparison box to compare your fractions."*	*"How can you check, using a Fractions Lab tool, that your solution is correct?"*	*"Compare the two fractions using the comparison box."*	n/a	Comparison box.

	TOP LEVEL RULES[1]			TASK LEVEL EXEMPLIFICATIONS[2] (i.e. examples only, based on Task 2.X)					
		IF...	THEN	IF...	THEN (guidance)[3]	THEN (Socratic)[4]	THEN (didactic: conceptual)[5]	THEN (didactic: procedural)[6]	THEN (highlight)[7]
15. End	E1	student completes task (1)	Affirmation	student correctly makes 9/12 and 3/4 and compares them in the comparison box	n/a	n/a	*"The way that you worked that out was excellent. Well done."*	n/a	
16. End	E2	student completes task (2)	Reflective (end of task)	student correctly makes 9/12 and 3/4 and compares them in the comparison box	n/a	n/a	*"Please explain what you did to the numerator and denominator of 3/4 to make an equivalent fraction with 12 as the denominator."*	n/a	