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DRAWINGS IN COMPUTER-SUPPORTED COLLABORATIVE LEARNING – EMPIRICAL AND TECHNICAL RESULTS

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Abstract. Self-constructed external representations are thought to be beneficial in teaching and learning, especially when embedded in peer interactions, and can positively affect the course and type of reasoning, for example by providing grounding for explanations and self-explanations, by helping to disambiguate students' mental models of phenomena, or by increasing and sharing the task focus. This paper reports on the results of research efforts investigating which conditions are advantageous in collaborative drawing activities in computer-supported learning scenarios for young students. We describe the design, technical implementation and empirical results of a study with 94 primary school students working on a collaborative drawing task in various conditions that include adaptive prompting and scripted activities. Results showed, partially in line with our expectations, that adaptive prompting as well as scripting positively affected students' learning outcomes and discourse quality. Students in both supported conditions more often critically reviewed the work of their partner and integrated ideas from their partner in their own reasoning.

Keywords: External representations, collaboration, shared workspace, primary school education, scripted collaboration, adaptivity

Mathematics Subject Classification 2010: 97U50

1 INTRODUCTION

Drawings and sketches are a common method used in teaching and learning for presenting and illustrating phenomena, models and processes. In primary school and even in pre-school education, drawings are used by teachers, on a chalkboard, by text-book authors and in multi-media learning materials. In addition, drawings can be used before children can read and write, thus constituting an early and universal form of illustration.

While drawings can be useful for presenting information, the active creation of drawings and sketches is widely regarded as having additional potential for supporting learning [1]. For example, in various studies, students' comprehension of scientific phenomena has been found to benefit from drawing activities as compared to text-only conditions [2, 3, 4].

Beyond the basic benefits seen from using drawing activities in educational contexts, the full potential of drawing may be best realized when it is used in collaborative learning scenarios [5]. In collaborative drawing settings, students are challenged to share their ideas and to disambiguate their conceptual understanding of the matter at hand. Research findings indicate that the creation of a shared representation in collaborative settings has the potential to stimulate students' individual cognitive elaboration [5]. A representation in the form of a drawing or a concept map can initiate students' dialogue about the domain-related content and may guide students' knowledge and consensus building process. Shared representations can evoke students' critical reflection on their own prior knowledge and ideas about the subject matter, which may enhance their learning [6]. Student-generated shared representations visualize the knowledge students agree upon [7] and make it easier for students to refer to concepts that were discussed at earlier stages of the learning process. Interrelating concepts and referring to and discussing ideas that were introduced by the learning partner are generally considered to constitute high quality interaction [9], and individual learning outcomes have been linked to the quality of students' dialogues. Following a framework presented by Weinberger and Fischer [8], we distinguish between the transactive quality of the dialogue (how students relate to each other) and the epistemic quality of the dialogue (how students relate to the concepts to be learned). Contributions in which students integrate their partners' ideas into their own reasoning or critically discuss their partners' contributions are considered highly transactive [8] and are associated with positive learning outcomes. An example of a dialogue excerpt with a relatively low level of transactivity would be the externalization of a new idea. With respect to students' interaction about the domain concepts to be learned, findings show that the mere exchange of facts is not associated with learning outcomes. However, attempts to explain and interrelate domain-related information could enhance students' understanding of the domain [9, 10].

Primary school students can be supported with a collaborative drawing script as additional support to structure students' drawing processes as well as their collaboration. Prompts have been used to provide students with information about the quality of their dialogue or product and collaboration scripts have been designed that structure students' activities and promote higher transactive and epistemic quality [11].

In the present study, we investigate the effects of two supportive measures that were designed to enhance collaborative drawing processes in computer-supported learning contexts. Specifically, we explore the effects of adaptive prompts that provide the students with information regarding the content of their collaborative drawing and a collaboration script that guides students' collaboration. The adaptive prompts and the collaboration scripts used in our study are domain-independent, but (obviously) a concrete subject domain is required. We chose photosynthesis as the learning domain, as it provides rich opportunities for drawing and visually representing key concepts and processes. Furthermore, in our target group of primary school children, we could count on little to no prior knowledge of this domain.

Prompts typically are requests that direct students to take up certain activities or process the learning material in a specific way [12]. Prompts can be used to elicit activities or processes that the students are capable of, but do not perform spontaneously. Within the present study, shape recognition technology is used to generate prompts that are based on students' intermediate products, i.e. stimulating students to (re)consider specific objects and characteristics (arrows, labels) they did or did not include in their drawings. In this way, students are provided with prompts that are tailored to the content of their drawing. Because the prompts focus on the domain content, we expect them to positively affect students' domain-related discourse (as reflected in the epistemic dimension of our coding scheme) as well as students' learning.

By structuring and sequencing students' collaborative learning activities, scripts shape the interaction and try to facilitate processes that lead to learning [8]. Basically, a script provides students with detailed and explicit guidelines about the task and its successive subtasks, as well as the expected mode of collaboration within each subtask [13]. Scripts may include individual as well as collaborative activities. Individual work may prepare students for the collaborative activities, which may result in higher quality contributions [14]. Scripts typically alleviate the need for coordination [15] by taking over part of the coordination and/or triggering students to focus on the coordinative activities that are necessary for successful collaboration. Research findings suggest that scripts may result in a more consistent level of interaction [16], and facilitate highly transactive interaction activities such as integration-oriented consensus building activities and critical consensus building.

We assume that the adaptive prompts will improve the epistemic quality of the discourse, because the prompts provide students with information regarding the domain-related content of their drawing. The script is designed to structure the collaborative process and facilitate students' interaction with their partners' ideas and reasoning; therefore, we expect the script to positively influence the transactive quality of the discourse as well as students' learning.

1.1 Research Questions

This article presents a study that investigates aspects of young students' exploration of scientific phenomena by producing drawings. We try to highlight two types of support (the adaptive prompting approach and collaboration scripts) from both a pedagogical and a technical perspective in the context of an empirical study with a control condition and two experimental conditions (reflecting the two support types). Bringing together the existing research results (as reviewed in the previous section) and our interest in the area of collaborative drawing activities in teaching and learning, we formulated the following research questions:

- To what extent do adaptive prompts support students' discourse quality?
- To what extent do adaptive prompts facilitate knowledge acquisition concerning the domain of photosynthesis?
- To what extent does the collaboration script support students' discourse quality?
- To what extent does the script facilitate knowledge acquisition concerning the domain of photosynthesis?
- What is the relation between the quality of the discourse and students' knowledge acquisition?

From a pedagogical perspective, we are especially interested in effects on discourse quality and knowledge acquisition. From a technical perspective, we will deal with the technical requirements (and the subsequent implementation) that arose from the theoretically founded research questions and the resulting study design. We will show how the presented approach benefits from the creation of "stable research prototypes" with the help of easy-to-use and easy-to-integrate frameworks and existing components. In the context of this article, a stable research prototype denotes the concept of an innovative piece of technology to investigate specific research questions. Designing empirical studies in the area of Technology Enhanced Learning often includes the design and implementation of specialised technological tools (which includes software, hardware, user interface paradigms, means of communication, etc.) to create a platform for rich and interactive learning scenarios. Here, where pedagogical and technical approaches converge, we try to provide insights and experience from both perspectives.

In what follows, we will elaborate on the details of the study setup, on the technical realization and on empirical findings. Section 2 explains the design of the study, its various conditions, planning over time and how data were gathered with the help of assessments, observations, recordings and the produced artifacts. Section 3 will elaborate on the technical requirements that resulted from the design of the study and their respective implementations. Because many software applications in the area of Technology Enhanced Learning can be regarded as highly specialized prototypes that constitute a central aspect of the research in this field, we think it is vital to share our (technical) design decisions, implementation efforts, experience and lessons learned in this respect. Section 4 presents the study results, after which Section 5 summarizes and discusses our empirical findings, and concludes with a future outlook.

2 METHOD

2.1 Subjects

Ninety-four fifth-grade students (47 dyads, aged 10-11), participated in this study; two dyads were removed from the data set because they did not complete the entire learning session (leaving 90 students, 45 dyads). Teachers assured us that the participating students had sufficient background knowledge to process the learning materials.

2.2 Learning Material and Assessment

To get acquainted with the subject matter, students in all conditions received an informative text on photosynthesis. Photosynthesis is typically a new, unknown topic in this age group and presents rich opportunities for the creation of an explanatory drawing. The informative text was based on primary school science materials that were developed by acknowledged educational organizations in the Netherlands. We consulted two primary school teachers to ensure that the learning materials were suitable for the participating students. The results of a pilot test indicated that the text as well as the accompanying instruction were comprehensible for fifth grade students.

2.3 Tests

Students' individual knowledge construction was assessed with a concept recognition test and an open recall test. Both tests and their answer models were judged by two primary school teachers, to ensure that they were comprehensible for the students. The concept recognition test was administered three times during the experimental session: before the learning session, after the students studied the text on photosynthesis, and after the collaborative drawing session (see also Table 1). The Cronbach's alpha ranged from .544 on the pre-test to .845 on the post-test.

The open recall test consisted of six questions that asked students to describe and explain specific aspects of the photosynthesis process, such as the gas exchange. The open recall test was administered twice (after students studied the introductory text on photosynthesis and after they completed the entire collaborative drawing session). A primary school teacher assisted in the construction of an answer key for this test. Students' answers were checked against this answer key and points were allotted for each answer. A second rater coded approximately 20% of the data. Inter-rater agreement (Cohen's Kappa) between the two coders was .82.

2.4 Procedure

Our experimental setup included three different conditions – one control condition with plain collaborative drawing activities and two experimental conditions, with adaptive prompts or with scripted collaborative activities. Between the various phases of the experiment, different types of assessments (concept recognition and open recall tests) were administered to the participants. Audio recordings of the students' discourse and general observations were gathered. A summary of the experimental sessions for the different conditions is provided in Table 1. All students completed a training and practice task that lasted 35 minutes. During the training, the experimenter explained the outline of the session and students received brief training in how to make a drawing based on an informative text. Together with the experimenter, students practiced locating the main concepts and relations in an informative text about the water cycle (a familiar topic for the students) and visualized them with the drawing software. The experimenter explained the use of arrows and text boxes. In this training phase, the students worked individually and no instruction regarding collaboration was given. Subsequently, students completed the first concept recognition test to assess their prior knowledge. Table 1 gives an overview of the plan of the experiment:

Then, again in all conditions, the students were given the informative text that explained the concept of "photosynthesis", which was followed by a second concept recognition test and an open recall test. After that, each dyad carried out a drawing task either in the control condition, in the adaptive prompts condition or in the script condition. In the script condition, the learners created individual drawings first, which were used as a basis to create a joint drawing. Finally, likewise in all conditions, the students had to complete a third concept recognition test and a second open recall test.

To summarize the experimental setup, all dyads experienced the same practice phase, the same tests and the same introduction to the subject domain of "photosynthesis". The split into different conditions only occurred during the main task of creating a drawing of the subject.

<table>
<tr><th>Time</th><th colspan="3"></th></tr>
<tr><td>35 min.</td><td colspan="3">Instruction, training and practice</td></tr>
<tr><td>5 min.</td><td colspan="3">First concept recognition test</td></tr>
<tr><td>15 min.</td><td colspan="3">Introduction to Photosynthesis</td></tr>
<tr><td rowspan="2">10 min.</td><td colspan="3">Second concept recognition test</td></tr>
<tr><td colspan="3">First open recall test</td></tr>
<tr><td rowspan="2">35 min.</td><th>Control Condition</th><th>Prompt Condition</th><th>Script Condition</th></tr>
<tr><td>Collaborative drawing phase</td><td>Collaborative drawing phase with additional adaptive prompting</td><td>Individual drawing phase, discussion and collaboration, collaborative drawing phase</td></tr>
<tr><td rowspan="2">10 min.</td><td colspan="3">Third concept recognition test</td></tr>
<tr><td colspan="3">Second open recall test</td></tr>
</table>

Table 1. Experimental setup with timing and various conditions

2.5 Process Analysis

A coding scheme was developed in order to investigate the influence of adaptive prompting and scripting on students' collaborative learning process, and more specifically on the quality of the discourse. Each utterance was independently coded on two dimensions; the epistemic dimension and the transactive dimension. Each utterances was coded as on-task or off-task communication. Pauses and noises made by the students were coded as paraverbal utterances. Each on-task utterance got a single code on both dimensions of the coding scheme. In the first round we coded, all utterances related to coordination, planning, and monitoring of the learning process were coded as coordinative talk, all utterances that related to the content of the learning task were coded as content-related talk, which we organized according to four different categories. *Concept naming* refers to utterances in which students named a concept or used a concept without defining it or relating it to other concepts or processes. *Concept definition* refers to utterances in which students attempted to describe the meaning of a concept. *Process definition* refers to utterances in which students attempted to describe a process. *Concept-process connection* refers to utterances in which students described the connection between concepts and processes.

In the second round we coded the level transactivity of each on-task utterance. Based on the framework presented by Weinberger and Fischer [8], we distinguished five types of utterances representing different degrees of transactivity, *externalization, elicitation, quick consensus building, integration-oriented consensus building, and conflict-oriented consensus building.* Integration-oriented and conflict-oriented consensus building are generally referred to as transactive communication. *Externalization* refers to utterances in which students articulate ideas to their partner without referring to their partners. During *elicitation* students question their partner to receive additional information. Externalization and elicitation primarily serve for the exchange of information. *Quick consensus building* occurs when students simply agree or disagree with the ideas their partner contributed, without further elaboration or critique. *Integration-oriented consensus* building is characterized by building on the ideas of a partner, integration of multiple ideas or viewpoints, or taking up the partner's perspective. *Conflict-oriented consensus building* occurs when students operate on their partner's reasoning by critiquing and modifying their contributions or presenting them with alternatives.

The second coder coded a sample consisting of 401 spoken utterances, which was about 10 percent of the available data. The inter-rater reliability coefficient for codes on the epistemic dimension was .86 (Krippendorff's alpha), and for the transactive dimension it reached .82 (Krippendorff's alpha). Percentagewise scores were calculated for each sub-category of both dimensions. These scores indicate the proportion of utterances made in that category.

3 TECHNICAL REALIZATION

In a technology-rich learning environment, such as the one studied here, the effects of interventions depend on the way they are technically implemented in a non-trivial way. Therefore, this section will describe by which technical means the learning environment was realized.

3.1 Requirements

3.1.1 Hardware and Input Devices

To create activities that resemble known and established activities in primary school environments, we needed input devices that would make the computer-supported creation of drawings as much like using pencil and paper as possible. Any deviation from this, e.g. using the computer mouse or a touch-based input method, could cause unwanted bias in the students' behavior and the resulting empirical findings.

Apart from the input device, computational devices were required as well to realize the planned scenarios. Sometimes the computational device and pen-based input device are combined in one device, e.g. in tablet PCs or convertibles. In other designs, a separate pen-based input device is attached to a computer or notebook, e.g. in the form of graphic tablets or interactive pen displays[1]. We could not rely on a suitable equipment or a network infrastructure that would readily allow implementation of the planned experiments in the targeted primary schools.

[1] Examples would be the tablet series from Trust (see `http://www.trust.com` for more details, last visited on August 28th, 2015) or the Cintiq pen displays from Wacom (see `http://www.wacom.com` for more details, last visited on August 28th, 2015).

3.1.2 Communication and Synchronization Infrastructure

The implementation of the planned collaborative drawing scenario required a means for communication and synchronization between pairs of the drawing application. Apart from synchronizing the data model (the actual drawing), features such as adaptive prompts or transitions between phases in the script condition (as mentioned above) also required mechanisms for executing remote commands in an RPC-like fashion. A convenient solution would allow both communication and data exchange.

The application situation – setting up an experiment on collaborative, computer-supported drawing in several primary schools – suggested building upon an ad-hoc, lightweight, and robust server solution. As a connection to a server outside the schools might not be easily available, a solution that possibly resided together with the actual drawing application stood to reason. Also, to prevent a single failure point, a communication infrastructure that worked separately for each pair of computers seemed appropriate.

3.1.3 Drawing Tool

The drawing tool needed to provide features for easy, stroke-based drawing activities. It needed to be as intuitive as possible to reduce the time needed for training and familiarization. Earlier experience revealed the need for a feature that would allow the students to create boxes with textual input in their drawings. Some objects or processes that need to be represented in a drawing are hard to visualize (e.g., in our case, "water vapor" or "sunlight"), so the young students asked for and appreciated the feature of adding short, textual descriptions to their drawings. Of course, the drawing tool also needed features for data storage and logging to allow an extensive analysis subsequent to the actual experiment. Data storage and logging should be accomplished automatically and be hidden from the user to avoid unnecessary distraction. The drawing application needed to be able to make use of various pen-based input devices, to react flexibly with different hardware configurations (tablets, pen displays, tablet PC, etc.). If schools provided their own computer equipment, the utilized operating system might vary – typical options would be Microsoft Windows, Linux, or Mac OS. Thus, the drawing tool should be implemented in a platform-independent way. Finally, the implementation of the drawing tool needed to be able to hook into the previously mentioned communication and synchronization infrastructure.

3.1.4 Experimental Conditions

Overall, the combined choice of hardware, communication and synchronization infrastructure, and the drawing tool features needed to allow the realization of the experimental conditions outlined in Section 2.

The control condition involved the joint creation of a drawing between two students in a shared workspace environment, following a "what you see is what

I see" approach in a co-located classroom situation, i.e., each learner had his/her own computer and his/her own pen-based input device. The software was synchronized to allow co-constructing the drawing. Dyads worked synchronously throughout the entire drawing session. Since the students were able to speak directly to each other (each pair of synchronized computers were positioned opposite each other at the same table), no other means of computer-mediated communication was necessary.

The "adaptive prompting" condition added helpful information in the form of pop-up prompts to the drawing tool used by the control condition. The prompts were supposed to be partly content-sensitive with respect to the learner-created drawing. Group clustering and sketch-recognition algorithms [17] were used to detect important features of the drawing and provide the students with prompts that were based on the content of their drawing (e.g., use arrows to indicate important processes or consult the text to find information about important domain-related concepts). Students in this condition also worked synchronously throughout the entire drawing session. Students were prompted to finish their drawing five minutes before the end of the session.

The script condition prescribed a sequence of activities, starting with an individual drawing phase, after which students could inspect their partners' drawing. This was followed by a phase in which students were asked to discuss both drawings and reach agreement about the elements from the individual drawing which they would like to include in their joint drawing. After selecting the elements for the joint drawing, students had 13 minutes to finalize the shared drawing. Five minutes before the end of this phase, the students were prompted to finish their drawing.

The following sections describe the specifications and implementation that addressed the previously described set of requirements.

3.2 Specifications and Implementation

3.2.1 Pen-Based Display

For the input device we chose Cintiq pen displays from Wacom. These displays act as an external, second display and thus can be connected to most notebooks or desktop computers. They allow a natural, pen-based use of software applications. In comparison to touch-based interfaces (as found in various tablet PCs or tablets), one major advantage of this technology is that it only reacts to the pen, and in particular, not to a wrist that may rest on the display while drawing or sketching. Experience has shown that using these pen displays comes very close to the use of pencil and paper. Also, we argue that using such types of pen display provides additional flexibility over other options, because they can be connected to any device that a school may provide or that will be used in the future.

3.2.2 SQLSpaces Communication Infrastructure

Based on the given requirements, a blackboard communication architecture was chosen for the communication and synchronization infrastructure [18]. The main reason for choosing such a loosely coupled architecture is that they are robust to irresponsive clients or slow, delayed connections, as clients are ignorant of each others' existence and would not be hampered by other clients' malfunctions (if the architecture is designed and used correctly). More concretely, we chose a TupleSpaces [19] approach as an instantiation of a blackboard architecture, and an implementation of this architectural approach called "SQLSpaces" [20, 21][2]. The idea of TupleSpaces is to provide a conceptual framework for building a distributed system based on a client-server architecture and on the exchange of data that consists of tuples, or ordered lists of primitive data (e.g. numbers, strings, boolean values, etc.). SQLSpaces is one implementation of this approach that allows clients to connect by using different programming languages such as Java, C#, Prolog, and more, which makes it highly suitable for implementing distributed systems that are spread over different platforms and devices. In addition, SQLSpaces can be configured and start up a server "ad hoc" at runtime, allowing a flexible and quick solution for use in school experiments. The rather quick and easy embedment of SQLSpaces in prototypical and experimental software developments (as is often necessary in implementing empirical studies in the area of Technology Enhanced Learning) makes it a suitable candidate for realizing a communication and synchronization architecture in this situation.

Clients can register callbacks that will be triggered by certain events, such as when tuples that match a given template are added, removed or modified. This feature eases the creation of shared workspace applications on the basis of replicated data models, in that each client and the SQLSpaces server holds a replica of relevant data (in our case, the learner's drawing).

Tuples are organized in so-called "spaces", which define a subset of all tuples stored on the server. It seemed natural to use one space to share the drawing data, and another space to exchange remote commands per pair of clients, which will be explained in more detailed in what follows.

Figure 1 depicts the implemented communication and synchronization architecture for a pair of clients, A and B. It shows the separation of the shared, synchronized content and the synchronization of the collaborative process by executing remote commands, which can be compared to asynchronous remote procedure calls [22], to enable two (or more) synchronized drawing applications to behave similarly, in this case concerning adaptive prompts or scripted behavior of the applications.

The content (the learner's drawing) is synchronized by mapping each stroke to a tuple containing the stroke coordinates and timestamps. Whenever a new stroke is created in a client's user interface, a tuple that represents this stroke is sent to the server. This tuple is stored on the server, and other clients are put in sync with

[2] For detailed information, please visit `http://sqlspaces.collide.info` (last accessed on August 28th, 2015).

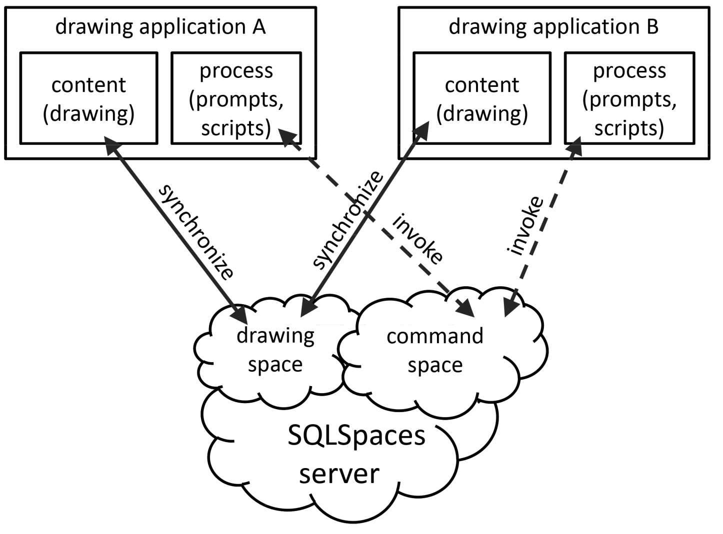

Figure 1. Communication and synchronization architecture based on SQLSpaces

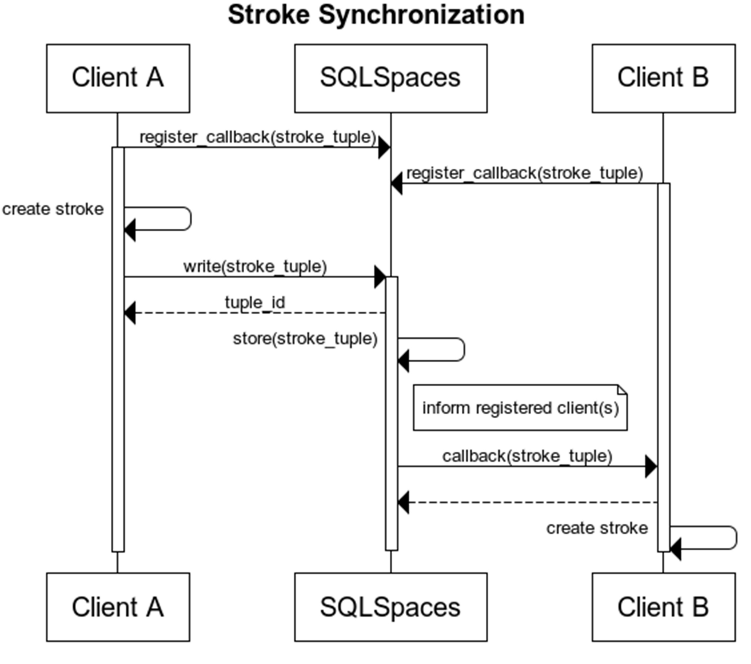

Figure 2. Sequence diagram of the stroke synchronization process between drawing clients and SQLSpaces server

this new tuple (which is reflected in the clients' drawings as well). Figure 2 depicts this process as the UML sequence diagram.

The asynchronous nature of the SQLSpaces communication architecture[3] allows for implementation of a synchronized drawing tool which used only non-blocking operations in a client-server communication. In highly interactive software, such as the drawing application at hand, blocking operations would cause short, but noticeable delays while drawing, which is obviously undesirable and would negatively affect the drawing experience.

The process visualized in Figure 2 is similar for stroke deletion or stroke editing (e.g. moving). Here, the "write(stroke_tuple)" operation would be replaced by a "delete" operation or an "update" operation, respectively.

As indicated in Figure 1, a different space is used to synchronize the behavior of the connected, collaborative application, in contrast to the shared content. The concrete communication protocol for synchronized, remote commands must be implemented on top of the SQLSpaces framework. For example, in the actual implementation, the following tuple would trigger the popup of a prompt with the given text in the user interface of all clients connected to the same command space.

```
{
"command": String,                      // indicating a command tuple
"f81d4fae": String,                     // the client ID
"prompt": String,                       // the type of command
"Consider the use of arrows.": String  // comm. property
}
```

SQLSpaces' ability to provide a light-weight server component that can be started up in an ad-hoc manner at runtime allowed us to use an SQLSpaces server for each pair of synchronized drawing tools. By so doing, we could distribute the load and overhead of synchronization over several notebooks, thus avoiding bottlenecks, for example in computational power or response times. Moreover, we avoided having a single failure point that could possibly crash a running experiment for an entire class.

3.2.3 Java-Based Drawing Tool

The drawing tool, which was built on top of the infrastructure described above, was implemented in Java, because

1. we could rely upon and reuse components that had been created in earlier efforts involving pen-based drawing scenarios [17, 23, 24],

[3] The SQLSpaces implementation allows for blocking operations as well, such as "waitToTake" or "waitToRead".

2. an SQLSpaces client is available in Java, and
3. Java is platform-independent and thus would allow us to run the application on different operating systems that we might encounter in schools.

Figure 3 shows the user interface of the drawing tool with a drawing created by two students in the adaptive prompt condition (i.e. the collaborative creation of a drawing with prompts for the students). The toolbar to the left provides features for drawing and erasing strokes and for the creation of text boxes. Additionally, the drawing tool contained features for automatically storing the drawings created as well as for writing detailed log files that would capture the students' actions, including deleted elements of the drawing and text boxes, which would otherwise not be present in the final stored drawings.

3.2.4 Scripting and Adaptive Prompting Features

The drawing tool includes some advanced features to allow the implementation of the experimental conditions. To realize adaptive prompts it is necessary to recognize distinct objects in a drawing that consists of a collection of strokes. A naive Bayes distribution model, which is available in the used data mining suite RapidMiner [25], was trained with data from previous studies with pen-based drawing applications and has been applied here. As a result, a drawing could be logically divided into segments, taking into account features such as stroke creation time, stroke dimensions, location on the screen, pen pressure, etc. In Figure 3, the algorithm would recognize groups of strokes that belong to the sun, the tree in the center or the figure next to the house to the left. Subsequently, this information could be used to prepare context-sensitive information prompts to the learner about the progress of his/her drawing.

A second type of adaptive prompt based on characteristics of the drawing was implemented by using the LADDER framework [26, 27]. This framework allows specification of shapes in terms of geometrical primitives, their characteristics and relations. In a stroke- or vector-based drawing, the LADDER framework is then capable of recognizing previously specified shapes. In our case, the use of arrows could be identified with a reasonable tradeoff between flexibility and accuracy. As a large variety of ways of drawing an arrow can be expected (e.g. varying sizes, angles and order of strokes), the framework used helped by allowing us to define an "arrow" rather generously as an object that consists of "one long stroke and two shorter strokes that meet the longer stroke in an acute angle at one end". To avoid student frustration, we gave false positive detection of arrows the preference over false negatives.

Figure 3 shows a popup-prompt that proposes the use of arrows, because the shape recognition framework did not find any arrows in the drawing. The adaptive prompts were triggered by time, so that three minutes after the drawing activity started, the tool would give information on the (non)existence of distinct objects in the drawing, after another three minutes the use of labels was checked, and after another three minutes the usage of arrows in the drawing was checked. If appropriate, prompts would appear synchronously on both students' screens.

The realization of the script condition, where the students begin by creating an individual drawing and then decide which parts of both drawing would go into one joint drawing and finalize it collaboratively, required a suitable interface to support the transition between the phases. This issue was solved by introducing a split-screen interface, where the students were able to select the elements from their individual drawings to create one joint drawing in a drag-and-drop manner.

A screenshot from the split-screen interface for the transition from the individual drawings to the joint drawing is given in Figure 4. The original, individual drawings can be seen to the upper left and lower left; by selecting elements of those drawings a new, merged drawing is created at the upper right. Selected elements of the individual drawings are moved (in a "cut-paste" fashion) from the left-hand drawings to the joint drawing. To the lower right, instructions are given to the learner, including a button for indicating the end of this phase.

On the level of the communication and synchronization architecture, the individual drawings were organized in separate spaces on the SQLSpaces server, while the command space was still used to synchronize the behavior of both tools. Merged elements from the individual drawing were then copied to a third, synchronized drawing space (cf. Figure 4).

Overall, our choices of using Wacom pen displays, an SQLSpaces communication architecture, a Java-based drawing tool and RapidMiner and LADDER to intelligently enrich the prompting functionalities, successfully led to a stable, collaborative drawing environment that fulfilled the requirements resulting from the original design of the experiment.

3.2.5 Stable Research Prototypes

As pointed out above, from a technical perspective, the implementation of the designed experiments was based upon a "stable research prototype" approach. Stable research prototypes in this sense are a means of carrying out scientific experiments in the area of Technology Enhanced Learning. They allow planning and conducting empirical research projects without having fully-fledged technology or software at hand. In our notion of stable research prototypes, they are the result of highly interconnected processes of designing and planning empirical studies on the one hand, and designing and implementing software tools on the other hand. In this article, they denote the "glue" between pedagogical/psychological aspects and technological aspects in an interdisciplinary research area. They provide a platform for researchers from different fields to outline, discuss, test and finally utilise an innovative piece of technology.

For a more detailed characterisation, we describe a number of features that discriminate a stable research prototype (as presented here) from mature software applications in the following.

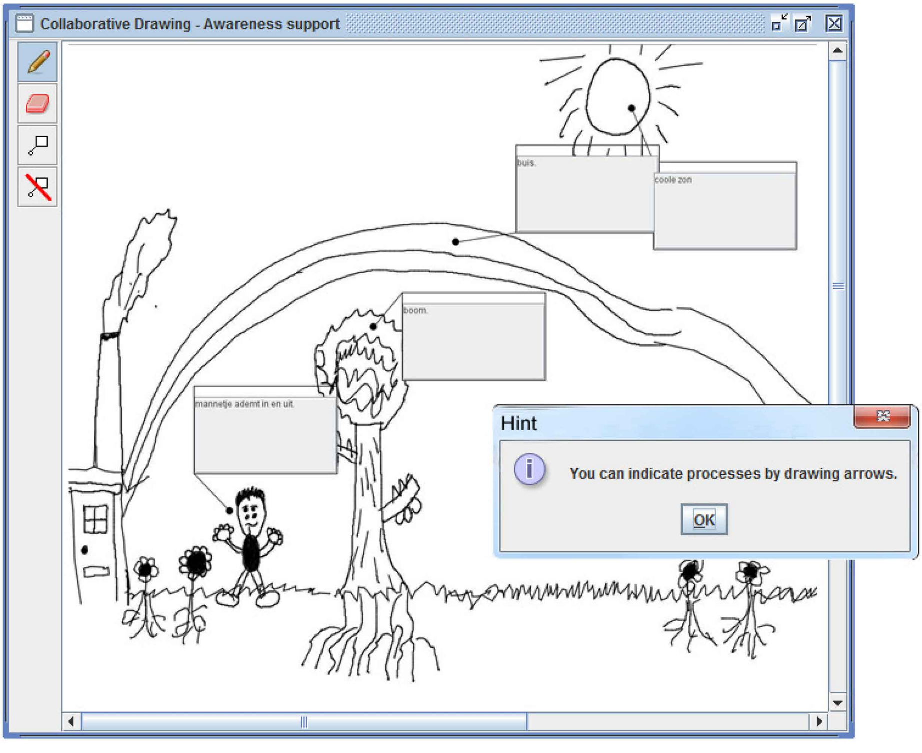

Figure 3. Drawing tool with an adaptive prompt proposing the use of arrows

The software prototype is not designed and implemented for a broader audience and target group or for domain-independent problems or tasks. Instead, it is specifically tailored for testing given hypotheses in a well-defined domain and for a known sample of participants. In that sense, the software that was developed and used in this study is not meant to be released to the public without detailed instructions and explanations.

For the type of research presented, it is vital to be able to quickly create preliminary versions for testing and piloting. The re-use of existing components from previous or similar experiments and implementations can help to achieve this goal. Obviously, the software architecture and communication infrastructure used needs to support the re-use of legacy solutions, as described above with regard to building upon the selected blackboard/TupleSpaces architecture. Here, components that may have been implemented in various programming languages are able to share and synchronize data and to operate in a RPC-like fashion.

Also, research prototypes in situations such as described here are often hardwired to a given network infrastructure, as schools and classrooms are often limited in their technical facilities, and may not be able to provide unhampered access to

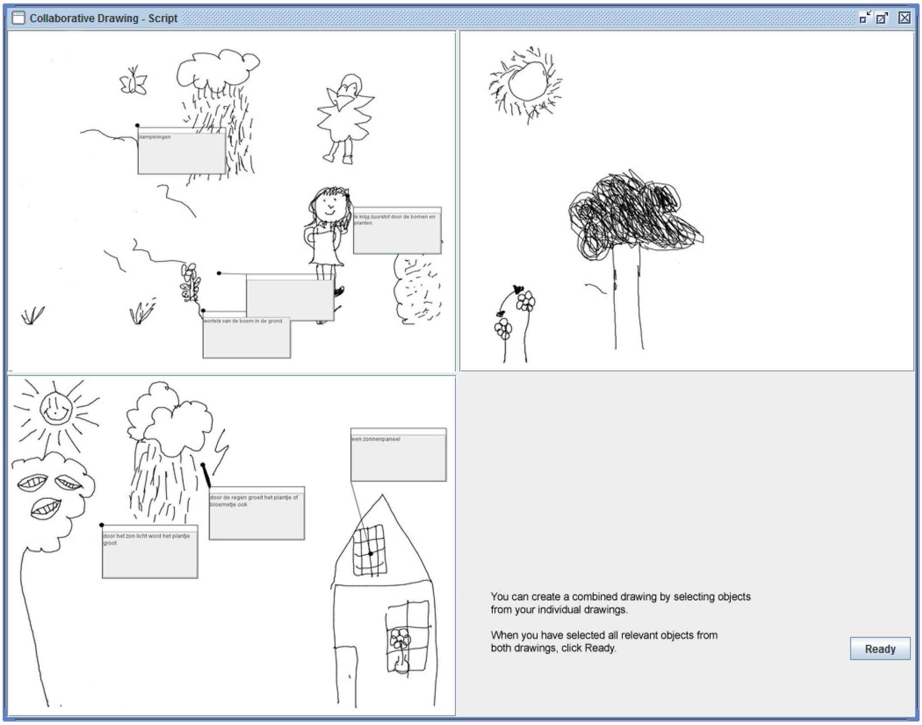

Figure 4. Split-screen interface to create a joint drawing

the internet, connection of network devices that are brought in or use of existing computer classrooms.

Due to their quickly built and to some extent immature implementations, research prototypes need to be based upon a fail-safe and robust architecture to prevent data loss. Here, each collaborating dyad was using its own synchronization server – the loss of one server would not disturb the other dyads' work.

All in all, the architecture and implementation presented above fulfilled these requirements and proved to be a "stable research prototype", which could be set up with little effort and allowed the testing of the hypotheses and investigation of the research questions of interest.

4 RESULTS

In this section, we first report the extent to which the supportive measures affected students' learning outcomes on both knowledge tests and students' discourse quality. Then we report on the relation between knowledge acquisition and discourse quality. Finally, to give a sense of how students collaboratively constructed knowledge and worked with the different forms of support, we present excerpts of students' epistemic and transactive dialogue moves in both experimental conditions.

4.1 Knowledge Tests

Two different tests (a concept recognition test and an open recall test) were administered to assess students' domain-related knowledge. All means and standard deviations for test scores are presented in Table 2. Learning gains for the concept recognition test (intermediate test scores minus pre-test scores, and post-test scores minus intermediate test scores) and the open recall test (post-test scores minus intermediate test scores) were calculated for all students. For the concept recognition test, the results of ANOVA revealed no significant effect of condition on the learning gain from pre-test to intermediate test ($F(2, 87) = .110$, ns). However, a significant effect of condition on the learning gain from the intermediate test to post-test was found, ($F2, 87) = 5.533$, $p <\ .01$, Cohen's $d = 0.56$). In line with our expectations, a post-hoc comparison of the means (using the Bonferroni procedure with adjusted alpha levels of .016 (.05/3) showed a significant difference in learning gains from the intermediate to post-test between the control condition and the script condition in favor of the script condition.

For the open recall test, results of ANOVA revealed a significant effect of condition on the learning gain from the intermediate test to post-test ($F(2, 87) = 5.449$, $p < .01$, Cohen's $d = 0.56$). No significant differences were found between the adaptive prompts condition and the script condition. A post-hoc comparison of the means (using the Bonferroni procedure) revealed that results were partially consistent with our expectations. Students in both experimental conditions outperformed their peers in the control condition in learning gains on the open recall tests (all $ps < .013$). Contrary to the expectations that we expressed in the introduction, no significant differences between the learning gains on the open recall were found between the two experimental conditions.

4.2 Discourse Quality

This section presents results of the analysis of student dialog along the epistemic and transactive dimensions. These results are summarized in Table 3.

4.2.1 Epistemic Processes

The epistemic quality of the dialogue focuses on the quality of the content-related activities students engage in when they work on the collaborative learning task. The epistemic processes can differ in complexity. Students can simply name concepts and processes, but might also define them or relate them to other concepts and processes. Making a connection between concepts and/or processes is a more complex epistemic process than simply naming a concept. Since students in the

Condition	N	Concept recognition test			Open recall test	
		Pre-test	Intermediate	Post-test	Intermediate	Post-test
Control						
M	24	4.71	8.91	10.67	7.63	9.29
SD		3.24	1.71	1.27	2.12	1.92
Prompts						
M	34	4.56	9.15	11.65	7.53	10.67
SD		3.37	2.19	1.54	2.23	2.82
Scripted						
M	32	4.03	8.39	11.79	7.06	10.15
SD		3.16	2.46	1.22	1.65	1.64
Total						
M	90	4.41	8.81	11.43	7.38	10.01
SD		3.24	2.19	1.43	2.00	2.26

Table 2. Mean scores and standard deviations on the knowledge tests

adaptive prompts condition were requested to draw concepts and processes, we expected to find a higher percentage of concept- and process-related utterances for the adaptive prompts condition. The results of MANOVA with the percentages of utterances falling within the epistemic categories as dependent variables and condition as independent variable revealed significant differences in the sub-categorical scores for the epistemic processes ($F(26, 88) = 3.402$, $p < .001$, Wilks' Lambda $= .40$, $\eta^2 = .368$). The results of subsequent ANOVAs followed by post-hoc analysis (using Bonferroni corrected alpha levels of .016) did not confirm our expectations. The post-hoc Bonferroni corrected comparisons indicated that students in the adaptive prompts condition defined a higher percentage of domain-related concepts than their peers in the control condition. However, students in the adaptive prompts condition did not produce a higher percentage of concept definitions than their peers in the script condition. With respect to the percentage of domain-related processes that were defined, post-hoc Bonferroni corrected comparisons revealed that students in the script condition exchanged a higher percentage of process definitions than their peers in the control condition. Contrary to our expectations, no significant differences regarding the percentage of process definitions were found between the adaptive prompts condition and the script condition. Furthermore, significant differences between conditions were found for the percentage of coordinative utterances ($F(2, 87) = 6.386$, $p < .05$, Cohen's $d = 0.56$) and the percentage of neutral off-task interactions ($F(2, 87) = 5.829$, $p < .05$. Cohen's $d = 0.56$). Post-hoc Bonferroni corrected comparisons revealed a higher percentage of coordinative utterances in the script condition in comparison to the control condition and the adaptive prompts condition. The percentage of neutral off-task messages was significantly higher in the control condition than in both experimental conditions (all $ps < .013$). An overview of the percentagewise scores and standard deviations is given in Table 3.

	Control		Prompts		Script	
	M	SD	M	SD	M	SD
Epistemic:						
Concept naming	37.25	9.27	38.47	8.50	34.74	6.54
Concept definition	.47	1.01	1.78	2.16	1.53	2.01
Process definition	.040	.19	.32	.65	.45	.75
Concept process	2.42	1.76	2.73	2.66	3.77	2.41
Coordination	29.24	8.03	29.69	8.27	35.59	7.17
Off Task: Neutral	19.57	7.82	20.12	7.56	17.17	9.45
Off Task: Conflict	2.69	3.40	1.24	2.08	.66	1.04
Para-verbal	8.32	4.74	5.65	4.80	6.09	4.23
Transactive:						
Externalization	33.02	8.13	32.26	5.65	34.16	7.21
Elicitation	17.06	5.10	21.36	5.43	22.09	6.38
Quick agree	13.19	4.78	10.20	4.02	10.32	4.13
Quick disagree	3.42	3.28	1.47	1.83	2.41	2.95
Integration	1.77	2.44	4.27	3.51	5.31	3.87
Critical	.94	1.32	3.43	2.64	1.79	1.93
Off Task: Neutral	19.57	7.82	20.12	7.56	17.17	9.45
Off Task: Conflict	2.69	3.40	1.24	2.08	.66	1.04
Para-verbal	8.32	4.74	5.65	4.80	6.09	4.23

Table 3. Relative scores and standard deviations for the epistemic and transactive dimensions of the coding scheme ($n = 90$)

Considering that the script encouraged students to compare, discuss and combine knowledge and ideas during the drawing activity, it was expected that students in the script condition would demonstrate a higher percentage of integration-oriented and critical consensus building e-processes than the students in the adaptive prompts and the control condition. The results of MANOVA with the percentages of utterances each student made, falling within the specific categories as dependent variables and condition as independent variable showed significant differences ($F(26, 88) = 3.402$, $p < .001$, Wilks' Lambda = 4.1, $\eta^2 = .291$) between conditions. Subsequent ANOVAs revealed differences between conditions regarding the percentage of quick consensus building activities aimed at reaching agreement ($F(2, 87) = 4.337$, $p < .05$, Cohen's $d = 0.67$), the percentage of quick consensus building utterances revealing disagreement between students ($F(2, 87) = 3.685$, $p < .05$, Cohen's $d = 0.48$), the percentage of integration oriented messages ($F(2, 87) = 7.623$, $p < .01$, Cohen's $d = 0.86$) and the percentage of critical consensus building activities ($F(2, 87) = 10.711$, $p < .01$, Cohen's $d = 0.43$). Post-hoc (Bonferroni corrected) comparisons revealed that the percentage of quick consensus building activities (both agreement and disagreement oriented) was significantly lower in both experimental conditions. In contrast to our expectations, results of the post-hoc comparisons showed higher levels of transactivity (both integration oriented and conflict oriented consensus building) for students in both experimental conditions and not just for students in the script condition (all *ps* $< .016$).

In line with prior research [28], we expected that the transactivity of the dialogue would be positively related to students' learning outcomes. This expected positive relation between transactive (integration oriented and critical consensus building) dialogue moves and learning outcomes was confirmed by the results of a stepwise regression analyses with the learning gains on the open recall test as the dependent variable. However, similar results were not found for the learning gains on the concept recognition test.

Predictors	Model 1	Model 2	Model 3
Integration oriented consensus building	.54*	.49*	.43*
Concept definition		.27*	.25*
Critical consensus building			.19*
R^2	.54	.60	.63
$R^{2\ \text{Change}}$ (df)		.06 (89)**	.03(89)*
*p <.05, **p <.01			

Table 4. Results of regression analyses predicting learning gain on the open recall test

4.3 Case Studies

The quantitative results show that there are important differences between the experimental and the control conditions. The findings also show that there are only minor differences with respect to the epistemic and transactive quality of the dialogue between both experimental (adaptive prompts and script) conditions. The excerpts we present here are extracted from the dialogues of Monica and Calvin, who worked in the adaptive prompts condition, and Dianna and Andrea, who worked in the script condition. All excerpts are translated from the Dutch. In both conditions, students are trying to define and draw abstract concepts such as chlorophyll, oxygen and carbon dioxide.

4.3.1 Monica and Calvin

Monica and Calvin are working in the adaptive prompts condition and have just received the prompts that they should use arrows to indicate processes and relations. Monica and Calvin already think their drawing is nice (line1). Calvin agrees and wonders what kind of processes they mean (line 2). Their next action (line 3), checking the original textual resource, is typical for students in the adaptive prompts condition.

Monica is suggesting that they could indicate that oxygen is going out (line 5). Calvin takes up this idea and continues that carbon dioxide is going in. Calvin's next utterance (line 8) suggests that they are comparing the concepts in the text with

Line	Student	Utterance
1	Monica	We should do this, but I think we have a nice drawing already.
2	Calvin	Yep. What processes do they mean?
3	Calvin	I can have a look in this. (referring to the text)
4	Calvin	Hmm.
5	Monica	Oxygen in, no, out.
6	Calvin	Carbon dioxide into the plant.
7	Monica	Yes, it is over here.
8	Calvin	So we have the plant, the green leaf stuff.
9	Monica	We should draw the green stuff.
10	Calvin	Yes, we need that.
11	Monica	Hihi, we don't need that, the plant needs it.
12	Monica	It's part of the plant machine.
13	Calvin	Aha!
14	Calvin	The plant factory.
15	Monica	An oxygen and sugar factory.
16	Monica	Okay, what's next?
17	Calvin	Check if we are missing something.

Table 5. Excerpt from the conversation of Monica and Calvin working in the adaptive prompts condition

their representation. Monica (line 9) suggests that they should draw chlorophyll (she refers to it as the green stuff). Calvin agrees. In the next phase (lines 11 to 15) they are joking around a bit and compare the plant with a machine and a factory (this metaphor is also used in their resources). In line 16, Monica is suggesting that they should move on. Calvin responds immediately by suggesting that they should check if they have missed something. The drawing by Monica and Calvin is presented in Figure 5. In their drawing, they used arrows to indicate that oxygen was leaving the plant. They also indicate that oxygen is used by humans (the little doll figure) and that carbon dioxide is produced by factories and humans.

4.3.2 Dianne and Andrea

Dianne and Andrea both made an individual drawing, and they have just created a new merged drawing by selecting elements from their individual drawings. In the excerpt presented in Table 6, they are trying to refine their new merged drawing.

In the conversation between Dianne and Andrea the difference between their two drawings forms the starting point of a conversation about stomata and oxygen (line 1). In the selection phase, they decided to take Dianne's plant to their joint drawing, because it was considered more complete. Andrea still thinks her plant looked better and Dianne explains why the stomata are needed (lines 5 and 6). She does this at a very basic level, talking about holes instead of stomata and about air instead of oxygen. Andrea (line 7) jumps in and adds her own idea referring to carbon dioxide. These moves suggest that she is trying to integrate her own idea

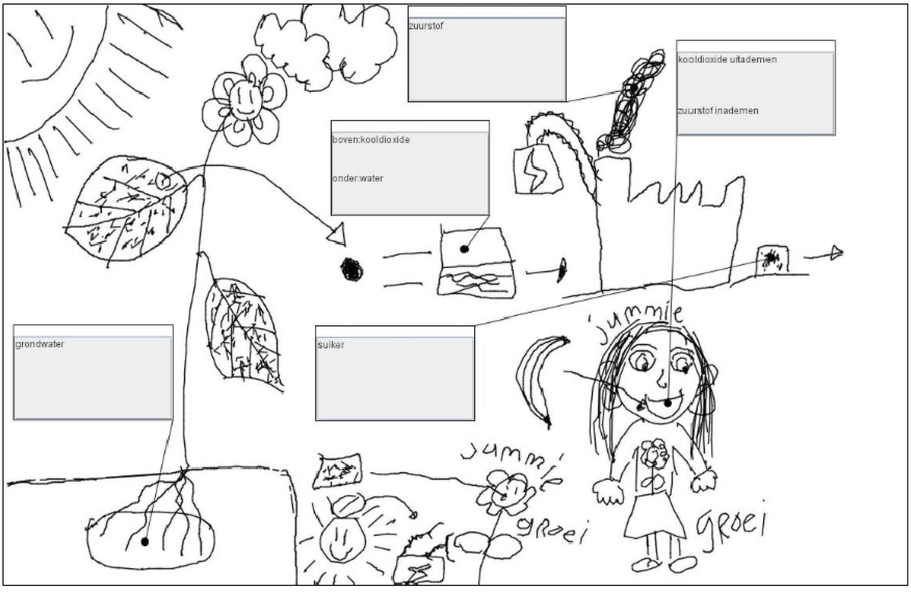

Figure 5. Drawing made by Monica and Calvin working in the adaptive prompts condition

into Dianne's line of reasoning. The dialogue can be considered transactive since both students try to build on the reasoning of their collaboration partner. Dianne refines her initial statement (line 8) and adds that the holes are called stomata and that they release oxygen. Andrea (line 9) thinks that oxygen should be visible in their drawing and her next move (line 11) suggests that she added something. Dianne makes a critical remark (lines 12 and 13). Andrea responds with a suggestion (line 14). Making a critical remark and responding to this critical remark by suggesting a solution is another example of the transactivity in the conversation between Dianne and Andrea. The results of their collaboration are presented in their final drawing (Figure 6). In Figure 6, we can see that they indeed included dots on the leaves of the plant and used wavy lines to indicate that oxygen is released by the plant. They also added the word oxygen to the drawing. This example illustrates that it is not only prompts that can cause students to discuss concepts and refine their drawings; confronting the work of other students might stimulate similar processes.

4.3.3 Synopsis

The excerpts suggest that it is not just the script that structures students' activities and conversation, but that the prompts also provide a structure. When students receive a prompt they change their activities. Monica and Calvin search the text for additional information. They discuss the concepts and processes and move on

Line	Student	Utterance
1	Dianne	Your plant looks nice but the leaves are missing the holes and the green dots.
2	Andrea	Huh, oh yeah, I forgot about the little holes.
3	Andrea	I think they make my plant look bad.
4	Dianne	Hmm, could be. Your plant looked nice.
5	Dianne	But the plant needs them.
6	Dianne	If the plant makes air for us the air comes from the holes.
7	Andrea	Yes, yes, yes, and it takes in the other stuff.
8	Dianne	They are called stomata and they let oxygen out.
9	Andrea	We should put oxygen in the drawing.
10	Dianne	Yes, yes.
11	Andrea	So, and so we can see that oxygen flows into the air.
12	Dianne	Do you think other kids can tell this is oxygen?
13	Dianne	Could be anything flowing around?
14	Andrea	Could be, we can add words.

Table 6. Excerpt from the conversation of Dianne and Andrea working in the script condition

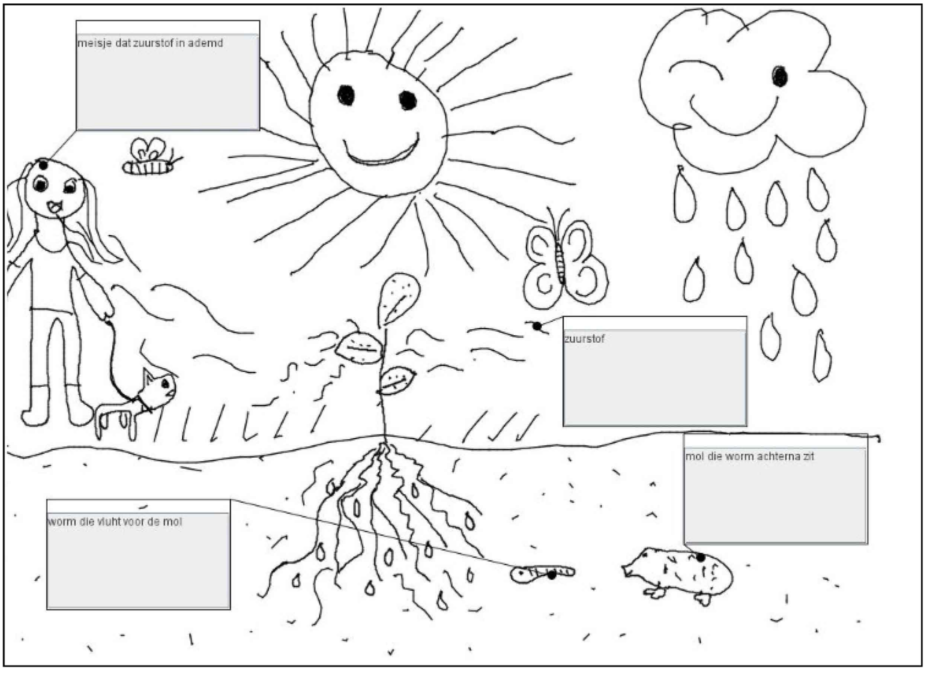

Figure 6. Drawing made by Dianne and Andrea working in the scripted condition

to check the rest of the text. Dianne and Andrea discuss the concepts and relations based on the differences between their drawings. This suggests that domain-related prompts (based on characteristics of the drawing) are not the only way to trigger students to consider the content of their drawing. Confrontation with the work of a peer student might also trigger students to reconsider the content information reflected in their own drawing. In both excerpts, the joint drawing activity with additional support helps students to maintain a common focus. Students build on the contributions of their peers. Critical remarks (see Dianne and Andrea) are followed up by suggestions, and ideas are integrated.

5 CONCLUSION AND FUTURE OUTLOOK

In the prior sections, we presented a study design, its technical implementation and empirical results in an experiment on collaborative drawing activities in primary school education. We showed that the chosen experimental setup along with the choice of the input device, communication infrastructure, drawing application and supportive features such as students' adaptive prompting and scripting support was successfully applied in several school environments with 94 participants. Computer-supported drawing activities with pen-based input devices proved to be a promising and intuitive way to create self-constructed external representations, especially when embedded in peer interaction scenarios.

Empirical results showed, partially in line with our expectations, that the learning results and discourse quality can benefit from guidance in the form of adaptive prompting or scripted collaboration, in contrast to the creation of a joint drawing without these features. Students in the adaptive prompts condition or script condition had higher learning gains on concept recognition and open recall tests. Students in the script condition engaged in more coordinative processes than their peers in the control and adaptive prompts conditions. This is in contrast to the findings of other studies that show that scripting alleviates the need for a coordination [29]. A possible explanation is that one of the subtasks provided by the script used in this study might have enhanced the need for a coordination. Within the present study, students were asked to compare their individual drawings and decide on the content that they wanted to present in their final collaborative drawing. Often both students represented the same object in their individual drawing and had to decide which of the two similar objects they wanted to include in their final drawing. Furthermore, students had to decide on the location of the objects on the shared canvas and had to decide who was responsible for dragging and dropping the objects. Scripts that provide students with more concrete tasks and define the tasks for both participating students might indeed alleviate the need for a coordination [29].

There were only minor differences between students' dialogues in both experimental conditions. The presented excerpts suggest that both the adaptive prompts as well as the script can stimulate students to reconsider domain-related concepts and relations. The script was intended to enhance students' transactive (integration oriented and critical) consensus building activities. The findings from our quantitative as well as qualitative analyses suggest that both the adaptive prompts and the script are beneficial for discourse quality and resulted in higher quality transactive processes and knowledge acquisition. Future research may reveal more details on the relations of other supportive features or combinations thereof in collaborative drawing activities.

Up to now, the detailed action log information has not been included in the analyses. From these log files, we may derive additional information about whether and how learning gains or discourse qualities relate to the students' drawing processes, for example, how many create/delete conflicts [21, 30] occurred or if there was a (im)balance of responsibility in creating the drawing.

A simplified version of the presented collaborative drawing tool and other drawing and learning related tools are available from `http://modeldrawing.eu`.

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