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Exploring activity theory as a tool for evaluating interactivity and learning in virtual environments for children

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Abstract

This paper explores the use of Activity Theory for the evaluation of user behaviour in immersive virtual environments. Specifically, the study of user behaviour focuses on interactivity, which is argued to be one of the most important processes that take place between a user and the system in virtual reality. The ultimate intention is to study the role and the effect of interactivity on learning and conceptual change and to examine how interaction and conceptual learning are related in the context of virtual environments developed primarily for informal educational settings. As a first step to this study, a set of exploratory experiments was carried out with children aged 7–12. The children were asked to complete tasks, such as the assembly of ancient columns from parts, which were designed to promote constructivist learning and explore the methods of carrying out in-depth experiments with children. This paper describes the analysis of these exploratory case studies from an Activity Theory perspective.

Keywords

Interactivity; Virtual reality; Learner–computer interaction; Activity theory; Conceptual learning; Evaluation studies with children

1 Introduction

The ultimate goal of our research is to investigate user interaction in virtual reality (VR), focusing on the role of interactivity in learning. More specifically, we aim to examine the effect that interactivity might have with regards to the conceptual learning of young users that experience immersive virtual environments (VEs).

Children represent a large and growing market for interactive products and while, until recently, immersive VR installations were limited to the research domain. Nowadays they have become increasingly popular in real world public settings. The location-based entertainment market or the informal educational institutions (science centers, museums), for example, have adopted or have started to consider various forms of interactive theme park rides (Schell and Shochet 2001) and multi-user high-end digital theatre experiences (Park et al.

2002) that target young visitors. In these public settings, the two essential properties of a VR experience, immersion (drawing the visitor in the experience) and interactivity (providing the visitor with some kind of control), are advertised widely in order to attract and motivate visitors. The pervasive use of the term interactivity has usually been tied to the idea of entertainment. In many cases though, the interactive features of a VR exhibit have been used to further validate the exhibit's potential pedagogical value and to essentially convince schools and parents to bring their children in. In other words, increasingly so, the interactive features of a virtual experience are touted for their significance to learning; it is commonly considered that a virtual learning environment is more effective if it is interactive. Although we do not object this assumption, we believe that little systematic research is available to substantiate it. To date, very few efforts exist that explore the value of interactive virtual environments and applications, especially the added value that these can bring to children's learning.

Although the broad objective of our work is to examine this dimension of interactivity in immersive VEs as well as its potential and limitations for learning, the objective of this paper is to explore Activity Theory (AT) (Bødker 1990; Nardi 1996) as a tool for the analysis of user interaction in virtual environments. The paper presents the results of an attempt to explore empirically, through qualitative case studies described with the use of AT, the relationship between interactivity and learning with children. Therefore, the following sections include a brief analysis of the background work that relates to this research, a description of the design of the exploratory studies that were carried out, a description of the analytical method and analysis of the studies, and concluding remarks.

2 Research setting and related work

This research inevitably draws from a number of different areas, including human–computer interaction and interaction design, VR and education, and, of course, learning technologies research and theories of learning. It is research that combines or intersects these areas that we look upon to extend. Furthermore, we have chosen to base the analysis of the observations and collected results on a framework of criteria that can be examined from the perspective of Activity Theory.

Interactivity is a widely used term of great concern to researchers and practitioners in communication theory and human–computer interaction (Steuer 1992) and the idea of interactivity certainly appeals to the broad public, as indicated by the attention that the term has received over the last few years (Rafaeli 1988). Despite this interest, there appears to be no consensus on what interactivity actually means; there is no agreed definition, leading to a range of interpretations (McMillan 2002). Most VR researchers would agree, however, with Pares and Pares (2001) in that activity in a VE involves one or more of three forms: to explore the virtual environment by way of navigation (explorative), to manipulate virtual objects or elements (manipulative), and to construct or modify the environment as a whole (contributive). This three-level definition of interactivity, which can actively involve the learner physically (i.e. bodily movement) and intellectually, will be adopted for the purposes of this research.

Most of the VR projects developed for educational purposes have not dealt directly with interactivity, except for some projects in the area of distance education. The interactive features of VR environments have mostly been studied from a usability perspective (Gabbard et al. 1999), or as factors that can have possible influence on the effectiveness of training using a virtual environment (Marshall et al. 2003). Very few projects have been specifically designed and developed for young students. Even fewer studies exist that single out and explore the influence of interactivity on conceptual learning or approach critically or even question the significance of interactivity as a facilitator of the learning process. Furthermore, there is a lack of frameworks to base such design, development, and evaluation on—with the exception of the work by Scaife and Rogers (2001) which, however, focuses on VE design guidelines.

A study which has specifically dealt with the impact of interactivity in the context of geometry teaching with diagrammatic representations, focused on the comparison between different graphical representations of the concept of stereographic projection and the effect that the addition of various interactive properties might have on the learning goal (Otero et al. 2001). For this study, interactivity was regarded as the ability to rotate virtual objects in a VRML space and perceive their spatial abilities, and the ability to manipulate the whole representation or individual elements (for example, to move or rotate the projection line). The hypothesis that the more interactive learning environment would provide better immediate learning results than the less interactive, was tested with four interactive learning environments that used different representations and varied levels of interactivity. The results led to the conclusion that just adding interactivity did not seem to increase the efficiency of the learning environment since the interactive 3D environment did not seem to provide the expected learning gains. However, it was noted that the study was exploratory and additional investigation was required, since learning seemed to be affected by a complex interaction of representations' properties, task demands, and within-subject factors. More detailed accounts of other relevant studies on interactivity and learning and VR in Education projects can be found in Roussou (2006) and Youngblut (1998).

For most of these studies, defining the learning component has been notoriously difficult. There are a range of different perspectives on learning and a great number of theories on how learning takes place[1]. According to one general school of thought, learning is related to behaviour (Skinner 1950). At the other, the experiential end (Kolb 1984), learning is the intellectual process of constructing knowledge, that is, acquiring, assimilating, processing, and integrating information. We have chosen to adopt this constructivist and social constructivist view of learning, as defined for example by Jonassen and Rohrer-Murphy (1999). Additionally, for the purposes of our research, we have grossly divided learning into factual and conceptual learning and have chosen to focus on the latter. Conceptual learning is identified with deeper, transferable understandings of generalisable, abstract knowledge. It has do to with logical

[1] The online database 'Theory into Practice' presents and provides references for over fifty different theories on learning, http://www.tip.psychology.org/theories.html [last accessed: April 2006]

thinking, the formation of scripts, stories, cases, mental models or constructs, concepts, associations, perspectives, strategies (Wiig and Wiig 1999). The process of change from such an existing conception to a new understanding, as a result of interacting with a virtual environment, is the kind of learning that we were interested in identifying. However, indications of additive knowledge or changes in behaviour were also sought. In other words, in the analysis of our data we looked for:

- Conceptual change, where learners revise their conceptions or change their interpretation of something, as evidenced through conversations of the type: ‘‘Why have you done this?’’, ‘‘Because I realised that there are now two different types of column instead of one...’’, and so on. When a participant says something and then provides a revised explanation later on, this may be an indication of conceptual change (Wiig and Wiig 1999).
- Additive knowledge, where learners have added to what they have already experienced. One could argue that this is the basis of constructivist learning, as long as this process of additive knowledge involves some kind of reinterpretation of what was done before rather than just the accumulation of information. Additive knowledge may be identified through a discursive process with the user, indicated by comments such as, ‘‘Oh I didn’t realise that before’’. When a participant says something during one task and then extends or develops this in the next task, that might be an indication of adding to previous knowledge (Slavin 1994; Von Glaserfeld 1984; Vygotsky 1978).
- Changes in behaviour. Even though a change in behaviour may not signify constructivist learning, since participants may change their behaviour and not understand why or may become better in something or succeed in a task and not actually understand it, we still need to recognise that this is a form of learning [at least, according to the behaviourists (Skinner 1950)]. Such changes in behaviour may be an important indication of learning in this study because all we may be able to infer with confidence from the observational data may be that behaviour has changed, rather than having evidence of understanding. Changes in behaviour are mostly identified through observation rather than through what the participants tell us. If the participants try to do something, fail and then try to do it again later on, we would try to identify if they did it in a different way. This would be an indication of behavioural change.

In this respect, Activity Theory was regarded as a particularly relevant framework to situate and analyse the results of our evaluation studies because it combines explicit reference to individual agency, the use of technology, and the social context, including the accepted rules of the social context. In Activity Theory the unit of analysis is an activity (Kuuti 1996). According to Activity Theory, the relationship between the individual and the world is not direct but mediated by the tools (e.g., technology) provided. Computers are a particularly interesting example of tools that are crucial mediators of human experience (Nardi 1996). Activity is usually mediated by one or more instruments and is directed toward a certain object. Therefore, an activity is composed of a ‘‘Subject’’ (a person or group engaged in an activity) and an ‘‘Object’’ (for instance, a learning objective held by the subject), mediated by a ‘‘Tool’’ or tools (that could be material as well as mental). Engeström (1987) extended this systemic model with the social context, that is the Rules (that regulate actions and interactions), the Community (one or more people who share the objective with the subject), and the Division of Labour (how tasks are divided between cooperating members of the community as well as the division of power and status), thus forming the complete Activity System. In AT the systemic and dialectic nature of the complex and constantly evolving interrelationships between individuals and groups, their tools, their past experience, the division of labour, the community rules, and so on are illustrated by "triangle" diagrams such as Fig. 1. Engeström (1987) extended the activity theory hierarchical framework further to include the concept of "contradictions". Identifying contradictions has been central to the analysis of user interaction for this research.

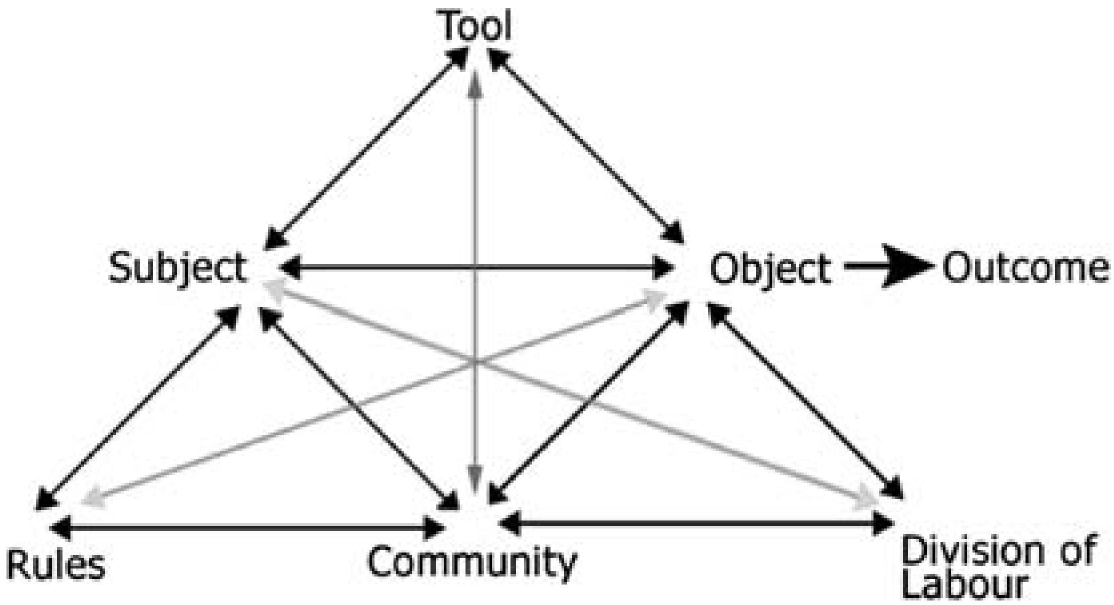

Fig. 1 The complete Activity System model depicting the structure of human activity [developed by Engeström (1987, p.78)]

3 Exploratory case studies

Our first experiments on the topic involved an exploratory approach for a number of reasons. First of all, an exploratory observation-based design was chosen because few assumptions need to be made regarding what is important in the work to be studied. The complex, contextualised nature of the topic and the medium led us to consider that, at this stage, it was premature to run a precisely defined experiment because of the large number of variables involved (levels of interactivity; conceptual, factual learning; different learning styles), their complex nature (learning, interactivity) and the differing content and contexts (abstract or concrete; school or informal education). Thus, at this early stage of the work, a small set of case studies that allowed the observation and analysis of such situations was considered most appropriate; the purpose of these studies was primarily methodological with a goal to explore the setting and therefore help shape the experiments to follow.

Secondly, no established frameworks were found in the existing literature that could advise on the kinds of information that should be gathered from empirical evaluations in order to determine the effectiveness of interactivity in a virtual environment. Hence, these exploratory case studies were intended to help formulate an analytical approach capable of relating the theoretical underpinnings explored in the literature review to actual data.

Finally, these studies were planned to act as trials for the practical aspects of the method: to establish techniques for subsequent studies; to identify early-on any problems that can occur in running such experiments (for instance, experiment design issues, virtual environment usability issues, practical and ethical issues related to handling of the participants, and so on); and then to develop and refine the design and method.

3.1 Methodological approach

As already mentioned a constructivist approach to learning was considered appropriate for studying interactivity in a VE and learning, coupled with Activity Theory as the guiding framework for the analysis of the experiment findings. However, no established methodology has been found that uses this dual theoretical grounding to study VR environments for learning. One study by Barab et al. (1999) with a comparable social constructivist dimension has been identified, which adopts AT as a method for analysing a series of design experiments on a VR-based astronomy course. This study used a naturalistic grounded approach based on both quantitative and qualitative data that were collected through direct observation, field notes, interviews, document and artifact analysis, and retrospective recall analysis. The collected data captured discussions between students and teachers, documented practices, resources and progress, and supported and refuted emerging hypotheses about how these practices and resources evolved over time. The data was then grouped into units of analysis called "nodes" and large databases containing these nodes of information were formed. We have chosen to adopt a similar methodology for this study. However, because our first study is exploratory in nature, this methodology was adjusted. For example, we did not intend to prejudge what counts as conceptual understanding and thus did not use the same descriptive framework to divide chunks of data into nodes and to group nodes into databases. Instead, we interpreted the participants' interactions within the VE by examining instances of activity that provided evidence of conceptual conflict, which were then resolved with the help of the tool. Like the study of Barab et al., this represents a grounded approach in that it documents practices and supports and refutes emerging hypotheses. Unlike that study, however, ours is not naturalistic since it is time-constrained and involves an environment designed to allow us to examine a certain parameter, that of interactivity.

Overall, our approach for these early experiments is qualitative in nature, considering the idiosyncrasies of the VR medium, the complexity and social context of the topic (learning, interactivity), and the fact that the research target group is young children. The main method followed during this first study involves observing the participants, where the researcher acts as observer and interviewer at the same time.

3.2 Experimental method

The exploratory experiments were conducted with three participants, one girl and two boys, aged 7, 9, and 12 years old, on different days. The virtual reality system used for testing was a CAVE-like display.[2] The CAVE is a cubic room-sized structure, where the front, side walls, and floor are projection screens displaying moving stereoscopic 3D graphics (Fig. 2). A tracked position and orientation interaction device with a joystick and buttons was used by the participants to complete the virtual tasks assigned. The user's head position and orientation was tracked by a sensor placed on a baseball cap, which the participant wears reversed so that the cable is well behind her head. For the first two tasks the use of only one button was required, both for selecting and letting go virtual objects. For the third task, two additional buttons could be used for scaling virtual objects (left button to increase size, right button to decrease; every button click represented a 5% change in scale). Navigation within the VE was not required thus the joystick was not used for any of the tasks.

The tools used for observation included a video camera for recording image and audio of all the sessions and the informal interviews. The camera was pointed toward the front wall of the CAVE, capturing each participant's back, the front screen, the floor and part of the side walls (Fig. 3). An external microphone connected to the video camera by a long cable was used to increase audio quality. Briefing, debriefing and questions took place inside the CAVE area and were also videotaped. The participants were trained on the use of the system within the virtual environment of the first task. The time the participants spent in the virtual environment performing the tasks ranged from 45 to 75 min.

A variation of the think-aloud technique called 'Active Intervention', where the evaluator prompts the children for explanations of what they are doing and to give a commentary on their interaction, was used to facilitate observation and analysis. Usability evaluation sessions with children carried out by van Kesteren et al. (2003) have shown that most verbal comments were gathered during Active Intervention sessions versus other methods such as the think-aloud or co-discovery, and that quiet children are better able to provide verbal comments when a more active way of prompting is applied, for example by asking questions.

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[2] The CAVE (CAVE Automatic Virtual Environment) is a Registered Trademark of the Board of Trustees of the University of Illinois, originally designed by the Electronic Visualization Laboratory of the University of Illinois at Chicago (http://www.evl.uic.edu). Although the VR display actually used for these experiments was not an original CAVE, for the purpose of brevity and simplicity, we will be using the word CAVE throughout the paper when referring to it.

Fig. 2 A child's activity of constructing a column in the CAVE-like virtual reality environment through placement of available parts

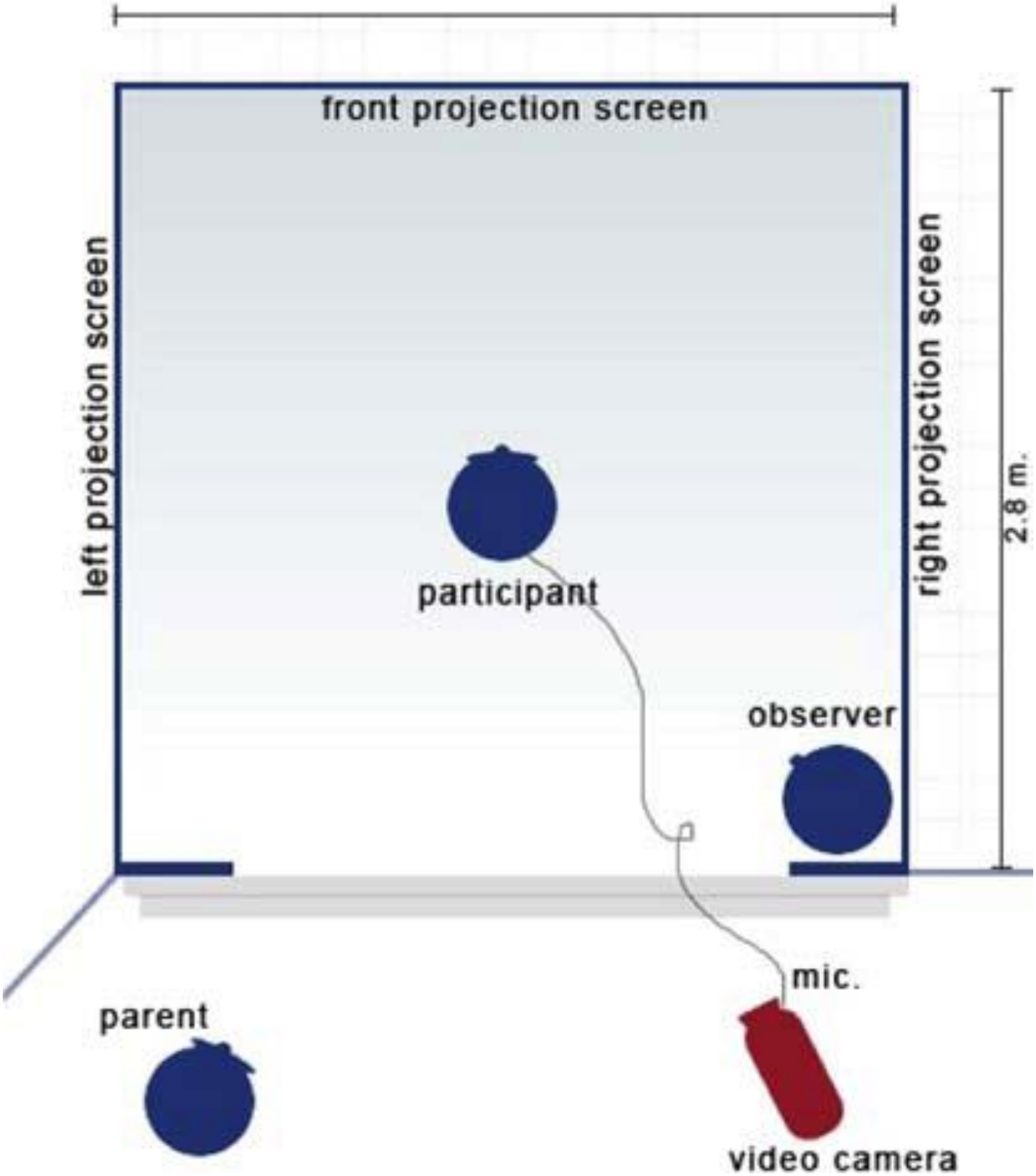


Fig. 3 The immersive VR experimental setup used for this research, depicting the positions of the equipment and the individuals that took part in the studies

3.3 Tasks

A virtual environment was designed with three separate tasks that were performed in sequence (Task A, Task B, and Task C) with breaks in between for the user to rest. The tasks were designed to follow a tiered structure, requiring a slightly different and progressively more complex activity and—it was hoped—greater thought for each one. All three tasks involved a construction activity, specifically the construction of columns through the placement and manipulation of their parts. Each column was made of a total of six pieces, including the capital (column head) and column base. In each task the column bases were positioned in, approximately, the middle of the CAVE floor and were the only parts in the environment programmed so that they could not be moved by the user. The other parts, when pointed at, displayed a red bounding box, which meant that they could be selected with the press of a button and "attached" to the user's hand. They were "dropped" by pressing the same button.

Task A involved the selection and placement of the parts of a column of Doric order. Task B, also involved the selection and placement of column parts, only in this case the pieces found in the virtual environment belonged to two columns of different order, a Doric column and an Ionic column. Task C also involved the selection and placement of the parts of a column; however, in this case, the column pieces were found in different sizes and had to be resized in order to be consistent with the column base.

The tasks developed, i.e. to construct columns from various parts, were constructivist tasks in that they required making decisions and building upon existing knowledge. No rules or instructions were given and there were only very few and subtle instances of system feedback to guide the user. For a detailed description of the tasks and their respective VEs, see Roussou (2006).

4 Analysis

4.1 Analytical method

The methods used in these exploratory studies allowed for two ways of gathering information, through direct observation and through a discursive process with each participant. Based both on observation and on what the participants told us during the sessions, but also on our conceptions of the learning we were looking to find, we were able to form the repertoire of the kinds of learning described in Sect 2. Our method of analysis, drawn from Barab et al. (1999), was based on supporting or refuting emerging hypotheses; we reviewed the video of all sessions and identified various points where interesting interactions seemed to occur. The organizational framework of Activity Theory provided us with the conceptual vocabulary to help interpret these points. AT uses the term contradictions to indicate problems, ruptures, breakdowns, or clashes; in other words, changes and imbalances in the elements of activities (Nardi 1996). When reviewing all three case studies, we looked for critical incidents or examples of contradictions occurring in the system. During the analysis, these incidents were closely described and categorised. We then proposed a hypothesis concerning what we saw, explaining this in terms of learning. We chose to focus on points where participants made a statement that indicated they had changed their belief or where we could conclude things from our observation of the learner's behaviour in the environment.

As discussed in the next section, two categories of incidents provoking internal contradictions emerged: incidents caused by the unintentional intervention of the observer (for instance, the observer's questions caused the participant to change her course of action) and incidents caused through direct response from the system (i.e. an action that was not allowed by the system caused the participant to think of alternative ways to handle a situation). We will call the first category "extrinsic" feedback and the latter "intrinsic feedback". Additionally, incidents that occurred through technical problems in the use of the system were also noted.

This analytical approach is not specific for studying interactions with children—it can be used to study any human interacting within a VE. However, the overall experiment design (e.g., the tasks described in Sect. 3.3) and the method of prompting and eliciting information were tailored to work best with children. The fact that these kinds of virtual environments are usually created for children provides the motivation for the development of such studies.

4.2 Interpretation according to AT

In the excerpts that follow, the relationship of participant and activity is examined by using ATs activity system notations. The components that constitute the activity system for this analysis primarily include each of the three participants, here called Subjects (using the transcription notations S1...S3), the Object (in this case, the construction of columns leading to the learning goal/objective which is learning about different types of columns), and the Tool (the virtual environment). On a second level, the relation between subject and object is mediated by the participant observer who in this case also represents the Community (and is indicated by C in the text), by rules, and division of labour (Engeström 1987). The Activity System diagram to illustrate these relationships is shown in Fig. 4.

Each Subject [S1 to S3] uses the Tool [the virtual environment 1, 2, and 3 that corresponds to each of the three tasks] to achieve the Object/Objective [constructing columns]. The outcome [to learn about columns] is what the Community expects from the Subject. The Community sets Rules for achieving the tasks. Each Subject understands the Rules in his or her own way (i.e. they may not be the same as the Community's).

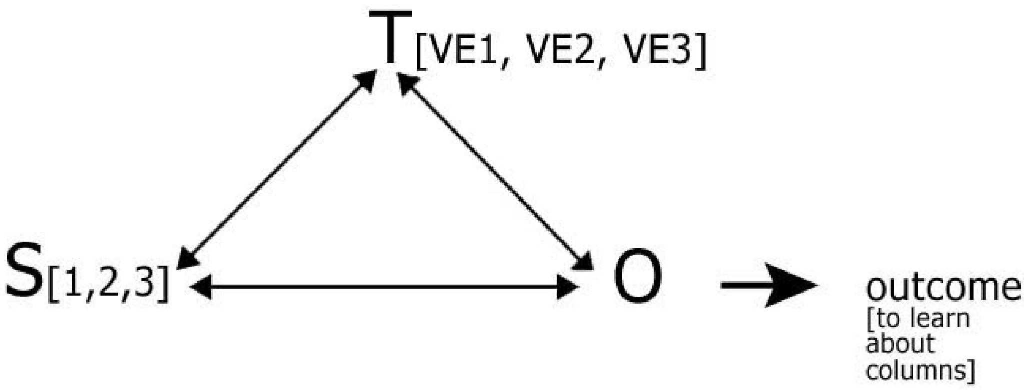
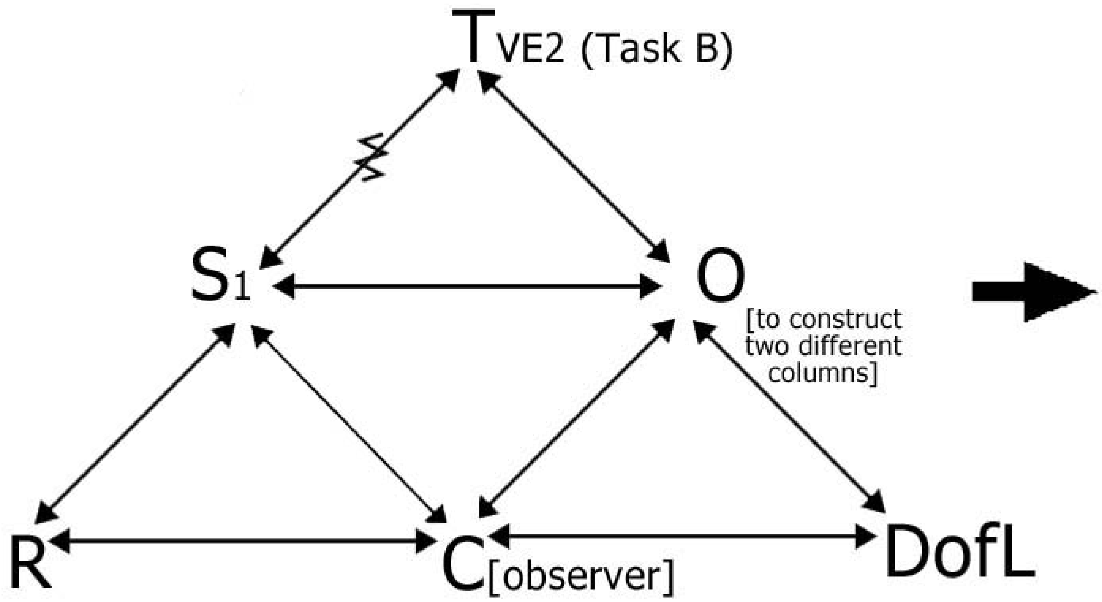


Fig. 4 The Activity System diagram illustrating the relationships between Subject, Tool, and Objective

4.2.1 Incidents caused by technical problems

A number of incidents caused by technical or usability problems occurred during the participants' interactions with the system. This is not surprising, as technical and usability problems can occur when interacting with any kind of software or system, not just a CAVE. Although incidents of this kind are not the focus of this paper, they provide a good starting point for illustrating the use of the AT diagrams. For example, there were a few cases where the participants were unsuccessful in picking or placing a piece due to the fact that it was occluded by another piece or where the children were not able to reach the top of a column in order to place the capital. In some of these cases the observer had to intervene in order to help resolve the problem or speed up the process. In particular, during S1's activity for Task B, the observer had to move in and reposition some of the column drums so that S1 could reach them. Since navigation was disabled, a few pieces that were farther away in the virtual space were not easily accessible by the participant. The activity system diagrams in Fig. 5 illustrate this technical/usability breakdown, where the problems that the subject (S1) had in using the virtual environment (shown as a break between S1 and T) caused the observer (C) to intervene (shown as a breakdown in the Division of Labour) in order to resolve the contradiction.

Overall, the participants learned a number of things about using the system and this technical learning was apparent after the first task since the time they spent on trying to pick and place the virtual objects was reduced, as was their frustration, and they generally seemed much more comfortable in carrying out their tasks. However, technical breakdowns such as the one illustrated above, where the contradiction occurs between S and T or where there is a breakdown in the division of labour (i.e. the observer steps in to help with the handset, or to re-set the system), although taken into account during the analysis of this exploratory study, are not the kind of instances that interest this research because they do not concern relevant conceptual learning.



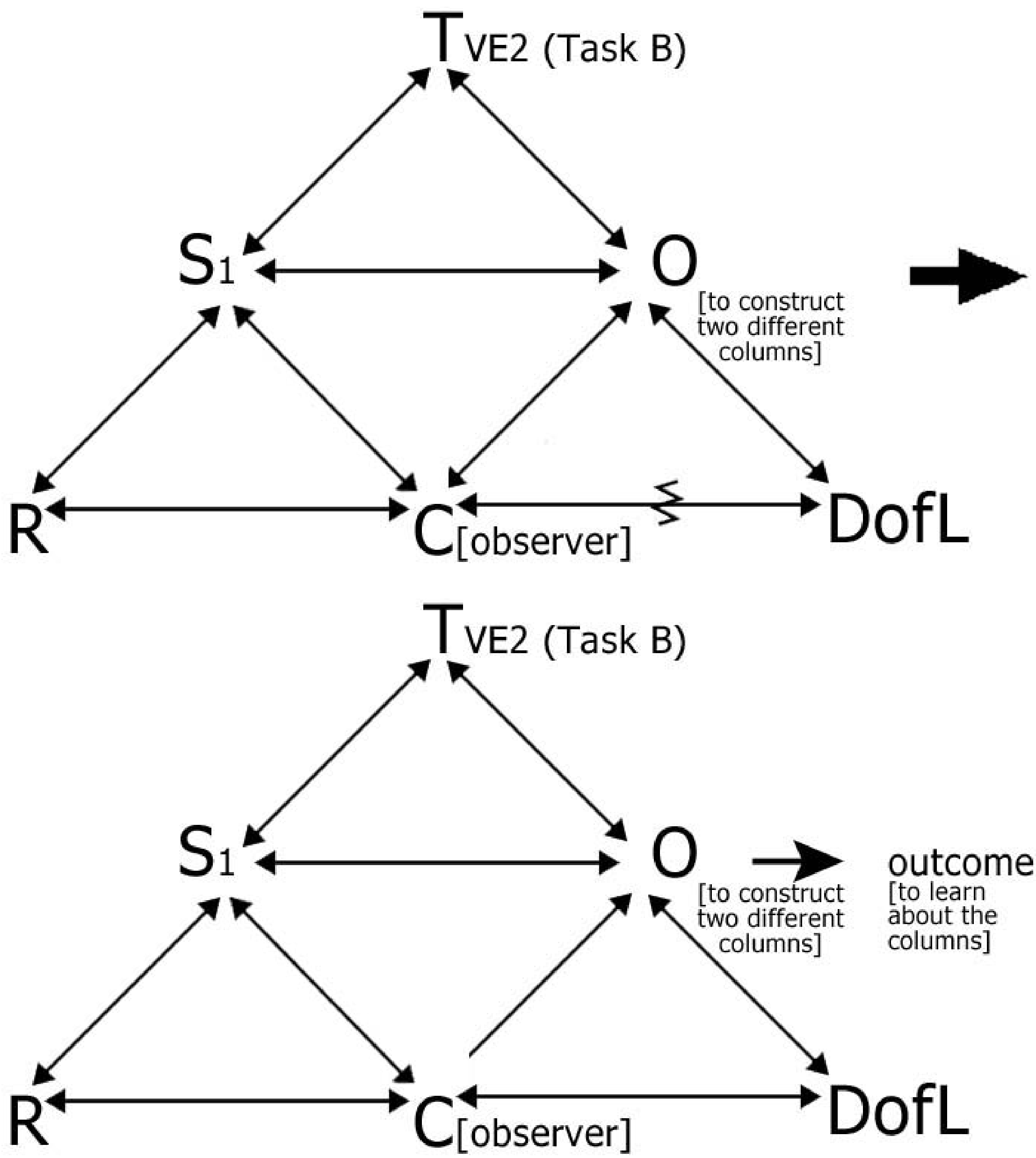


Fig. 5 An activity system illustrating a technical/usability breakdown between the user and the VE and the observer's intervention in resolving the contradiction

4.2.2 Incidents caused by observer intervention

As mentioned, the observer's role was to remind the participants to think out loud by asking questions at instances where participant activity seemed to entail some kind of contradiction, and to help with the use of the system if problems occurred. Any other intervention by the observer that may have caused the participant to change her course of action was unintentional. However, such instances of unintentional intervention were recorded for the purposes of this exploratory study.

The dialogue that follows is an example of such an instance. It occurred during Task B, after S1 had incorrectly constructed two columns, the Ionic with an extra piece that normally belonged to the Doric.

C.: Why did you choose some pieces over others?
S1: I chose the thicker pieces for one column and the thinner for the other.
C.: And how did you decide to put the thick pieces on this column [showing Doric column] and the thin pieces on the other one?
S1: Because one base is thin and I put the thin pieces there.

S1 was very confident of her reply and, technically speaking, her reply was correct in terms of what she should have done. This indicates that, in this case, she understood the Rules. However, the thick piece remained in the column with the thinner pieces, so what she claimed to be doing in theory was not done in practice. The intervention did not seem to have any effect at this point, and further questions were asked.

C.: So do these look right to you?
S1: They look funny.
C.: How so?
S1: They are not straight.
C.: That's all?
S1: And one is smaller and shorter; the other is taller and long.
C.: Why?

She stood back to think about what she had said before (which indicates that she indeed had not made a conscious decision when acting). She then observed the columns more closely, identified the misplaced piece and corrected her columns. The observer's intervention, although not intended as a pedagogical prompt, caused a change in behaviour.

In S1's view, the Object (to construct two columns) was achieved. The subject explained the Rules (that all thick pieces go to one column and all thin to the other) to C. There was common understanding of the Rules between C and S1; however, S1 did not use these Rules (Rc) to achieve the Objective. This indicates a break between what the Subject understands as Rules (Rs) and the action she makes to reach her goal, which is resolved with Cs intervention (Fig. 6).

In this case, it is argued that this change of behaviour is an indication that learning occurred. However, one cannot be certain of the exact outcome (if deep understanding about the differences between columns was achieved) since no other methods for investigating it further were used (such as, asking more specific questions, completing a posttest, and so on). Moreover, the learning that did occur was a result of the conversation between S1 and C and not purely of S1's activity with the system, even though the activity with the system was the material that triggered the discussion between S1 and C.

4.2.3 Incidents caused by the system or by system feedback

The system was not programmed to provide any explicit feedback. However, it was designed with certain features that provided intrinsic feedback, such as the fact that the column bases could not be moved. This was enough direct feedback to provoke some interesting incidents. Furthermore, this is the kind of feedback we are interested in examining since it represents the system's interactive capabilities.

Example 1

The following occurred with S2, at the beginning of the construction of the column in Task A:

> C.: Why did you decide to start with that piece over any one of the other pieces?
> S2: It doesn't matter... because they all look the same. He reaches the top piece and sees that it protrudes, so then starts rearranging the pieces.
> C.: What are you doing now?
> S2: The column is not straight. I think this piece [top piece] must go to the bottom... It is protruding.
> C.: You said before that all the pieces are the same.
> S2: Yeah.
> C.: So did you change your mind?
> S2: Every drum is different at the top than at the bottom. The top piece is the thinnest.

He proceeds in carefully examining both ends of all pieces before rearranging them. He then places the pieces and completes the column correctly (Fig. 7). S2 follows a complete interaction circle: he has an intention, he performs an action, he observes and evaluates the effect of an action (examines, places, turns, compares each piece), and he modifies/corrects the action based on the results of his assessment. His observation of the system's rules guides him in evaluating his actions. S2 has created an initial understanding of the Rules which he then revises, assessing for himself the contradiction within the system and resolving it in order to achieve the objective (Fig. 8).

On the other hand, in the case described in Sect. 4.2.2, S1 and C initially also have different understandings of the Rules, but that only becomes apparent when C asks S1 questions which eventually cause her to reevaluate the Rules. In both cases, there is a breakdown or contradiction in behaviour and it is this progression or process of resolving contradiction where we argue that learning is occurring. The difference between S1 and S2 is that S1 changes behaviour when there is intervention from C, not from interaction with the system.

This difference where S2 self-corrects whereas S1 requires intervention, we suggest, is consistent with Vygotsky's Zone of Proximal Development (ZPD) (Vygotsky 1978), which concerns the internalisation of social rules. S2 is already able to internalise the Rules whereas S1 is not able to do the same without discussion with the Community. S1 is within the ZPD, i.e. she can learn with support from a more able peer, but is not yet able to complete the task unaided.

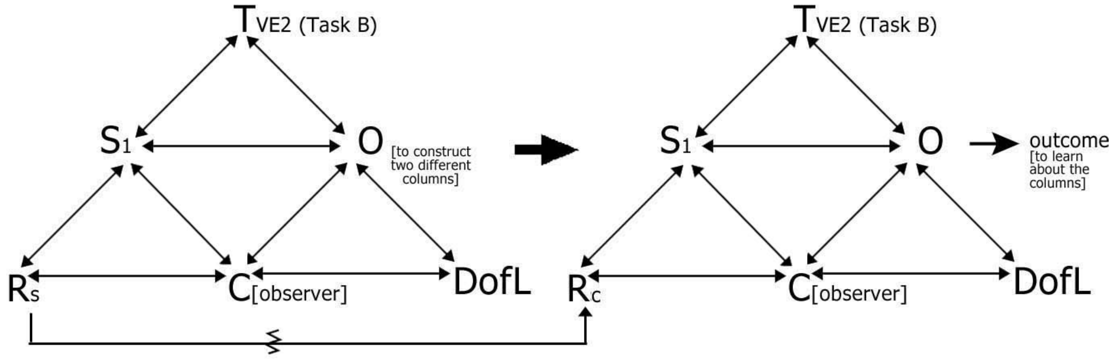
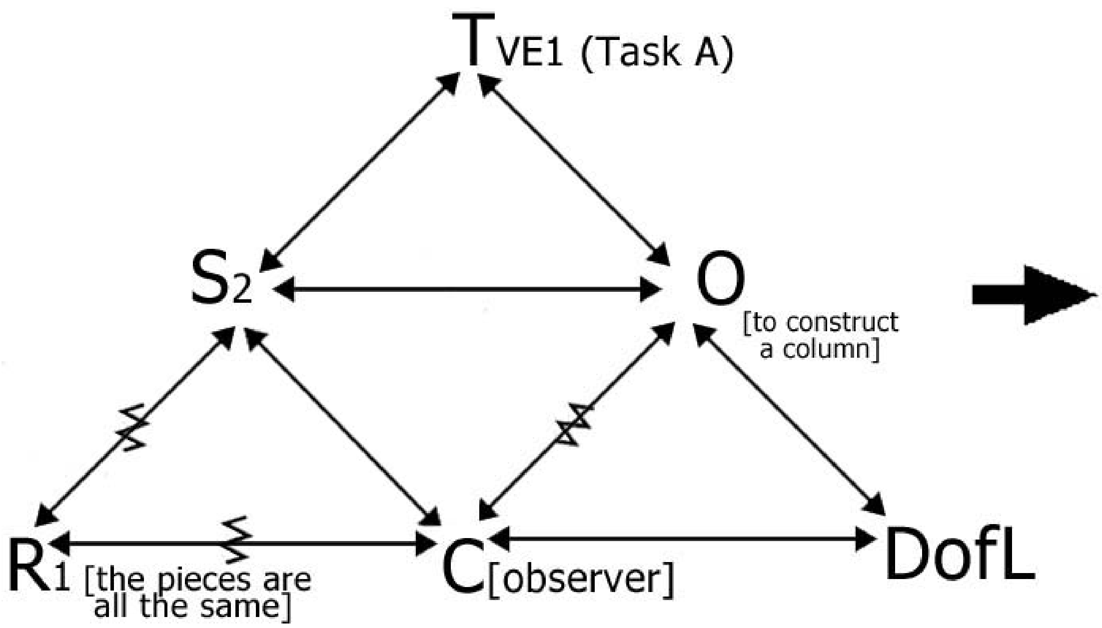


Fig. 6 An activity system illustrating a contradiction between the Subject's understanding of the Rules (Rs) and the Community's understanding of the Rules (Rc), which is resolved after the observer's unintentional intervention

Fig. 7 S2—completing the Ionic column by placing the capital on top



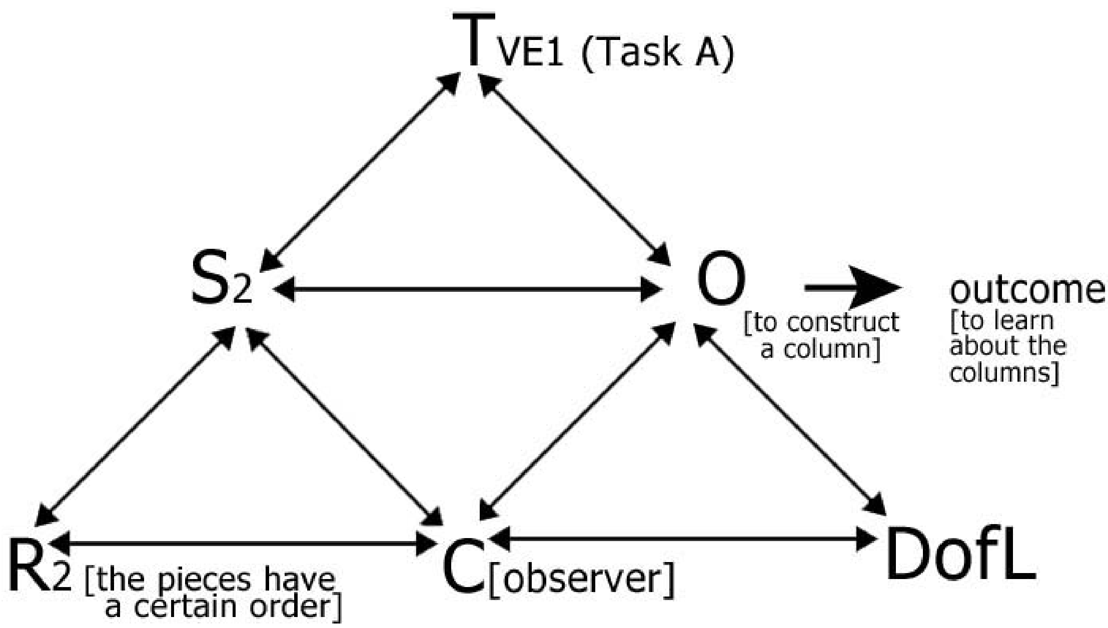


Fig. 8 An Activity System illustrating a breakdown between the user's initial understanding of the Rules (R1), which he then revises (R2) in order to resolve the contradiction and achieve the objective

Example 2

S3 in Task B had completed the construction of the two columns. However, the Doric was shorter than the Ionic by one piece. He found the wide piece in the Ionic and moved it to the Doric.

> S3: I see that something is not right here.
> C.: Which piece is not right?
> S3: That [showing a wide piece in the Ionic column].
> C.: Why?
> S3: Because it is thicker. Both columns now have the same number of pieces.

However, these are not necessarily the correct pieces. A bit later, S3 realises this:

> S3: I found a mistake.
> C.: What mistake?
> S3: This here [showing a piece on the Doric] doesn't belong here; it belongs down there [switches the piece with one in the Ionic].

In an activity system, this is shown as a break between S and R1, leading to a new system with no break between S and R2 (the revised rules). The conflict between the subject and the rule set is resolved after a conceptual revision of the rules (Fig. 9).

This is an example where the subject spontaneously changes the way he acts, based on what he observes, on reflection or consideration. He proceeds in correcting his mistakes as a result of what he sees (what "looks right") and not as a consequence of the interactive properties of the system. This conceptual revision of rules may be an indication of learning but is not an example of learning that arises from the unique features of VR, the kind that explores the effect of interactivity, as a VR property, on conceptual learning.

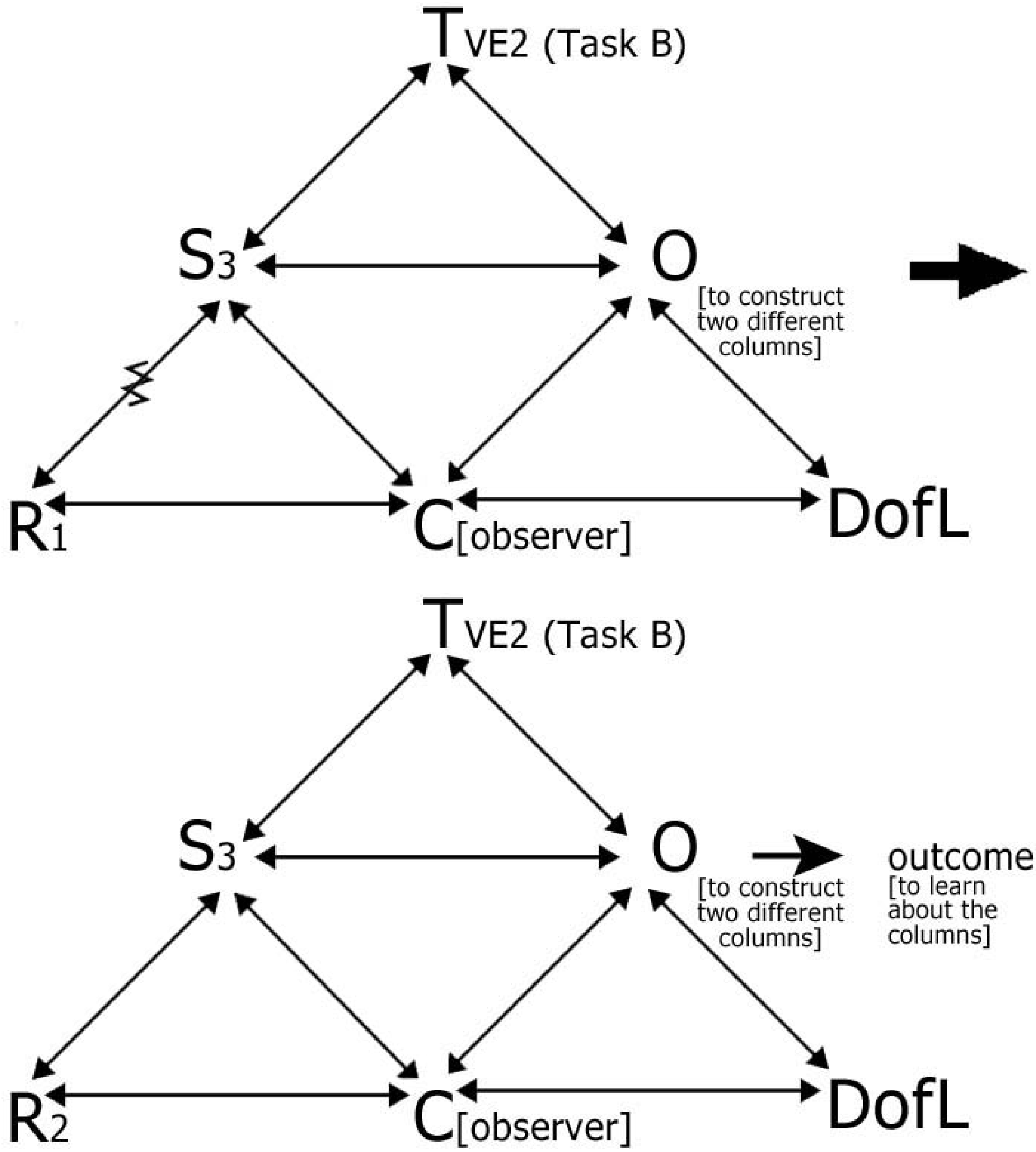


Fig. 9 An Activity System illustrating a breakdown between the Subject and the Rules (R1), which is resolved after a conceptual revision of the Rules (R2)

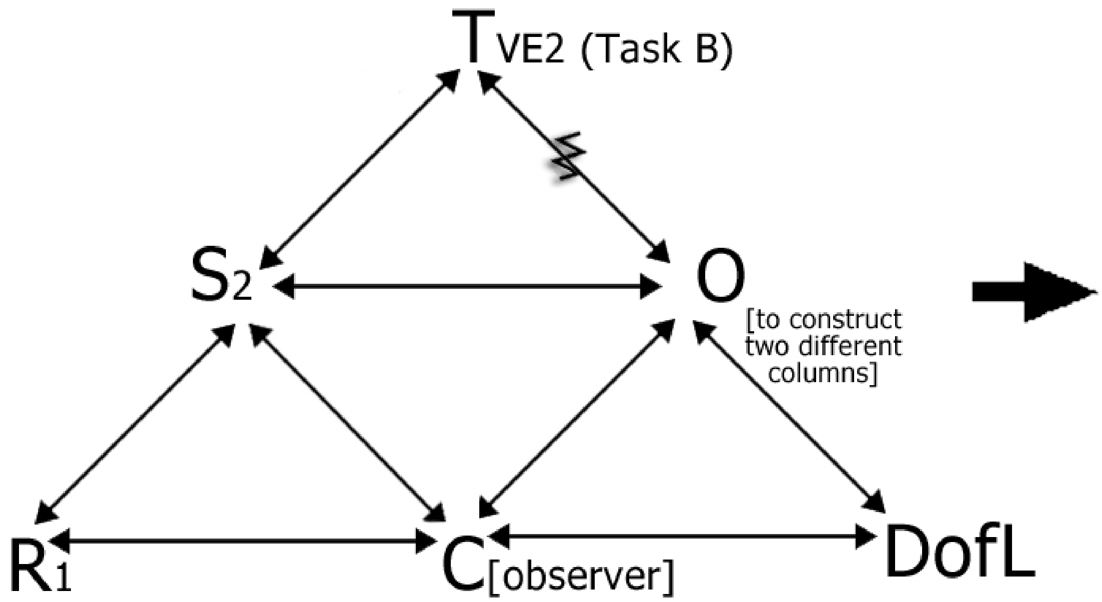
Example 3

In Task B, S2 reached the point where he had to find the base of the Doric column, from which he would start building that column. He was not sure whether the base was the square flat piece which lay flat on the ground or another piece that looked like it but was more curved (which, in fact, was the capital). He seemed to have solved this when he realised that he could not pick up the base; however, he was not able to explain this well.

> C.: How about those pieces? [referring to the Ionic and Doric column bases]
> S2: [showing in the general direction] On one side is one base and on this side is the other base.
> C.: How did you conclude this?
> S2: Well, this base [pointing to the Ionic column base] is definitely one base

> because I saw it in the previous [task]. And this [showing the Doric column base] is the other base because this other piece [showing the Doric column head which he originally thought may be the base] has a kind of a curve.

S2 can use the Tool but the Tool does not let him achieve what he sets out to do. Specifically, since he does not know how to distinguish between bases and capitals, he tries to move a piece that the system will not allow to be moved. Within this action, his use of the tool is technically correct, but its target is not. The contradiction that arises is thus between the Tool and Object. Rather than resolving this breakdown directly (for example, by using a different tool or learning a new technical approach) he changes his expectations, he revises what he wants. This is represented in Fig. 10 by a change in the rules: as indicated in the excerpt from the transcript, he reviewed the differences between pieces in the light of his failed attempt to move them. From this reflection, he learned to distinguish between capitals and bases and between Doric and Ionic columns. The feedback from the system alerted him that not all pieces were the same, so that he then attended to other differences between pieces. This is what we hope to achieve, as an indication of conceptual change: that the subject revises their rules. We can thus clarify our aspiration for conceptual change, as defined in Sect. 2, as the revision of personal beliefs through the acquisition of the rules of the community.



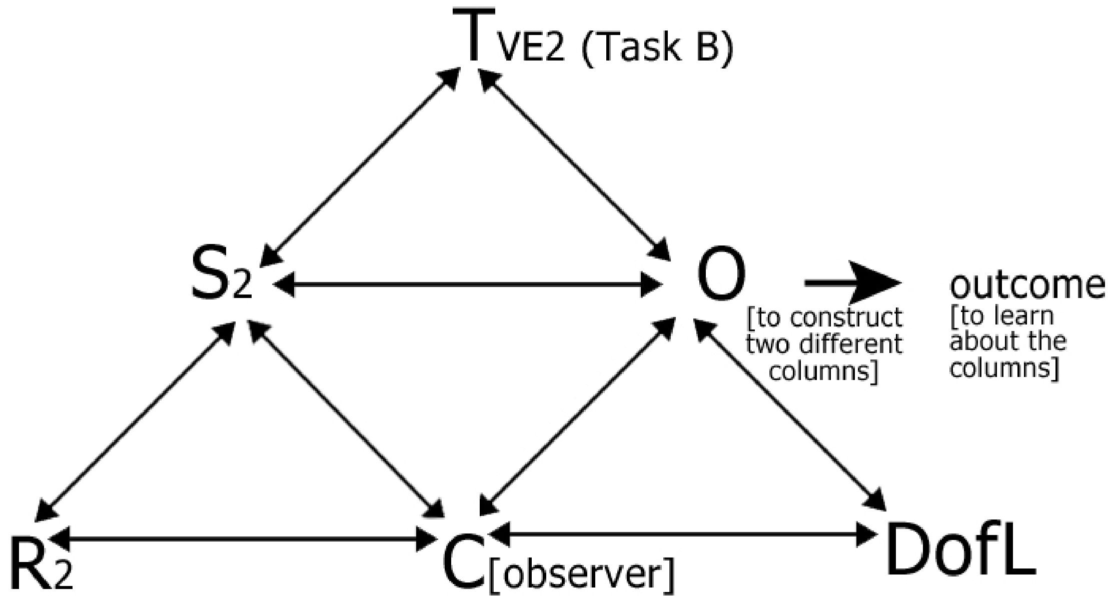


Fig. 10 An Activity System illustrating a breakdown between the tool (the VE) and the user's goal (Object), which is resolved by a revision of the Rules (from R1 to R2)

Example 4

The same type of intrinsic feedback (that the column bases could not be moved) aided S3 in changing his course of behaviour. For Task A, S3 started constructed the column from the capital, which he placed in the air and then begun building downwards by placing the drums underneath. He had managed to squeeze the last drum under the others and attempted to pick up the base.

> C.: How do you see that this piece goes at the bottom rather than the top.
> S3: It's the last piece.
> C.: How do you know that it is the last piece?
> S3: Because I put that one [showing the bottom last column drum] and saw that there is no other one that fits below it... Anyway, you can tell it's the last piece.
> S3: [trying to pick up the last piece] It is glued on the floor...
> C.: Why would it be glued on the floor?
> S3: So it doesn't show... [thinks for a moment...] Oh! So that I can put the other pieces here.

He started taking apart the column he had constructed in the air and constructing it piece by piece on top of the base. He de-constructed the column he had made in the air by starting from the top drum, which he placed at the bottom (directly over the base) and then every other piece on top of it until he placed the capital. The "Oh!" is the "Eureka" moment that both triggers his change in behaviour and indicates a change in his conceptions. Furthermore, in the tasks that followed (Task B and C) S3 identified the bases immediately, having learned and remembered from Task A that the bases do not move, and started constructing the columns from the bottom working up.

In an activity system, the above incident would be illustrated with a break between T and O, which is resolved not by S3 learning how to use the tool better, but instead by him realising that he is not supposed to do this (Fig. 11). Thus, it is resolved by a new system involving a revised rule set, R2. In other words, in this example, the subject changes the way he acts after the system prevents him from doing something. As in the previous example, a revision of personal beliefs takes place, through the acquisition of the rules of the community. This, we argue, is an example of conceptual learning from interaction with the VR system.

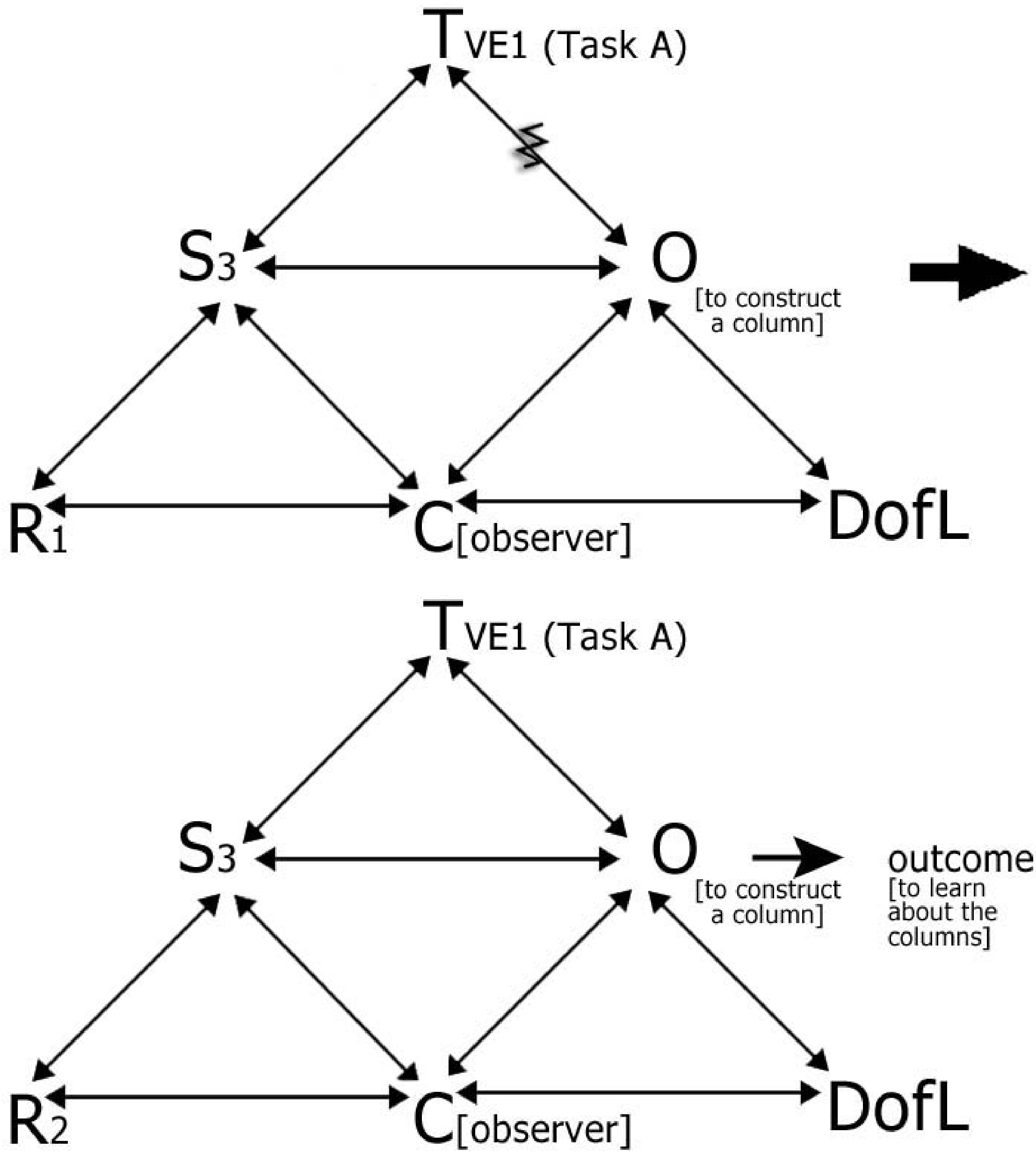


Fig. 11 An Activity System illustrating a breakdown between the tool (the VE) and the user's goal (Object), which is resolved by a revision of the Rules (from R1 to R2)

5 Lessons learned

The case studies described above formed the first part in a series of studies that set out to explore the research question— how to test whether interactivity influences learning. As such, the main focus of these case studies, and of this paper, has been to explore the viability of Activity Theory as the main analytical approach for the evaluation of user interaction in VEs.

Despite the small number of participants (which, however, was considered adequate since enough incidents occurred for this analysis to take place), the study succeeded in clarifying many of the technical and practical issues concerning the development of the methods for carrying out in-depth experiments with children. At the same time, the study also highlighted some of the inadequacies of the methods used to collect and interpret the data. The participants, being young children, have difficulty in explaining their actions and, most of all, externalizing their thought process, while direct observation alone seemed unable to provide adequate insights into these internal thought processes. The active think-aloud protocol that was used to obtain verbalization data can be quite effective, but this still largely depends on the participant's learning style, capacity to verbalize, level of extroversion, or even gender (Markopoulos and Bekker 2003). Also, the observer had hoped to be as unobtrusive as possible but it proved difficult given that the participants had to be asked questions while interacting with the virtual environment. This is a particularly common problem, especially in VR where achieving presence is paramount to the success of an experience. Any direct method of eliciting information from the user during the experience can cause breaks in the user's sense of presence (Brogni et al. 2003). Although the study of presence and its effect is not within the scope of this research, breaking the illusion of presence could affect participants' engagement and interaction with the VE.

The above observation led to the conclusion that thinkaloud should not be used as the only method to elicit information from young users. Consistent with the methods of Barab et al. (1999), but also with what researchers that work with children report (Markopoulos and Bekker 2003), the need to use multiple research methods was established and reinforced. This exploratory study led to a process of identifying the methods which were finally used in the subsequent main study. These include, in addition to direct observation with complete video–audio recording and the think-aloud technique, a number of different formal and informal tools for collecting the data, such as semi-structured interviews, pre- and post-task questionnaires, activity log files and informal discussions probing retrospective recall. These methods were necessary for looking through multiple data sources at what the participants did/thought so as to triangulate interpretations.

In this exploratory study, Activity Theory proved to be a useful tool for our purposes. It provided the study with the analytical power to present and understand the relationships between the user, the virtual environment, and the learning objective that formed the dynamic activity system of the study. AT provides the opportunity to ''see'' incidents and form them into categories which reflect the different kinds of things being learnt; it served as an observational record to look for changes in behaviour that arise from contradictions such as breakdowns within the use of the VR system. The main contribution of the AT analysis has been the formulation of the understanding that learning occurs through particular types of interaction, where learning is understood as the changed intentional behaviour following failure and interaction is defined in terms of socially situated, tool-mediated activities on three levels: explorative, manipulative, and contributive (see Sect. 2).

However, the exploratory study was not adequately designed to provide opportunities for interaction on these three levels. Also, the analysis illustrated that the exploratory study fell short of providing enough evidence of task learning and conceptual change. Although the construction of columns did include problem-solving activity, the intended learning goal or the inferred ‘‘learning problem’’, which involved understanding the differences between columns and the importance of scale and symmetry, remained unclear. Nonetheless, the incidents described above showed evidence of some kind of learning, albeit, in most cases, it was not learning that resulted from interaction with the VR system alone.

6 Further work

Based on our experience with this exploratory study, we identified a number of further research and design directions, which we pursued by designing and implementing a follow-up study. Since what is sought is evidence of conceptual change arising from a process of scaffolding and feedback generated by the system, the experiment tasks described here had to be re-designed to focus on achieving such change. At the same time, the design of the new study had to be such so as to minimise the occurrence of other kinds of learning, such as technical learning or learning as a result of external aid from the observer. It would also have to introduce into the system properties that could capture the moments where users may have incorrect conceptual models of a topic, which they then change as a result of their interaction with the system. Thus, for the next study, a different learning domain, that of mathematics, was chosen in order to exploit the capabilities of the VR medium in visualizing abstract and difficult conceptual learning problems and providing feedback. Hence, in order to examine ‘‘interactivity’’, explorative, manipulative and contributive levels of control over the parameters of the system were designed into an experimental VE in which children are asked to complete constructivist tasks (such as planning the layout of a playground) that are designed as mathematical fraction problems. Fractions were chosen as learning topics due to the difficulty that primary school students have in understanding and connecting them to real-world situations (Harel 1991). The specific tasks required by the new VE involved modifying (resizing and placing) the various elements of the playground according to rules that require fractions calculations. The system was designed to provide intrinsic feedback to respond to the children’s activity, including feedback on the rules of the task, communicated by a semi-intelligent agent instead of a human observer. Based on the lessons learned from the exploratory study, the new study, performed with 50 children, adopted an experimental method that includes direct observation, interviews, computer log files, pre-tests and post-tests, designed in collaboration with maths teachers, for three different participant groups (two experimental VR groups and a non-VR group). The analysis of the results also adopted a mixed quantitative and qualitative methodology, which was based on Activity Theory and thematic categorization of incidents (Roussou and Slater 2005; Roussou 2004, 2006; Roussou et al. 2006).

In a nutshell, the adaptation of the explanatory framework of Activity Theory to this research follows a pragmatic approach that can be briefly summarised as follows: real-time observation recorded on video captures verbalisations and the participants' interactions with the virtual environment, which are examined in a process of identifying interesting incidents or contradictions. These are then described in terms of their effect in the activity system, and the descriptions are collected in categories that are formed through an emergent thematic coding. The pre-tests, posttests, and log files are analysed quantitatively but are also used to support the qualitative analytical process further, based on the mandate to triangulate methods that can offer complementary perspectives.

This process was tested through an exploratory study with three young participants in a virtual environment, described in this paper. The study involved an experiment with column construction tasks and aimed at testing out the method while attempting to examine, ultimately, the effect of interactivity on learning. Activity Theory aided in structuring the incidents caused by the user's interaction with the system and in identifying different kinds of learning (tool mastery, at a trivial level, but also the internalisation of socially-defined rules and concepts about acceptable column construction). The analysis revealed that the minimal and subtle cues that were provided by the system (e.g., the column base that could not be moved) led, in some cases (Sect. 4.2.3, Examples 3 and 4), to indications of conceptual change through the revision of the participants' personal beliefs and rules.

The shortcomings of the study informed decisions on the direction that we then followed in the next studies. Therefore, based on the insights gained from this process, it was decided that the main study should involve a system designed to provide more opportunities for interactivity on various levels, and for occurrences of conceptual learning, manifested through indications of conceptual change. The methods for gathering the data would be enhanced to include a combination of methods, ranging from the quantifiable pre- and post-questionnaires to the more qualitative observations and interviews probing participants' understandings. Finally, the analysis would continue exploring Activity Theory as a descriptive method of interpretation, in order to identify manifestations of learning through the examination of critical incidents or contradictions.

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