Facilitating Design Research by Mapping Design Research Trajectories

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Abstract: Design research is an emerging paradigm in the study of learning. It is far from a mature methodology, as it faces a variety of difficulties, one of which is the characterization of the research process. We mapped the design trajectory proposed by Sandoval to capture the complex process of design research. The design trajectory map develops Sandoval's conjecture mapping in two ways, with the capacity to capture movement along the trajectory. We apply the proposed mapping to a well-known design study that described the design history of an inquiry-based learning project. The limitations of the proposed mapping approach are discussed.

Introduction

Sandoval (2004, 2014) proposed *embodied conjecture* and developed the technique of *conjecture mapping*. An embodied conjecture specifies how theoretically derived conjectures about how learning occurs can be reified as a concrete design in a learning environment. The technique of conjecture mapping involves the visual representation of conjectures about how design elements are predicted to bring about the desired learning outcomes. Continuous evaluation of the enactment of the design results in the refinement of the conjectures, which serves to develop theories of learning. The evolution of conjectures about learning theories during the various iterations in a design-based study constitutes the design research trajectory. In other words, conjecture maps that represent the evolution of conjectures document the design research trajectory.

The goal of this paper is to further develop conjecture mapping in two ways. First, design research requires not only the *proposing* of conjectures about how a design will work, but also the testing of these conjectures. Sandoval's conjecture mapping (Sandoval, 2014) acknowledged the need for testing conjectures, but to date has not represented this in a conjecture map. A sequence of conjecture maps along a timeline represents the design research trajectory, but does not evaluate the result of the conjectured mechanisms. Nevertheless, the evolution of conjectures results from testing them. We propose that the extent to which the predicted relationships between design elements and outcomes are observed during testing should also be mapped to provide a more comprehensive documentation of the design research trajectory, and to present how the conjectured learning theories are empirically supported. We developed a technique with such a capability by mapping the evolving degree to which the conjecture relationship is achieved. We hope that this attempt addresses Sandoval's (2014) concern that "the current formulation of conjecture maps does not easily capture movement along a research trajectory" (p. 34). Second, in the mapping, we addressed the challenges observed in a design's implementation by taking into account the role of conjectures in informing potential refinements of the design, thus further enriching the conceptualization of the design research trajectory.

In the next section we describe the components of the design research trajectory to be mapped. Guidelines for the mapping are then provided and applied to a seminal report on design research (Edelson, Gordin, & Pea, 1999), which examined an early attempt to use scientific visualization technologies in high-school earth science courses. Although this is not a *recent* design study, it remains valuable because of the number of iterations involved and the amount of detail reported regarding the design decisions. What can be gained from the mapping is then discussed.

Mapping the Design Research Trajectory

Documentation of the Design Research Trajectory

In the design research trajectory, the design is implemented in a targeted context: researchers monitor how the design works in that context and make decisions to revise, modify, and refine the design to achieve the desired outcomes. In this trajectory, knowledge relevant to the design, context, and learning is developed. Documentation of the design research trajectory is suggested by researchers to show the "trace of the decision making" (Joseph, Bryk, Bransford, Gomez, & the Information Infrastructure Project, 2003). This practice is intended not only to guide communication and coordination across the contexts of different studies, but also to allow research audiences to evaluate the credibility of design decisions and the quality of lessons learned from the research (Collins, Joseph, & Bielaczyc, 2004; Joseph, 2004). In addition, documentation of the evolution of design ideas and the underlying rationale may inform the broader community's understanding of the research process, which is essential for distinguishing educational design research from educational design (McKenney, Reeves, & Herrington, 2012).

Documentation of the design research trajectory needs to be based on a thorough understanding of the features of design research. Design research involves continuous evaluations (Edelson, 2002) and iterative refinements (Collins et al., 2004), so a sequence of evolving maps that represent the evaluation results of the conjectured components could be used to document the design research trajectory. Each map represents the evaluation result of a particular phase in the research. The sequence of evolving maps aims to document the longitudinal process of design, enactment, and refinement, which responds to Sandoval's (2014) call for capturing movement along the research trajectory. This documentation of the longitudinal process is required for design research, because recent instructional research has illustrated the fluid and non-linear nature of educational design processes.

As both conjecture development and conjecture testing are involved in design research, mapping the conjectures and the evaluation results is needed to represent the design research trajectory. Sandoval's (2004, 2014) work addressed the mapping of conjectures, whereas our focus is on the mapping of evaluation results. Combining the maps of Sandoval (2014) with those proposed here for the same research would produce a more comprehensive representation of the design research trajectory.

Components in the Trajectory to Be Mapped

Previous attempts to document the design research trajectory have addressed different features of the design research process (Barab et al., 2002; Collins et al., 2004). These attempts did not adequately link the processes of enactment to outcomes, which may impede the development of theories that explain why a design succeeds or fails in supporting learning (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Design-Based Research Collective, 2003). Sandoval (2004) proposed the idea of embodied conjecture, and argued that developing a conjecture map would facilitate the refinement of the conjectures to develop learning theories that explain how a design brings about learning outcomes. The conjecture map consists of design elements, intermediate outcomes, and intervention outcomes. Intervention outcomes refer to the "typical sort of outcomes that psychologists look for, like whether students learn what they are intended to learn" and intermediate outcomes refer to "observable patterns of behavior predicted by a model of how an embodied conjecture functions to support learning" (p. 215). Observation of intermediate outcomes in the enactment of a design is the basis of the achievement of intervention outcomes. If an intervention outcome is not observed, then this suggests that some intermediate outcome may be absent in the enactment.

Predicted relationships between design elements and intermediate outcomes, and between intermediate outcomes and intervention outcomes, are mapped to specify how the conjectures are embodied within the learning environment to support learning. Sandoval (2014) further developed the technique to capture the longitudinal progress of design and enactment from his earlier work (Sandoval, 2004), in which the components of the conjecture map were represented statically rather than being updated as the enactment proceeded.

Sandoval's conjecture map articulates the links among particular interactions between design elements and mediating processes (intermediate outcomes), and between mediating processes and intervention outcomes. That is, the conjecture map represents a hypothesized set of causal links specifying all of the intermediate outcomes that each particular design element is predicted to bring about, and all of the intervention outcomes that each particular intermediate outcome is predicted to bring about. Moreover, these causal links also specify all of the predicted causes of each intermediate outcome or intervention outcome. As the design is evaluated indirectly through its predicted impacts on the intermediate and intervention outcomes, the specification of the causal links in the conjecture map enables researchers to retrospectively identify the weaknesses of a particular design element when a predicted outcome is not observed after implementation. This may facilitate the iterative refinement of the design.

The components addressed in the conjecture map articulate some salient features of the design research trajectory. However, considering the features of design research, we argue that *challenges* relating to preconditions and constraints in terms of realizing desired learning should also be mapped. Design research can be characterized as a process in which a designed product or artifact is placed in the context of its use to obtain feedback for further refinement. In the process of enactment, we should not expect that the designed intervention will promote the intended learning behavior and processes without encountering challenges. McKenney et al. (2012) suggest that in design research, constraints such as not being able to change standards or assessment methods and limited participant time should be taken into account when developing the design. In addition, as already mentioned, design research typically introduces an innovative learning environment with the expectation that students will change how they learn. This change may be even greater if students learn in a technology-enhanced learning environment that differs substantially from those that they experienced previously. These challenges may, as a result, block the achievement of intermediate and intervention outcomes. For the documentation of the design research trajectory to better inform design research, the challenges should not be overlooked when developing and evaluating conjectures, and thus should be incorporated in the map.

In addition, the design research trajectory involves both developing and evaluating conjectures. The extent to which the design produces the desired learning outcomes, as represented by the conjectures, should be mapped in the interest of refining the conjectures and the design. McKenney et al. (2012) reviewed existing models and frameworks depicting the design research process (Jonassen, Cernusca, & Ionas, 2007; Reinking & Bradley, 2008) and found that many consider problem characterization, design or development, and evaluation or empirical testing, as necessary phases. This seems to require documentation of the design research trajectory—a series of characterizations of each of the phases. It is not sufficient only to characterize how the designed learning environment is expected to support learning; it is also necessary to depict the results of the evaluation of its enactment. Doing this informs subsequent refinement of the design and the problem characterization, and results in updated conjectures about how the design would work in the context of use. Sandoval's conjecture maps specify how such conjectures evolve over the course of design research. However, although informed by evaluation of the enactment, the sequence of conjecture maps does not depict the results of that evaluation. Thus, maps representing the results of continuous evaluation complement conjecture maps in documenting the design research trajectory.

In considering the mapping presented here, we found it useful to draw on Sandoval's (2004, 2014) conjecture maps. This paper uses a series of maps to depict how the components and the links in the design research trajectory evolve. We highlight some of the features here to introduce the maps. In the next section, we demonstrate how the maps were developed, using a design research example for illustration.

Mapping the Design Research Trajectory: An Example

This section describes an example of mapping the design research trajectory. We briefly explain the selection of a design research study for analysis, and summarize that study, and then describe the resulting design research trajectory maps.

Construction of the Mapping

The construction of design research trajectory mapping involves identifying the components and determining whether and how the predicted relationships between the components as given by the conjecture are empirically supported.

Several features of the mapping should be highlighted. *A sequence of maps* is used to represent the longitudinal process by which the design and insights about it evolve. Each map in the sequence represents the results of evaluation of the conjectures in the corresponding phase of the design research. We found it useful to draw on Sandoval's (2004) conjecture maps when considering which components needed to be mapped; thus, each map shows design elements, challenges, intermediate outcomes, and intervention outcomes. The design elements in a map result either from the initial design and the underlying conjecture, or are added as a refinement to the original design. Intervention outcomes represent what students are intended to learn, such as conceptual understanding of subject matter (Sandoval, 2004). We also added the *challenges* existing between the design elements and the intermediate outcomes to show how the context of use may impede the achievement of intermediate outcomes. Challenges represent preconditions or barriers that make the targeted learning difficult to realize. They can be identified through teacher-implementers' comments on the instruction, researchers' reflection on the design, and students' reports on their learning and assessment results. Finally, we used different styles of arrows to indicate the extent to which a predicted relationship was achieved, representing the results of the evaluation of the conjectures. For example, arrows were used to show whether a particular design element contributed to address a particular challenge and the extent to which overcoming a particular challenge contributed to a particular intermediate outcome. In summary, the sequence of maps serves to document the design research trajectory with a focus on continuous evaluation during each phase of the design research for development and validation of the conjectures.

There is a lack of consensus on the rubric for determining to what extent a predicted relationship between two components is empirically supported based on the information in the research report. To exemplify the mapping, we propose the following guidelines. These guidelines are not intended to be universally applicable to design research or to fit best with the mapping for this research example. It is also noted that although the research example we analyzed here is one of only a few in design research that details the research trajectory, the information reported was still insufficient to determine the extent to which each link in the diagram is empirically supported.

To evaluate the extent to which the conjecture is confirmed, we developed four guidelines. (1) The extent to which a predicted relationship is achieved is determined by how this relationship is empirically supported. (2) Three levels are used to indicate the extent to which a predicted relationship is confirmed—"fully supported," "partially supported," and "unsupported"; these are represented in the map by a solid arrow, a dashed arrow, and a dash-and-dot arrow, respectively. (3) A relationship is designated as fully supported if it is considered to have no significant problems, as partially supported if it could be further improved or an improvement solution is in progress, and as unsupported if it is not observed. (4) The maps are read from left to right, such that the achievement of a left-hand component assumes achievement of the successive component to its right. In other words, if a left-hand component is not fully achieved and the component that is predicted to be achieved, this is indicated by an unsupported relationship between them unless specific information is provided.

The Study under Analysis

The literature contains a substantial number of studies purporting to be design research. However, many papers reported single case studies that do not involve iterative improvement of the design and the underlying conjectures (Krajcik et al., 1998; VanSledright, 2002). In other papers such refinements were reported, but these refinements were not always based on formative assessments of the design in its iterations (Bell, Hoadley, & Linn, 2004; Kolodner et al., 2003; Zhang, Scardamalia, Reeve, & Messina, 2009). For example, Zhang, Scardamalia, Reeve and Messina (2009) reported a post-hoc analysis of three successive social arrangements in students' on-line work with Knowledge Forum, implemented by the same teacher and with the same curriculum in three successive school years. Although this study provides important evidence of the effectiveness of each design, design changes were based on the teacher's satisfaction with each design, with empirical analyses being carried out later. Furthermore, most of the aforementioned papers in fact report on *research programs* consisting of multiple studies and publications. Findings may be reported in many articles without necessarily clearly discussing the relationship of the study to previous studies from the same research program, which makes the research trajectory difficult to understand. A succinct way in which to depict these connections thus seems necessary.

Edelson, Gordin and Pea (1999) did describe the relationships between their evidence, obtained from formative assessments and refinement-oriented decisions, although they did not report the details of the formative evaluations. We thus selected this study to illustrate the mapping procedures. Edelson et al. (1999) presented a design history of software and a curriculum that aimed to use scientific visualization technologies to support students' inquiry-based learning in geoscience. The researchers aimed to design a learning environment in which students could conduct authentic scientific inquiry as scientists in a laboratory. The topic of inquiry in the study was climatology (e.g., weather and global warming). Students worked on this topic by analyzing large collections of authentic quantitative data that were provided. The data were displayed in the form of rectangular arrays that used colors to represent ranges of numerical or categorical values, designated as scientific visualization. All of the data and tools for investigation were integrated in a designed software environment. Students were expected to investigate specific problems in this environment, through which process they achieved objectives such as general inquiry abilities, specific investigation skills, and the understanding of science concepts through participation. As the implementation of the design proceeded, challenges were recognized. The researchers iteratively refined the software and curriculum activities to address these challenges and to promote the desired outcomes. As a result, four versions of the design were developed and implemented, each constituting one phase of the research. Formative evaluation was conducted for each version. Accordingly, we may obtain evidence on the extent to which the design brought about the desired outcomes as conjectured in each of the four phases of the research.

Developing the Map

We highlight some of the features in the first phase of the research example and illustrate how the design trajectory can be mapped. In describing the mapping, we first introduce the components of the map, comprising design elements, challenges, and intermediate and intervention outcomes, and the predicted relationships between them. Thereafter, we map how these predicted relationships were achieved, as indicated by evaluating the design. As Sandoval (2014) devoted a paper to discussing the mapping of components in the design research trajectory, we provide more details here about mapping the evaluation of the predicted relationships.

The first version of the design was the Climate Visualizer (Gordin, Polman, & Pea, 1994). Figure 1 shows the map for the first phase of the research, read from left to right. Here, we focus on representing how the design would lead to the desired outcomes as conjectured. *Datasets* for inquiry in a data library related to weather information, a topic assumed to interest students, to address the challenge of *motivation* to engage in inquiry. A *supportive user-interface* was developed to address the challenge of *accessibility* of investigation techniques. Students were expected to *understand the techniques available* to them well, which would bring about the acquisition of *specific investigation skills* and an *understanding of the science content*. In addition, assuming that the students would have difficulty in planning, organizing, and coordinating the inquiry process, the researchers developed the Collaboratory Notebook to overcome the challenge of *managing extended activities* in inquiry-based learning. This environment was a *structured hypermedia environment*, in which students could plan and record their investigations, coordinate work efforts among collaborative teams, and receive feedback from teachers and mentors. *Technological effort* (e.g., software architecture) was made to address the *practical constraints* in the real classroom, such as available resources and fixed schedules. It was expected that by facilitating this, students could do better in *recording the process and products of the investigation*, which contributed to the improvement of their *general inquiry abilities*.

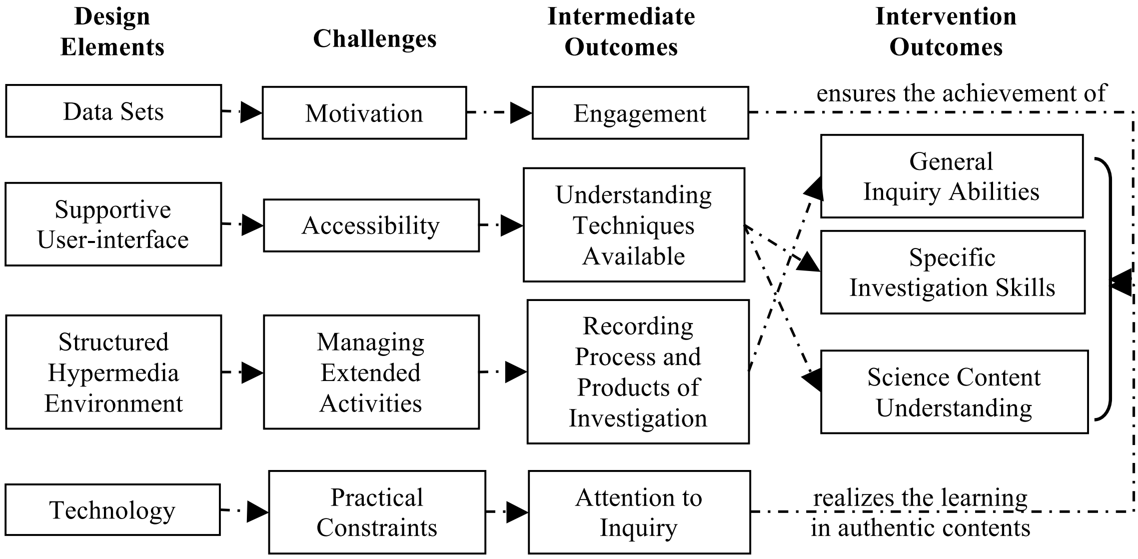

Figure1. Design trajectory map for the first version of the design in the research example

The first version of the design was reported to have "failed to provide teachers and students with an understanding of the full range of visualization techniques" (p. 410), and "failed to address student motivation" (p. 411). In addition, the software ran so slowly that it failed to draw students' attention to the inquiry itself, which was seen as "a practical failure to meet the constraints of the classroom" (p. 412). In other words, the link between the "datasets" as a "design element" and the "motivation" challenge, and the link between the "accessibility" as a "challenge" and the "understanding techniques available" as an "intermediate outcome," were both unsupported (dash-and-dot arrows).

The other relationships in the map were considered unsupported (dash-and-dot arrows) if their left-hand components were not achieved, unless specific information was provided. In general, insufficient information was provided in the original text of the research example, so that the map had to be developed literally according to the text. For example, information about whether the structured hypermedia environment addressed the challenge of managing extended activities was not presented in the paper. We thus assumed that in the first version of the design, all of the links between the components were not supported empirically, as no sufficiently specific information was provided.

Evolution of the Design Research Trajectory

The mapping of the first phase of the research shows that the predicted relationships between the design elements and outcomes were not well supported empirically. To address the potential problems observed, Edelson et al. (1999) made refinements to their conjectures, and developed second and third versions, the Radiation-Budget Visualizer and the Greenhouse Effect Visualizer (Gordin, Edelson, & Pea, 1995). Several design elements were revised, such as changing datasets to focus on more interesting topics, and the development of curricular activities.

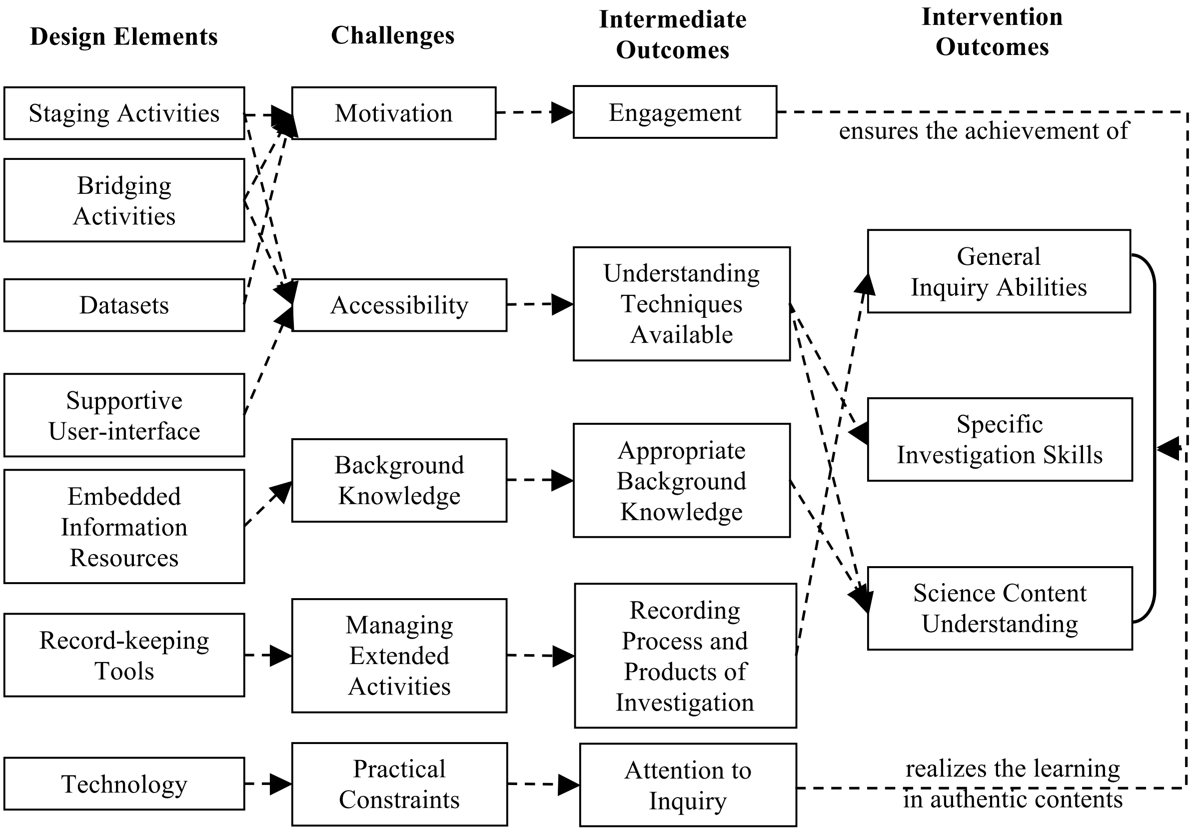

Figure 2. Design trajectory map for the fourth version of the design in the research example

To illustrate how the *mapping* represents the evolution of the design research trajectory, we describe the mapping for the fourth phase of the study. The fourth version of the design, WorldWatcher, further addressed the challenges through a series of attempts. The map of this phase is shown in Figure 2. We highlight the following features. First, the researchers expected that broadening the datasets, improving the user-interface, and introducing staging activities into the curriculum to motivate students to investigate a wider range of topics of interest could address the challenge of motivation. For example, the database was broadened to include datasets that supported a much broader range of investigations, which provided meaningful problems for students to inquire into. With this challenge addressed it was expected that students would engage in inquiry, which assumed the achievement of the desired learning objectives. Second, the design attempts in the previous phases of the study aimed at addressing the challenge of accessibility included improvement of the user-interface to help interpret the visualizations and the development of staging and bridging curriculum activities to allow the learning and practice of investigation techniques. For example, the staging activities provided a context within which students practiced using the techniques. The supportive interface, along with the specific operations in the software environment, provided students with access to powerful investigation techniques such as performing quantitative analyses of the data and viewing data in other visual representations. These attempts were expected to equip students with specific investigation skills, through the performance of which they would come to understand science content knowledge. Third, the researchers expected that the embedding of information resources and staging activities would alleviate the challenge of background knowledge for inquiry. Equipping students with appropriate background knowledge would help them to understand the science content knowledge. Fourth, the researchers provided various forms of record-keeping tools in the software and expected these to alleviate the challenge of managing extended activities. This made it possible to record the process and products of the investigations, which contributed to the learning of general inquiry abilities. Finally, the researchers aimed to improve the performance of the software to address the challenge of practical constraints, which would help realize learning in authentic contexts.

As reported, the challenges encountered in the enactment, such as motivation, accessibility, background knowledge, managing extended activities, and practical constraints, were not revealed as being as serious as those encountered in the enactment of the previous design. However, problems still existed, as seen from the researchers' observations and reports on the enactment. For example, students were observed to have difficulties with retaining sight of the overall inquiry context as they became involved in individual activities, which required reestablishing the motivating context. The information reported in the text was not sufficient to determine how each of the links between components was empirically supported, since "little formal evaluation has been conducted" (p. 438) on the uses of this version. Given that issues raised by classroom experiences existed and that this design was being revised, it seems more appropriate to consider the links in the map as partially supported (dashed arrows).

Looking at the maps of the first and the fourth phases as a sequence, we can observe a progression in the design and the conjectures. First, the conceptualization of the design research trajectory evolved. The components and relationships mapped conceptualize the design trajectory by showing the salient features of each design. As shown in the sequence of maps, components were added, modified, replaced, and refined, and the relationships between the components were revised and validated. As a result, these researchers obtained a better understanding of the interactions between the design and the context of its use. Second, the theoretical knowledge of why the designs succeeded or failed in promoting learning outcomes also evolved. The maps were intended to represent the extent to which the predicted relationships between the design and the desired outcomes were supported. The processes of enactment were thus linked to the outcomes, which is expected to permit theoretical knowledge to be developed concerning why the design succeeds or fails in supporting learning. As shown, each map represents the extent to which the conjectured theoretical knowledge was empirically supported in each phase. Thus the sequence of maps presents the way in which this theoretical knowledge developed in clarity and was validated. In summary, creating a sequence of maps, each representing the reality in one phase of the research, was helpful for documenting both the conceptualization of the design research trajectory and the development of theoretical knowledge.

Discussion

Sandoval (2004, 2014) proposed the idea of embodied conjecture and developed the technique of conjecture mapping. His conjecture maps document the evolution of conjectures about how design elements are predicted to work together to support learning over the course of design research. The components in the sequence of conjecture maps characterize the salient features of the design research trajectory that links the design elements to the processes of enactment and to the desired learning outcomes. Conjecture maps thus facilitate systematic design research and the development of learning theories. This paper draws primarily on the technique of conjecture mapping, but makes some revisions intended to enhance the role of the mapping in facilitating design research.

First, we mapped the extent to which the predicted relationships between the design and the desired outcomes were supported. This supplements Sandoval's conjecture maps, as not only were conjectures about how the design would work to support learning mapped, but also how these conjectures were empirically supported. This revision is expected to provide a more comprehensive representation of the design research trajectory. Second, we incorporated a challenge component between the design elements and the intermediate outcomes. This component reflects the role of constraints in the context of use in impeding the achievement of intermediate outcomes. We suggest that mapping the challenges would be helpful for informing the design and evaluation stages in design research. We agree with Sandoval (2014) that the conjecture map represents an argument. A sequence of conjecture maps visualizes the hypothesized causal processes that link a design to its outcomes. These causal links may enable researchers to "look forward," by reading from left to right, along the pathways from design elements to desired outcomes. In the maps in the present work, the representation of the extent to which such causal links were validated informed how success or failure in observing some outcome could be traced back to a particular design element, when read from right to left. This paper contributes to the development of the technique of conjecture mapping by including the capability of capturing the movement of the design along a research trajectory, thus documenting a more comprehensive design research trajectory.

We acknowledge that the work reported here needs further improvement. For example, the issue of determining the level of support for the conjectures remains to be addressed. Sandoval (2004) distinguished between design-oriented conjectures and theoretical conjectures. It is reasonable to assume that different definitions and different standards for level of support are required for these two types of conjecture, given the difference in nature between them. The rubrics for determining the level of support as presented also need further clarification. In addition, as the design trajectory maps were constructed based on post-hoc analysis of published work, it remains to be seen how such maps could be useful in guiding new iterative design research. Research on the practice of applying such mapping in new design research projects is necessary for the evaluation and refinement of the technique.

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