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The Interaction Between Multimedia Data Analysis and Theory Development in Design Research

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Mathematics education researchers conducting instruction experiments using a design research methodology are challenged with the analysis of often complex and large amounts of qualitative data. In this paper, we present two case studies that show how multimedia analysis software can greatly support video data analysis and theory development in design research. The software can (a) act as a type of mould for organising large amounts of data; (b) contribute to improving the trackability and reliability of the research; and (c) support theory generation and validation. We propose an integrated model that elucidates the complex process of data analysis by showing how each of the components that are involved in the data analysis procedures feeds into the emerging local instruction theory. The model combines the intricate cycles of coding and analysing raw video data with the cumulative cyclic process that characterises design research in mathematics education. Our experiences with this model may support other mathematics education researchers in the development of thorough and empirically supported local instruction theories from complex qualitative analyses.

Design research in mathematics education has both a theoretical and an applied purpose: theoretical in terms of coming to an understanding of mathematical thinking, teaching and learning, and applied in terms of using this understanding to improve mathematics instruction (Schoenfeld, 2000). As a result, researchers do not settle for answers that merely illustrate what works best. Instead, they use methods that both aim to understand *why* as well as *how* mathematics instruction works in practice (cf. Freudenthal, 1983; Gravemeijer, Bowers, & Stephan, 2003).

What characterises the process of data analysis in design research is the interaction between data analysis and theory development. At a practical level, this interaction is illustrated in Jacobs, Kawanaka, and Stigler's (1999) cyclical process of analyzing video data. Oriented more towards theory development, Gravemeijer (2004) describes design research in terms of a cumulative cyclic process. In this paper, we propose to embed Jacobs et al.'s (1999) model into Gravemeijer's (2004) model for a more encompassing representation of the intricate interactive processes that are essential for theory development in design research. The significance of this integrated model is that it encompasses the steps that are necessary for keeping track of the process of analysing raw qualitative data for theory development in design research.

The challenge of qualitative mathematics education research is that the investigations often entail a large amount of data that derive from complex educational settings (cf. Gravemeijer & Cobb, 2006). Multimedia data analysis software is therefore a welcome tool for analysing raw qualitative data (Powell, Francisco, & Maher, 2003; Stigler, Gallimore, & Hiebert, 2000). This allows for the interactive and automatic coding of rich text, image, audio, and video materials. After importing raw data in the form of, for example, a video, screenshots, or scans of written work into the program, the researcher can organise the data by segmenting the data into "quotations" (i.e. video clips or "meaningful chunks"; Stigler et al., 2000), adding comments to the quotations, creating codes to label the quotations, and linking the appropriate codes to specific quotations.

In this paper, we argue that the use of multimedia data analysis software can help to conduct a cyclical analytical process in design research as implied by the integrated model that we propose. This is valuable for warranting the validity and reliability of conclusions that are drawn from raw qualitative video data. We discuss how multimedia data analysis software can be used to cultivate the interaction that is inherent to observing and analysing qualitative design research data. Furthermore, we present several benefits of using multimedia data analysis software for organising the complex raw qualitative data and for supporting the quality of the research.

To illustrate the benefits of using multimedia data analysis software, we present the MENS research project (Van Nes & De Lange, 2007; Van Nes & Doorman, 2009) and the ToolUse research project (Drijvers, Doorman, Boon, Van Gisbergen, & Gravemeijer, 2007). These are two examples that bring the integrated model into practice. We describe how the multimedia data analysis software ATLAS.ti[1] supported the organisation of and connection between different sources of qualitative data, how it encouraged the sharing and discussing of the research with others, and how this contributed to the reliability and trackability of the research. The interaction between data analysis and the evaluation and subsequent adjustments of conjectures is what stimulated theory development in both projects. This contributed to bridging practice with theory for drawing valid and reliable conclusions.

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[1] Designed and produced by ATLAS.ti GmbH in Berlin

Brief Introduction to Design Research in Mathematics Education

Design research in mathematics education is oriented towards generating empirically based theories. It was first described by Glaser and Strauss (1967) and further developed into a methodology that is characterised by the cumulative, cyclical process of theory development (e.g., Freudenthal, 1973; Gravemeijer, 1994; Cobb, diSessa, Lehrer, & Schauble, 2003). This cyclical process involves an iterative procedure of theory-driven adjustments to the intervention and amendments to the hypotheses, which, together, are intended to lead to an improved and empirically supported theory.

Realistic Mathematics Education (RME) inspires the development of mathematics education by offering a pedagogical and didactical perspective on mathematical teaching and learning. Mathematics in RME is seen as a "human activity" that is driven by the act of mathematising (Freudenthal, 1973, 1991). Mathematising means more than gaining mathematical knowledge and becoming adept at performing mathematical operations. Rather, it involves understanding underlying mathematical abilities such as ordering, classifying, generalising, and formalising (Treffers, 1975). Freudenthal (1973, 1991) posits the importance of guided reinvention for stimulating mathematisation. This principle underlies the construction of knowledge as if the student "reinvented" it. It differs from the discovery perspective (which states that symbolic systems exist and that children must try to understand them with help from adults), because in the (re)invention perspective, the children really (re)invent the mathematics by being placed in situations that require mathematising (Gravemeijer, 1998). Hence, the designer's role in this "active learning process" is to encourage the children's spontaneous strategies without imposing the mathematical knowledge on them. It is the task of the designer to offer children tools with which to build upon earlier knowledge for constructing and internalising new insights. Together, this is implied by the term "guided".

In practice, guided reinvention means that the teacher can anticipate the types of mathematical thinking that children may develop at particular moments, and provide the concepts, models, and symbols when the children may find them necessary. At a classroom level, the designer must help the children converge their mathematical ideas with each other and with the teacher so that a shared mathematical standard can be achieved. To achieve this, (re)invention includes the introduction of concepts, models, and symbols that are directly related to what is necessary for the children's learning and understanding at that particular moment, and ideally builds upon the children's present knowledge.

Freudenthal (1991) used the term “instruction experiment” to refer to a research design that includes an instructional sequence that is meant to broaden the children’s insight into a particular mathematical construct, while it, at the same time, provides the researchers with a greater understanding of the children’s learning processes. The aim of developing such an instruction experiment, then, is not necessarily to conclude *that* the instructional sequences teaches the children about a particular mathematical construct, but more to come to an analysis about *how* this instructional sequence may or may not have stimulated the children’s thinking (Gravemeijer et al., 2003).

Theory development in design research concerns the generation of local instruction theories (Gravemeijer, 1994). This theory is a learning trajectory based on mathematical, psychological, and didactical insights about how researchers expect the children to progress towards an aspired level of reasoning. In practice, it encompasses an instructional sequence, a description of the coinciding learning processes, a description of the classroom culture, and an analysis of the proactive role of the teacher. The progression should take into account both the cognitive development of the individual students, as well as the social context (i.e., the people involved, classroom culture, and type of instruction) in which the instruction experiment is to take place (Cobb & Yackel, 1996). This implies that the outcomes of the research should not be generalised beyond this particular setting. Instead, the local instruction theory is intended to inspire researchers to implement the instruction experiment in other settings as a way to evaluate the local instruction theory and contribute to the development of a more encompassing theory.

The cyclical process that characterises design research is illustrated in Figure 1. To come to a local instruction theory, researchers define a hypothetical learning trajectory that shapes the design of each instructional activity in the instructional sequence (Simon, 1995). Researchers then implement an instructional sequence in an “instruction experiment,” perform retrospective analyses on the transcripts from these lessons, adjust the hypothetical learning trajectory accordingly during a “thought experiment,” and improve the instructional sequence to cohere with the amended hypotheses and conjectures about successful patterns and the ways to support them. Finally, the procedure is repeated by entering a new cycle of implementing the new instructional sequence and learning from the class-experiences during a thought experiment.

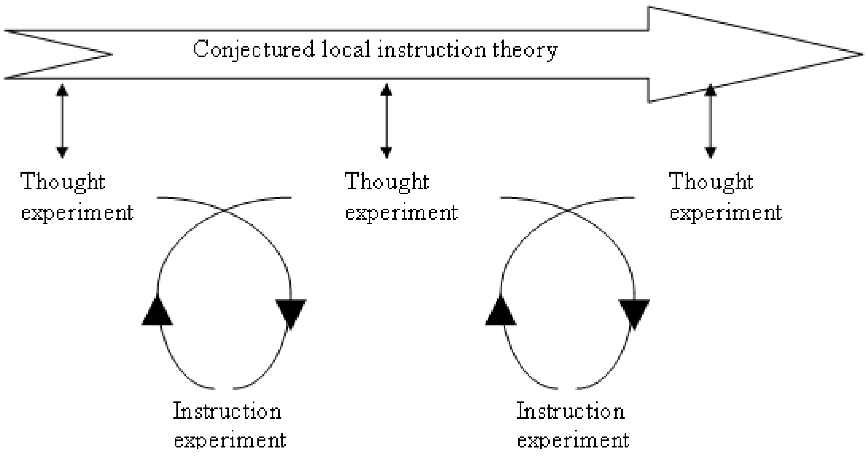


Figure 1. The cyclical procedure involved in design research (Gravemeijer, 2004).

The type of data that researchers collect in an instruction experiment should help them gain insight into behavioral patterns that may confirm or refute their hypotheses and contribute to answering the research questions (Gravemeijer & Cobb, 2006; Powell et al., 2003). However, the analysis of such qualitative data is usually more comprehensive than the statistical manipulation of quantitative data. The often large amounts of qualitative data have to be reduced and transcribed to become manageable before any analysis can take place. Strauss and Corbin (1998, p. 13) underlined the need to organise the raw data in qualitative data analysis, since the process of organising itself contributes to: (a) building rather than testing theory, (b) providing researchers with analytic tools for handling masses of raw data, (c) helping analysts to consider alternative meanings of phenomena, (d) being systematic and creative simultaneously, and (e) identifying, developing, and relating the concepts that are the building blocks of theory.

Given the small-scale and often exploratory type of studies in qualitative design research, it is also challenging to guarantee external validity of emerging (theoretical) conjectures (Jacobs et al., 1999). This is because qualitative analysis "draws on both critical and creative thinking" and relies on "the interplay between researchers and data" (Strauss & Corbin, 1998, p. 13). In theory, qualitative researchers may approach external validity by enlarging their pool of data, but in practice, the time-consuming data collection and analyses often place limits on the size to which the study can grow. Consequently, design researchers work towards more reliable results through, for example, triangulation, combining data sources and establishing the trackability of their conjectures (Gravemeijer & Cobb, 2006; Smaling, 1987). This requires an as thorough and exhaustive as possible documentation of the observations, considerations, decisions, and changes that the researchers make to the instructional sequence, to their conjectures, and, ultimately, to the local instruction theory, as they progress along the cycles of design research. In the section below, we suggest how such analyses may be enhanced through integrating Jacob et al.'s (1999) cyclical analytical model with Gravemeijer's (2004) cumulative cyclic process of design research.

Merging Two Models

Jacobs et al.'s (1999) cyclical analytical process (see Figure 2) integrates qualitative and quantitative approaches for the analysis of video data. This cyclical analytical process summarises how the researchers initially "watch and discuss" the videos and subsequently "generate hypotheses" about what they are discovering. Their goal is to ultimately "transform the video images into objective and verifiable information" (Jacobs et al., p. 718). Such video data allow for a unique iterative process of data analysis that otherwise depends on a complicated comparison of data that has to be collected linearly (Jacobs et al.).

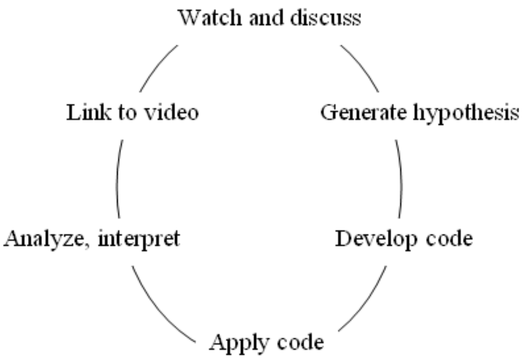


Figure 2. Model for the cyclical analytical process of analysing video data (Jacobs et al., 1999)

While Jacobs et al.'s (1999) model for the cyclical analytical process of analysing video data points to an iterative process of data analysis, Gravemeijer's (2004) model of design research analogously describes cumulative iterative cycles that illustrate the interaction between theory and practice. Both models focus on interaction as a way to propel the research towards a local instruction theory. Thus, we propose to embed the specific process of analysing video data as described by Jacobs et al.'s model (Figure 2) into the cyclical process of interpreting instruction experiments in light of the overall research objectives as described by Gravemeijer's cycles of design research (2004, Figure 1). The integrated model is depicted in Figure 3.

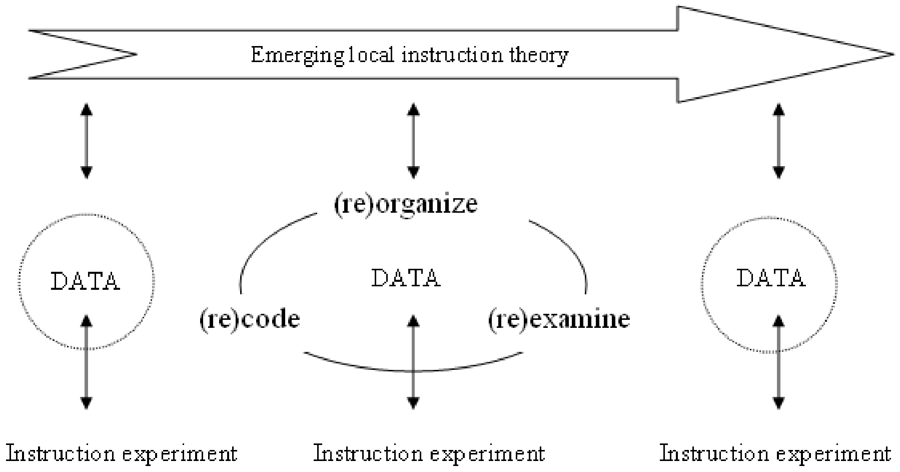


Figure 3. The proposed integration of Jacobs, Kawanaka, and Stigler's (1999) model for the cyclical analytical process of analysing video data into Gravemeijer's (2004) model of the cumulative cyclic process of design research.

The integrated model highlights the process of data analysis that occurs immediately after performing one instruction experiment and just before the start of the next instruction experiment in design research. In this phase, the data that is collected in the first instruction experiment is analysed and the patterns in the data are used to reassess the researcher's hypotheses, the design of the instruction experiment, and, ultimately, the emerging local instruction theory (Gravemeijer, 2004). This is how the model adheres to Gravemeijer's cycles of design research.

To describe the process of data analysis that occurs inbetween two instruction experiments at a more practical level, we turn to Jacobs et al.'s model (1999). The analysis of video data involves iterative cycles of organising, examining, and coding the data. This cyclical process contributes to the development of the overarching theory of the research by welcoming quantitative findings as a supplement for interpreting the results. This leads to new research questions and it helps to refine codes and locate footage that can support the researchers' conjectures (Jacobs et al.). In Gravemeijer's (2004) terms, such an overarching theory denotes the emerging local instruction theory in mathematics education research.

What links the two models in our proposed model together, then, is that the components that make up the data analysis procedure (organising, examining, and coding) are not only reflexively related, but can also feed into the emerging local instruction theory at any of the steps in the analysis. This interaction is what characterises the process of theory development in design research in mathematics education (Gravemeijer & Cobb, 2006). As such, the integrated model shows how Jacobs et al.'s (1999) analytical process for "watching, coding and analyzing the data, with the goal of transforming the video images into objective and verifiable information" (p. 718) can be applied to design research to enhance the value of conclusions that are drawn from it.

Analysing Raw Qualitative Data

The integration of the cyclical process of analysing video data as described by Jacobs et al. (1999) with the design research cycles as described by Gravemeijer (2004) provides more insight into the use of multimedia software analysis programs for elucidating the intricate and interactive process that is involved in generating questions and theories in analysing raw qualitative data from specifically design research in mathematics education. Powell et al. (2003) extensively reviewed literature on the role of videotape data in mathematics education research. This has led them to distinguish a sequence of seven interacting nonlinear phases in an analytical model for studying the development of learners' mathematical ideas. These are viewing the video data attentively, describing the data, identifying critical events, transcribing, coding, constructing a storyline, and composing the narrative (p. 413). Powell et al.'s analytical model for studying mathematical learning using video data recognises that research on the development of mathematical thinking "is not a linear, unidirectional process" (p. 432). Hence, the phases that they distinguish must be interpreted as a "cyclic and recursive process that requires multiple visits with data as well as collaborative exchanges with researchers with different analytical and theoretical foci" (p. 432). In this way, they suggest that the model may be "a step forward in developing an analytical approach using video data for observational investigations into the development of learners' mathematical ideas and forms of reasoning" (p. 432).

In contrast to how Jacobs et al. (1999) highlight the search for explanations and generating hypotheses, Powell et al. (2003) put a relatively greater accent on the search for patterns in the data. In support of Powell et al.'s model, we note that multimedia data analysis software is an important tool in design research for bridging observations from educational practice to theory. This advantage can be described in terms of several benefits. First, multimedia data analysis can relieve researchers of the *cognitive strain* that may be associated with trying to keep track of all the thoughts and observations that could be shaping the conjectures and contributing to the theory. ATLAS.ti can act as a mould for configuring and organising the often large amounts of raw qualitative data into quotations that mark critical events (Stigler et al., 2000). Once the first set of quotations is defined, the researchers can add comments to the quotations and create storylines with analytical notes. The researchers can tailor and subsequently amend the length of the quotations according to what seems to fit best for answering the original and emerging research questions. Subsequently, the researchers can refine the units of analysis and define codes to describe the quotations in any order and with any frequency that may be necessary for identifying the importance of the episode for the developing theory. The codes can further be combined into "families" as a way to organise their hierarchical structure.

After organising the raw video data into quotations with corresponding codes, the researcher can play a specific clip from the resulting list of quotations that are part of one particular video, look up the (network of) codes that are associated with the clip, and create outputs that summarise the details of the clip, the type and number of codes that are linked to the clip, or, more generally, the frequency with which particular codes are linked to the entire video. This video data may be supplemented with other data sources, such as scans from written student materials, which can be imported and coded in the program. Further, the researcher can define queries to search for specific patterns and frequencies in how the quotations are coded. These features of the program allow for the researcher to spiral into particular episodes as a means to generate theory in an organised way. The software helps to make the raw data more accessible for analysis because it supports the organisation of the raw data and correlated reflections and ideas of the researcher.

A second benefit of using a multimedia data analysis tool for video data analysis is that it can *supplement qualitative analyses with quantitative data*. The frequency counts for coding the quotations can become the subject of quantitative analyses (Jacobs et al., 1999). Although much of the data may be gathered according to qualitative research traditions, the frequency counts in the tool give it the potential to bridge with larger-scaled statistical analyses. Assuming that the data adheres to the strict conditions that are required for statistical procedures, the researcher can export the counts to other statistical software, run statistical analyses, and visually represent the outcomes. The outcomes of such quantitative analyses can then be interpreted and linked back to the videos to reintegrate the quantitative findings with the qualitative interpretations.

Next to organising the raw data and making it accessible to both qualitative and quantitative analyses, a third benefit of using multimedia data analysis software is that it can help to *improve the trackability* of inferences that are drawn in the data analyses. The quotations, for instance, are convenient to refer to when discussing conjectures or conclusions with others (Stigler et al., 2000). They make it easier to transcribe and present particular instances of one video or of a combination of data sources to illustrate one specific inference or to find patterns in the data. The researcher can also make reference to specific quotations and codes while communicating the analyses in a presentation or a written report. This makes it accessible and attractive for others to trace the researchers' argumentation. This makes it convenient to share the raw data with colleagues and to, for example, determine interrater reliabilities by comparing how each researcher segmented the videos and defined and assigned the codes to the quotations.

Taking these three benefits of multimedia data analysis software outlined above together, it becomes clear that working with such a tool contributes to theory generation and validation for theory development in design research. This relates to an essential interaction between the qualitative data and the analyses that shape conjectures about data. In what follows, we describe two research projects that put the integrated model into practice and that illustrate the role of multimedia data analysis software ATLAS.ti in theory development of design research.

The Role of ATLAS.ti in Two Research Projects

In this paper, we make use of two examples of design research to illustrate the role of multimedia data analysis software in developing a local instruction theory. Both examples involve an instruction experiment that is designed to inspire, test, and retest hypothetical learning trajectories about how the children are expected to acquire a particular mathematical construct as they work through the instructional sequence. The hypothetical learning trajectories that coincide with this instructional sequence ultimately contribute to the development of a local instruction theory. Hence, the aspired outcome of the instruction experiment in each project is a local instruction theory that contributes to insight into the learning processes of children in a particular setting and for a particular mathematical construct.

The MENS Project

The first example is the Mathematics Education and Neurosciences (MENS) project. This is an interdisciplinary investigation into the development of spatial thinking and number sense of young children (Van Nes & De Lange, 2007; Van Nes & Doorman, 2006, 2009). We turn in this paper to the mathematics education component of the project. The researchers are building upon studies by Battista and Clements (1996) and Battista, Clements, Arnoff, Battista, and Van Auken Borrow (1998) as well as by Mulligan, Mitchelmore, and Prescott (2005), and Mulligan, Mitchelmore, Martson, Highfield, and Kemp (2008), which have highlighted the importance of spatial structuring for the development of early mathematical abilities. Examples of spatial structures that are considered relevant to the development of kindergartners' mathematical abilities are finger patterns and domino-dot configurations. It is essential for children to gain insight into spatial structures so that they can learn to abbreviate basic numerical procedures and to develop more sophisticated numerical strategies (Anghileri, 1989; Van Eerde, 1996). Hence, the main conjecture is that children's early insight into and use of spatial structures can stimulate the development of their emerging numerical abilities. This conjecture is supported by studies showing how children with numerical difficulties often do not develop counting strategies beyond unitary counting procedures (Mulligan et al., 2005; Pitta-Pantazi, Gray, & Christou, 2004).

To gain insight into how kindergartners' spatial structuring ability may be related to their emerging number sense, the researchers designed an instructional sequence to better understand how kindergartners can be encouraged to abbreviate numerical procedures by recognising and making use of spatial structures. This sequence consisted of five lessons that were implemented in two subsequent rounds in the instruction experiments after the first and before the second interview. The aim of this instruction experiment was to (a) better understand how children learn to make use of spatial structures to abbreviate mathematical procedures, and (b) highlight ways to amend the instructional sequence so that the activities in the lessons interweave with children's level of mathematical understanding and promote spatial structuring to support kindergartners' number sense. After performing the first round, the researchers analysed the instructional setting, adjusted the instructional sequence accordingly, and tried out the revised instructional sequence in the second round.

The children were video-taped during the interviews and the classroom instruction activities. This resulted in a total of almost 50 hours of video recordings. Hence, the first challenge for the researchers was to organise this raw data into a format that would help make sense of how the children were solving the problems; how the children were developing in their understanding; how the researcher, the teachers, and the instructional activities had played a role in this development; and how proactive individual and classroom instruction could ultimately support the children's learning. We will discuss how the multimedia data analysis program ATLAS.ti provides a format that proved to be essential for organising and making sense of all the data.

The ToolUse Project

The second example that we discuss in this paper is the ToolUse Project. The ToolUse project concerns the use of computer tools for grade 8 (13-14 years old) students' acquisition of the mathematical concept of function, in an effort to identify the relationship between the use of technological tools and the learning of mathematics (Drijvers et al., 2007).

As in the MENS project, the research design of the ToolUse Project involves a cyclic process of instructional design, instruction experiments, and data analysis (Gravemeijer, 2004). Teaching materials and a computer tool were developed in the design phase of the project. This computer tool, "AlgebraArrows," is meant to support the construction of input-output chains of operations. The applet is embedded in an electronic learning environment and the researchers, as well as the teacher, can monitor and compare the students' responses with class results. The activity of investigating this applet in pairs was expected to foster a learning process of "trial-and-improve" and "negotiation-of-meaning." During these investigations, students could find patterns and develop strategies while dealing with dynamic input-output dependencies. As such, the computer tool was expected to provide students with a means to structure inquiry about these input-output dependencies through constructing and modifying arrow chains and through generating and comparing argumentations. The aim of the project is to understand how computer tools can be integrated in an instructional sequence on the function concept so that their use can foster learning.

The instruction experiments were conducted with three grade 6 classes at three different schools. The children were video-taped during each teaching session and group work (17 hours), and screen videos of three pairs of students working with the computer were collected (6 hours). Students' final answers to the activities were saved on a central server (41 pairs of students). In addition, the researchers collected students' written work and the results of a written assessment at the end of the instruction experiment. The data was qualitatively analysed and coded using ATLAS.ti. Ultimately, the outcomes of this research may contribute to improving the instructional sequence and to preparing a second instruction experiment for finding empirical support for the conjectured process of teaching and learning of the function concept using computer tools.

Together, the analysis procedures in the MENS project and in the ToolUse project illustrate the cyclic process of data analysis and theory development that is inherent to design research. In what follows, we discuss how the analysis procedures in both projects benefited from the use of multimedia data analysis software.

Multimedia Data Analysis and Theory Development in the MENS and ToolUse Projects

The MENS project and the ToolUse project serve as illustrations for the benefits of using multimedia data analysis software that we described above: organising the raw qualitative data, contributing to the reliability of the research, and making the data more accessible to others. This has supported both projects' theory development and it embodies the integrated model that was proposed in the section regarding the analysis of the qualitative data. Despite this convenient use of ATLAS.ti as a tool to organise the raw data, it took the researchers in both projects a considerable amount of time that should not be ignored. We will reflect on this complication in the conclusion of this paper.

Organising Data

For the analyses of the instructional sequence in the MENS project, the researchers created quotations of any events and occurrences that would give them indications of (a) how the children were learning from the instructional setting, or, otherwise, why no learning occurred, (b) how the teacher was guiding the lesson and stimulating the children's learning, (c) what revisions would be necessary to improve the instructional setting, and (d) any instances that could contradict the hypothesis, to control for any self-fulfilling prophecies. As the researchers spent more time watching and discussing the quotations, the quotations became increasingly more refined to highlight one particular aspect of an instructional activity or an interesting remark or expression.

In the process of creating the quotations of the instruction experiment, it initially seemed most useful to code the quotations with the names of the people who were involved. In this way, each of the quotations could be identified according to who was involved in that particular event. As the researchers were discussing the quotations, however, they realised that, although this was a useful way of organising the complex raw data, it hampered the generation and validation of theory. This is because separating the output into each individual gave the false impression that insight into the children's learning processes required only data from separate individuals. One important component of a local instruction theory, however, is a description of the overarching instructional setting, which includes not only the individual children, but also the teacher, the instructional activity and materials, and the interaction between the children (Cobb & Yackel, 1996).

The researchers' second approach to organising the raw data took more of the social setting of the instruction experiment into account. The codes were still pre-categorised into "child," "teacher," and "researcher," but within these categories, the coding occurred more inductively; as the researchers were observing the quotations, they analysed the situations against the background of the research questions, and defined codes that could encompass the notable events that they were flagging. An example of such a code is "teacher: makes external link," indicating that the teacher made reference to, for instance, a spatial structure that the class had discussed in a previous activity. Another example is "child: overt moment of insight," which refers to an "aha-moment" when a child explicitly communicates a new understanding.

The inductive and reflexive process of watching the videos and defining relevant codes illustrates the interaction that is key to theory development in design research (Gravemeijer et al., 2003). This interaction is also central to Powell et al.'s (2003) analytical model for studying mathematical learning, as well as Jacobs et al.'s (1999) cyclical analytical model for data analysis. As the researchers in the MENS project were analysing each quotation, defining relevant codes, applying the codes to the quotations, and sometimes redefining the codes, they developed a list that was as exhaustive as possible to encompass the behavioural patterns that the researchers conjectured to be essential for attaining the research objectives.

Yet, this thorough organisation of the raw data into quotations with codes still marks only the beginning of the analytical process. During the coding phase, the researchers were also discussing the relative contribution of the codes for answering the research questions. From these discussions it became apparent that some codes deserved more attention than other codes. For example, the code for "child: uses spatial structuring" is more relevant to the research than the code for "child: is distracted." At the same time, the discussions about the relative contributions of the codes led the researchers to begin to use memos as a way of keeping track of their thoughts and reasoning. An example of a memo is "a missed chance," where the researchers noted that the teacher seemed to have missed the opportunity to stimulate the child in a particular quotation.

As more and more memos were added to the list, there also emerged relative differences in the types of memos that were defined. Not only could the researchers relate and physically connect more memos to individual quotations, they could also connect more memos to other memos. Groups of memos inspired the researchers to think about memos at a higher, more theoretical level. A diagram of this network helped to define and focus on the physical and theoretical connections between clips and conjectures that emerged during the process of organising and making sense of the data (see Figure 4). The network not only physically pictured the codes that were linked to a quotation (i.e., nodes with connecting lines), but also sometimes made the nature of the link apparent. A code such as “C: Focusgroup,” concerning a child (“C”) from the focus group, was connected to a code such as “C: Grade 2” by the summarising link “is part of.”

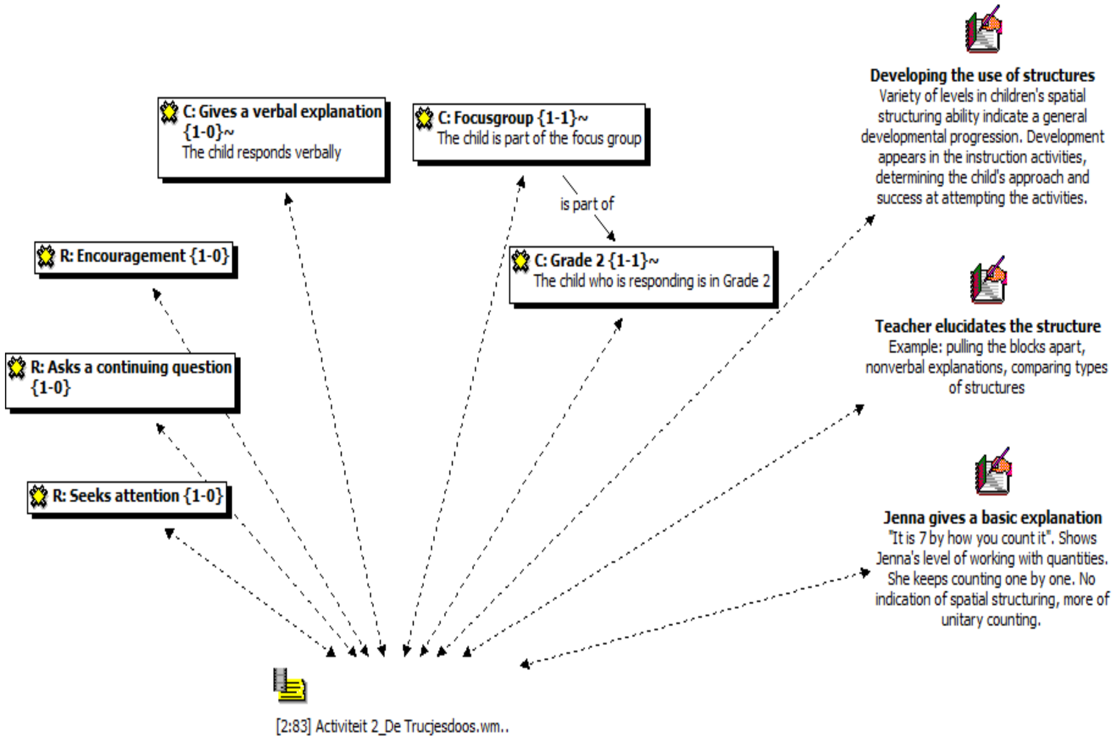


Figure 4. An example of a network of nodes picturing the codes, theory-type, memo-type, and commentary-type memos that are attached to quotation 2:83.

To denote the differences between types of memos, the researchers redefined the memos into a hierarchical structure of *commentaries*, *memos*, and *theories*. Most of the memos became commentaries, which were defined as incidental observations that may be interesting for theory development, but that were linked to only one particular observation (i.e. one quotation). A commentary in Figure 4 is "Jenna gives a basic explanation." This refers to a particular child who, on one occasion (i.e., this quotation), seemed more focused on unitary counting rather than on structuring.

One type of memo above commentaries is memos in the broader sense of the term. These memos came to denote episodes that can directly be related to children's spatial structuring and the role of the instructional sequence, which may provide essential clues for theory development. An example of a memo is "Teacher elucidates the structure," alluding to the role of the teacher in stimulating children's insight into spatial structures. Higher up in the hierarchy are theories, which are general impressions based on the memos and commentaries that could contribute to the final theory development. An example of such a theory is "developing the use of structures," which is a collection of factors (e.g., the teacher asking children to explain their strategy to others, having the children compare a familiar structure to an unfamiliar structure that represents the same quantity) that the researchers found to appear to be important for stimulating the children's learning in this particular instructional setting. The networks that the researchers were able to make in ATLAS.ti with connections between and within theories, memos, commentaries, and codes are what contributed to reaching the top of the hierarchy in analysing this data, namely a local instruction theory about the children's spatial structuring ability and the role of the instructional sequence in stimulating this ability.

Similar to the organisation process in the MENS Project, the codes in the ToolUse project were initially used to browse through the data and to correlate events with the other data sources in ATLAS.ti. First, the data from the ToolUse project – screen videos, photocopies of written work, and screenshots of students' computer activities – were imported into ATLAS.ti. The units of analysis for the clipping of the videos into quotations were the exercises that the students did. The quotations in the ToolUse project were then coded with the number that corresponded to the activity and the names of the student. The researchers started the analysis by watching and annotating the work of one pair of students, Lisa and Romy. They first gave a short description of the quotation using the comment tool and additional analytical notes. These notes then guided the description of a storyline about Lisa and Romy's learning processes in terms of the learning environment and the relation between tool use and mathematical development (e.g., Kieran & Drijvers, 2006; Doorman & Gravemeijer, 2009).

Reliability of Data Reduction

One way in which ATLAS.ti played an important role in contributing to the reliability of the MENS and ToolUse projects was allowing the researchers to supplement the qualitative data with quantitative output and compare the strategies within and across different groups of children. This enriched the qualitative description of children's and students' strategies in both projects. The quantitative output provided supporting evidence and more inspiration for spurring on qualitative analyses.

The contribution of quantitative output to the qualitative data exemplifies Jacobs et al.'s (1999) cyclical analytical process of coding and analysing video data. After coding and analysing the videos qualitatively, the researchers analysed the frequency counts quantitatively. The researchers could then interpret the frequency patterns in light of the behavioural patterns that emerged out of their qualitative analyses. This concluded one cycle of Jacobs et al.'s analytical process. Yet, at the same time it motivated the next cycle because the quantitative outcomes gave rise to more research questions that could again be investigated qualitatively.

Trackability

In both the MENS and the ToolUse projects, the ATLAS.ti unit that contained all the quotations, comments, and codes of the interviews was shared amongst project members. The procedure for discussing the results from the data analysis was convenient and clear because each quotation isolated one question or activity that could be analysed separately from the rest of the interview. The discussions helped the project members to come to a consensus about the types of strategies that the students used to solve the tasks and about the validity and reliability of the instrument itself. This interaction contributed to adjusting and improving the classification of the typification of strategies and emerging conjectures concerning the learning processes.

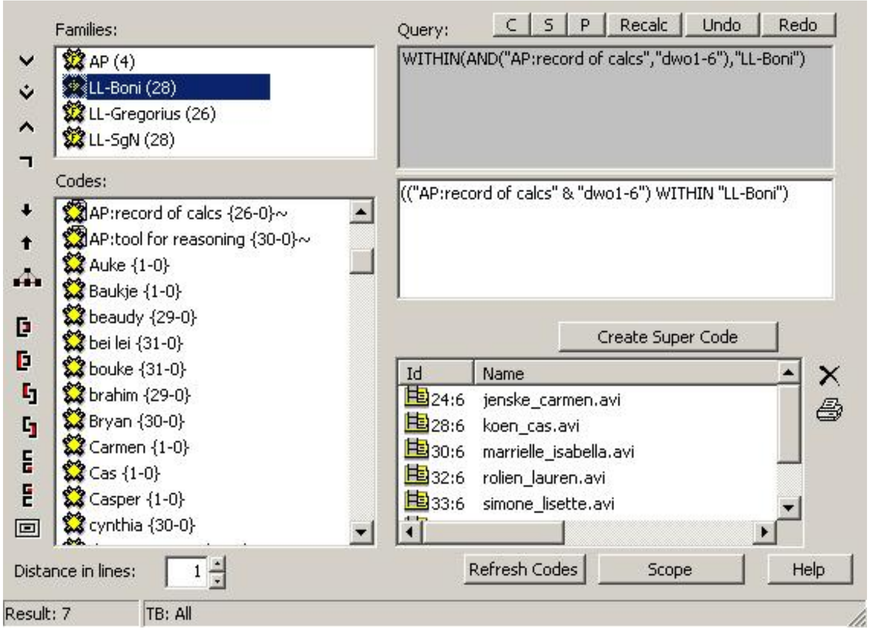
In analysing the instruction experiment, it was helpful for the researchers to be able to report on conjectured patterns in the teaching and learning processes while making direct reference to specific quotations that provided supporting evidence. In this way, project members could understand the reasoning behind a conjecture, examine the relevant quotations and judge the value of the clip or a code as representative of the pattern. The acceptances, refutations, and subsequent amendments to these conjectures were fundamental to the theory building process. This is what lead to defining the commentaries, memos, theories, and, finally, preliminary indications for local instruction theories. This process of negotiation illustrates the interaction that is involved in analysing qualitative data in design research.

Organised, Reliable, and Trackable Data for Developing Theory

To understand the children's learning processes during the instruction experiment of the MENS project, it was important to grasp the behavioral patterns that occurred as the lessons progressed. The network of codes, the different types of memos, and the query tool in ATLAS.ti were tools that proved to be essential for elucidating the effects of the instructional sequence and the role played by the interaction between the teacher and the children as well as amongst the children. The use of ATLAS.ti helped the researchers in the MENS project to cultivate the interaction between watching the data and evaluating their conjectures. The outcome of one interactive cycle stimulated subsequent cycles of analysis that refined coding systems and further identified parts of the video that best illustrate particular findings. For analysing the instruction experiment, the process of coding and recoding each of the quotations and building a hierarchy of commentaries, memos, and theories made gradually more accessible those behavioural patterns that contributed to the development of a local instruction theory about young children's spatial structuring.

In the ToolUse-project, the researchers initially analysed the work of two students qualitatively. The idea was that emerging conjectures could be tested quantitatively using corresponding codes and the clipped data. The two students were expected to use calculation chains in their reasoning about input-output-dependencies, and this reasoning was thought to change to the use of tables and graphs as basic structuring elements. In line with the premises of realistic mathematics education, these expectations were based upon the idea of emergent modeling. One of the key aspects of emergent modeling is the development of a *model of* a particular situation into a *model for* ways of mathematical reasoning about situations in general (Gravemeijer, 2004). From analysing the successive lessons during which the two students were provided with one tool, it appeared that the manifestation of the input-output chain itself did not change, but, instead, that the function of the representation changed. As such, the focus of reasoning in the model shifted from individual calculations to dependency relationships and dynamic processes.

One outcome of this analysis was that the principle of a form-function-shift (Saxe, 2002) could describe what happened in the learning process of the two students. The articulation of this shift appeared to be helpful for differentiating phases in the learning process with codes and for identifying two illustrative items among the activities. The researchers characterised different solution strategies using the form-function-shift to construct codes for these items (i.e. from "a record for calculations" to "as a tool for reasoning"). The solutions of all the students were coded to investigate patterns in these solutions and to find quantitative backing for the emerging conjecture. During this coding process, the researchers discussed several individual cases to fine-tune the code definitions and their interpretations of the codes. The query tool of ATLAS.ti could then be used to make an inventory of and to count strategy codes. With that tool it was possible to see which students from a specific class used a code at a specific activity (see Figure 5).



Query: WITHIN(AND("AP:record of calcs","dwo1-6"),"LL-Boni")

(("AP:record of calcs" & "dwo1-6") WITHIN "LL-Boni")

Id	Name
24:6	jenske_carmen.avi
28:6	koen_cas.avi
30:6	marrielle_isabella.avi
32:6	rolien_lauren.avi
33:6	simone_lisette.avi

Distance in lines: 1

Result: 7 TB: All

Figure 5. An example of a query that shows that 7 students from class "LL-Boni" were coded "AP:record of calcs" at activity "dwo1-6."

The analysis offered quantitative evidence for the conjecture of a shift in the students' reasoning with the computer tool (Doorman et al., in press). This example illustrates how the researchers could analyse individual processes as well as check their emerging conjectures quantitatively against the work of all the other students.

Conclusion

The MENS and the ToolUse projects that we presented in this paper illustrate three ways in which multimedia data analysis software such as ATLAS.ti can contribute to cultivating the interaction that is inherent to the analysis of qualitative design research data for the development of a local instruction theory. First, the organisation of the data itself helps researchers to explore the data and consequently begin to build a network of commentaries, memos, and theories that can contribute to outlining a local instruction theory. Second, supplementing the qualitative data with quantitative counts can help to reevaluate initial conjectures and support the reliability of the research. Third, the organisation of the data as well as the documentation of ongoing analyses stimulates researchers into discussing the data with others as a means to ensure the trackability of the data. Hence, the process of organising the raw qualitative data in a multimedia data analysis program contributes to more than just organised, and therefore manageable, data analysis. Rather, it fundaments the quality of the research and supports the interaction that is necessary to reevaluate researchers' initial conjectures towards developing the local instruction theory. This enhances the objectivity and verifiability of the research.

Both the MENS and the ToolUse projects show how organising the data into manageable quotations greatly supported the theory development. The multimedia data analysis in the MENS project exemplifies the generation of theory about how young children develop spatial structuring ability and how this ability may be stimulated in an instructional setting. The ToolUse Project shows how its theoretical framework was developed through simultaneously analysing the video clips of a pair of students and testing emerging conjectures about these clips against the solutions of all the other students.

The researchers in both projects organised the data of instruction experiments into coded quotations. This triggered the notation of memos, which subsequently inspired the definition of specific commentaries, new memos, and broader theories. Further, the counts of codes and quotations that resulted from this contributed to improving the reliability of the qualitative analyses. The trackability of the research was also supported by how conveniently the researchers could present and discuss their findings and conjectures by making reference to the quotations, the codes, the different types of memos, and the network views.

The two projects bring into practice the integrated model that we proposed earlier in this paper. The interaction between data and analysis, which holds Jacobs et al.'s (1999) and Gravemeijer's (2004) models together and which propels the research towards the development of an overarching local instruction theory, can be recognised on two levels in both projects.

First, the interaction between the raw video data and the coding procedure as described in Jacobs et al.'s model is illustrated by how the researchers coded the quotations for the instruction experiment inductively and amended the code book as necessary, depending on further observations of the quotations and discussions with project members.

On a second level, with regard to Gravemeijer's (2004) model, the interaction between the students' responses to the first instruction experiment, the adjustments to the researchers' conjectures about the learning processes, and the successive instruction experiments, is what ultimately contributed to the development of the local instruction theory in both projects. Importantly, however, the two levels of analysis (i.e., at the level of data and at the level of the instruction experiment) are interwoven in that the coding of the data at a more practical level fundaments the interpretation of the students' responses to the instruction experiment at a more theoretical level. This, in turn, influences the researchers' conjectures about students' learning processes. As such, the two models lend themselves to being integrated into a more encompassing model of theory development in design research.

Despite the benefits of using multimedia data analysis software for qualitative design research, it is important to note that an enormous amount of time is needed for all the work that is involved in clipping the videos into quotations, organising the clips, and developing hypotheses and theories about the data. In addition, it is important for researchers to realise that the data input in a multimedia data analysis tool will not result in a theory output that is a clear-cut answer to the research questions. Instead, the benefits of using a multimedia data analysis tool such as ATLAS.ti depend on the amount of effort that researchers choose to put into the process of data analysis. Hence, researchers must keep a balance between the (sometimes tedious) time within which the research has to be completed and the time that must be invested in organising the data.

In this paper we have presented two case studies that show how the benefits of using multimedia data analysis software extend beyond merely simplifying the complex process of collecting, coding, and analysing raw qualitative data. If care is taken to balance the amount of effort that is spent organising the data with the time that is left available for actually interpreting the data, such software can serve as a valuable tool for cultivating the interaction, essential to theory development in design research, between watching the videos and evaluating conjectures. We have proposed an integrated model that may help mathematics education researchers optimise the complex process of analysing qualitative design research data for the benefit of developing a thorough, reliable, and well-founded local instruction theory.

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