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Role of conjecture mapping in applying a game-based strategy towards a case library: a view from educational design research

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Abstract

Despite the prevalence of case-based reasoning in systems design, many of the established design principles are based on theory rather than empirical studies. This study describes the evolution of a case library learning environment and its transition to a game-based learning approach using educational design research (EDR). We discuss our iterative processes of design and development and situate these processes within the broader framework of educational design research. We discuss how the earlier versions of the problem-based learning environment were based on design principles extracted from case-based reasoning theory. Subsequent studies caused us to rethink the intersection of theory and design, along with its impact on learning outcomes. Using a variety of data collections (e.g. analytics, causal maps) and EDR strategies (e.g. conjecture maps), we identify the following new design principles based on CBR theory: emergent design principles that focused on optimal case length, mechanisms to prompt case retrieval and decision-making, and visual presentation. Implications for problem-based reasoning, case-based theory, and interface design are discussed.

Keywords Problem-based learning · Inquiry-based instruction · Problem-solving · Case-based reasoning · Design-based research · Case libraries · Contrasting cases

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Introduction and background

Proponents of problem-based learning (PBL) assert that learning should be an active process that allows learners to confront domain-specific problems (Hung 2015; Kim et al. 2017). According to case-based reasoning theory, as learners solve the cases posed in PBL, they develop a more robust set of knowledge structures that allow them to better transfer the lessons learned to new problems (Kolodner et al. 2005; Schank 1999). To date, a variety of technologies have been developed which embody the principles of PBL and support deep learning, including PBL modules embedded with question prompts or other scaffolds (Belland 2017).

An emerging PBL approach that has gained substantial interest is digital games-based learning (DGBL), whereby "characters' actions are directed toward a goal in the story" (Adams et al. 2012, p. 235). Indeed, interest in DGBL has been steadily growing (Hwang and Wu 2012). Research indicates that DGBL can promote positive learning and behavioral impact across a variety of learning domains, with empirical evidence suggesting promising outcomes in areas such as knowledge acquisition, understanding, affect, etc. (Hainey et al. 2016). In relation to PBL, Hung and Van Eck (2010) argue that games situate problem-solving within rich contexts, thereby providing meaningful opportunities for learners to apply domain knowledge. That is, games provide a context to overcome challenges, define roles, narrate backstories, and advance the storyline (Dickey 2005; Squire 2008). Within the game setting, learners can engage in decision-making and causal reasoning as they seek out a way to solve the presented problem. Moreover, games allow learners to iterate their problem-solving as they observe the outcomes of their decision-making (Gee 2007).

Given the emphasis on active learning in education, game-based learning has caused designers to rethink prior approaches to PBL and ways to engender case-based knowledge structures (Tang and Clariana 2017). The purpose of the current study is to describe how our team redesigned an existing problem-based learning module and supporting case libraries using a game-based approach. We begin with a discussion of our learning problem and the rationale to employ a case library strategy towards our design. We then explain the iterative processes of design and development that took place as we transitioned to a game-based approach and situate these processes within the broader framework of educational design research (McKenney and Reeves 2014). We present our design case as an educational design research (EDR) macro-cycle, comprised of three nested meso-cycles of analysis and exploration, design and construction, and evaluation and reflection. We especially highlight the role of conjecture maps to uncover design tensions and opportunities, which revealed new insights about the iterative nature of problem solving and the importance of case libraries. In particular, we discuss the principles that guided our design processes, describe how those principles are embodied in the design of our learning environment, and explain how the design principles evolved over time.

Problem-based learning

Modern theorists contend that learning is best achieved when individuals have the ability to learn materials within a context (Glazewski and Hmelo-Silver 2018; Kim et al. 2017). The contexts are often set within broader, ill-structured problems, for which no clear or direct solution exists. Instead, an individual must generate a solution through decision-making (Wilder 2015), causal reasoning (Eseryel et al. 2013), and argumentation (Jaakkola and Veermans 2018; Ju and Choi 2017) given the available perspectives and evidence. Rather than identifying a predefined "correct" answer, the challenge for learners is to generate the most viable solution that can be defended (Hemberger et al. 2017; Jonassen and Kim 2010). A PBL approach engages learners in problem representation and solution generation, in contrast to a lecture-based approach which dictates information to the learners. The belief is that the inquiry process of PBL allows learners to engage in questions they generate with their peers (Lazonder and Harmsen 2016). As learners discuss proposed solutions, they are able to identify discrepancies, negotiate new knowledge, and engage in meaning-making (Lucas et al. 2014; Lu and Chan 2015). Arguably, solving ill-structured problems allows learners to better retain congruent concepts given the relationship between ill-structured problems and meaningful contexts (Graesser et al. 2018; Hung 2015).

PBL is among the most prominent of classroom strategies that focus on ill-structured problems. Barrows (1986), a proponent of PBL, first proffered that medical education students lacked the reasoning skills requisite for clinical practice. In his original version of PBL, he argued that learning should be administered as follows:

- Focused on ill-structured problems,
- Curriculum around meaningful cases,
- Opportunities for peers to collaborate,
- Students are able to self-direct their learning,
- Teachers act as facilitators of student learning, and
- Teachers play an important role in reflection.

Although PBL was first implemented in a medical education context, it has been utilized in other domains, such as pre-service teacher education (Ertmer et al. 2014; Hmelo-Silver et al. 2009) and STEM education (Henry et al. 2012; Jonassen and Cho 2011).

Overcoming limitations of problem-based learning through case library scaffolds

Despite the espoused benefits of PBL, some have argued that learning new content while concurrently solving complex problems severely strains the limitations of working memory. They argue that this results in cognitive overload, which precludes meaningful learning and transfer (Jerrim et al. 2019; Kirschner et al. 2006). In consonance with such critiques, proponents of PBL hold that providing sufficient and appropriate scaffolding is imperative to support learners in their problem-solving

(Hmelo-Silver et al. 2007; Kim et al. 2017). Empirical studies suggest that when provided such scaffolding, learners are able to produce higher gains in terms of knowledge representation (Lazonder and Harmsen 2016), conceptual knowledge (Belland et al. 2015; Walker and Leary 2009), and collaborative problem-solving (Vogel et al. 2017).

The emergence of technology affords new mechanisms to support learners during problem-solving; for example, by means of embedded question prompts, pedagogical agents, and other techniques. While such approaches have been shown to be effective, they still may be limited in their ability to facilitate transfer when solving new problems. For example, learners may understand how to solve the problem at hand, but may struggle to apply those same lessons when solving new problems (Belland et al. 2015; Puntambekar and Hubscher 2005). That is, students become so focused on understanding the complexities of the immediate issue that they struggle to address the underlying structural characteristics across multiple contexts (Jonassen 2011a).

One way to better support transfer is by providing learners the opportunity to view an array of experiences accessible in a database as they solve problems, known as a case library. These case library learning environments are a database of experiences and use narratives of how others encountered relevant problems as a form of problematized scaffold (Tawfik and Kolodner 2016). This strategy is situated within case-based reasoning theory, which argues that learners retrieve and reuse similar cases when solving a new problem (Schank 1999). Although novices lack experience, the case library is embedded within the learning environment to bridge the experience gap. It is further argued that access to different cases exposes learners to multiple models, decision-making strategies, and causal reasoning paths (Jonassen 2011a). To date, a number of qualitative studies have explored how learners are supported with case libraries, with generally positive results (Bennett 2010; Ertmer and Koehler 2014; Kim and Hannafin 2011; Kolodner et al. 2003). Case-based reasoning (CBR) theorists argue that allowing learners to explore a concept across multiple contexts in case libraries allows learners to focus on the structural transfer of the concept, which better affords meaningful transfer when compared with other scaffolding strategies (Kolodner et al. 2004).

Methodology

This study seeks to address the following research question: How do the design principles of case-based reasoning theory impact learning outcomes associated with problem-based learning? Thus, the overarching goal of the learning environment described here, entitled *Nick's Dilemma* (described later), is to provide case libraries as a form of "vicarious memory" (Jonassen 2011b) so as to support learners in overcoming potential experiential gaps as they solve an ill-structured decision-making problem. The catalyst for the creation of the learning environment was a collaboration with an instructor in business education. Specifically, the instructor (who also served as subject matter expert; SME) indicated how he wanted to better prepare his junior/senior level University learners for the

types of ill-structured problems that they would encounter in domain practice. The SME also emphasized that he wanted to break the mentality of solving for the predefined right answer and instead focus on justifiable solutions. Although the SME had used various case studies in the past, he found them to be lacking in their ability to support transfer. That is, learners were focused on solving the problem, but were unable to postulate how the lessons could be applied when the problem space and/or context changed. Based on conversations with the SME, the design team identified a PBL approach as being congruent with identified learning needs.

The design and development of *Nick's Dilemma* was guided using an Educational Design Research (EDR) approach. Also referred to as Design-based Research (DBR), EDR is an iterative, usage-inspired approach to solving complex educational design problems in a manner that is contextually and methodologically relevant, and which ultimately focuses on establishing and sustaining the educational impact of an intervention. The process of EDR begins with the identification and analysis of an educational problem, which is typically followed by iterative phases of design, enactment, evaluation, reflection, and revision (Cobb et al. 2003; McKenney and Reeves 2014). McKenney and Reeves (2014) represent the EDR process in a general model comprised of three distinct phases: (1) analysis and exploration, (2) design and construction, and (3) evaluation and reflection. In this model, design iterations are nested and reflexive, with each distinct phase representing a micro-cycle within a larger framework of meso- and macro-cycles. As design researchers iterate their designs over time, the impact of those designs grows in terms of both implementation and spread. Borrowing from McKenney and Reeves' generic model, the research presented here consisted of one initial micro-cycle, followed by three meso-cycles (see Fig. 1). The initial micro-cycle explored the literature on case-based reasoning and problems-based learning to understand the role of case library design in scaffolding learners' problem-solving. This led to identification of important design principles that were explored in Meso-Cycle 1, in which the initial version of *Nick's Dilemma* was developed and tested. Meso-Cycle 2 expanded on this via appended scaffolds, which were designed to support retention of the case. Meso-Cycle 3 consisted of two iterations. In the first iteration, we explored the degree to which success or failure cases might impact learning outcomes in alternative means of assessment

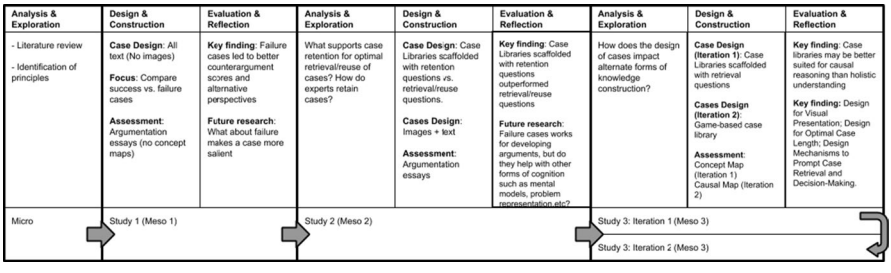

Fig. 1 EDR research design, Adapted from McKenney and Reeves (2018)

(concept maps). In the second iteration, we employed emergent design principles from the prior meso-cycles to redesign the learning environment in a game-based format as a way to support deeper interaction with the cases and more directly support causal reasoning.

Design principles for supporting case-based reasoning in problem-based learning

The design principles (DPs) discussed in the following sections were identified in the initial analysis & exploration micro-cycle, based on the theoretical tenets of case-based reasoning theory. The following DPs, as drawn from the literature, are discussed: (DP1) leverage case libraries to scaffold problem-based learning, (2) apply case libraries as vicarious memory, and (3) scaffold learners using questioning approaches.

Design principle 1: leverage case libraries to scaffold problem-based learning

Although the literature on PBL has shown it to be a beneficial instructional approach, there are those that question the degree to which learning is possible when novices are faced with solving complex problems (Kirschner et al. 2006; Kirschner and van Merriënboer 2013; van Merriënboer 2013). That is, the concurrent requirements of knowledge acquisition and solution generation exceed the limitations of working memory for novices who lack experience. As such, a considerable amount of research has focused on the degree and nature of scaffolding provided to learners during the problem-solving process (Belland 2017; Kim et al. 2017). For instance, scaffolds are embedded in learning environments in the form of question prompts, avatars, or intelligent tutors. While these are indeed important, the scaffolds may not afford opportunities to project how the concepts are transferred to other contexts (Kim et al. 2017; Raaijmakers et al. 2017).

To address the need to scaffold student problem-solving and support transfer, CBR argues that individuals leverage previous experiences to solve new problems. Specifically, CBR suggests that learners will progress through the following stages:

1. *Retrieve* previous case from a repository of cases within memory (case library).
2. If appropriate, s/he will *reuse* the case based on their assessment of the problem and the deemed relevancy of the retrieved case.
3. If s/he realizes that the situation is beyond what the case can offer, s/he *revises* the case library.
4. S/he will then *retain* the case within the larger database of memories. The case library now includes a case related to adult diabetes and juvenile diabetes

Nick's Dilemma embodies this principle by including various cases centered around key decision points. Given that novices have limited experience, these cases were derived from the SME using the Jonassen and Hernandez-Serrano (2002) protocol.

Design principle 2: apply case libraries as vicarious memory

CBR is important for PBL and scaffolding in various ways. First, it provides a mechanism to understand how learners retain the lessons learned when learners solve a PBL module. Secondly, CBR provides insight into the inquiry process that learners undergo when they reach an impasse. The theory posits that learners reference their own internal case library and utilize these experiences to inform a solution (Kolodner 1991; Schank 1999). Another important implication discusses how to address learning gaps. When a learner lacks the relevant case to retrieve and reuse, CBR suggests that a case should be provided to the learner to fill that gap. In terms of systems design, a series of cases can be strategically embedded within a learning environment as a form of 'vicarious memory' (Jonassen 2011b). These cases serve as problematized scaffolds and describe how others tried to solve similar problems using a given index, which supplements the novice's experience gap.

Nick's Dilemma scaffolds PBL by including the cases as hyperlinks around key indices, especially around important decision points. As learners read the main problem to solve, they are able to click on the case and discover how a practitioner encountered the problem. The narrative promotes decision-making and elucidates the causal reasoning process for the learner.

Design principle 3: scaffold learners through reflection of cases

Given the literature around learners' struggle with identifying structural characteristics in an experience (Jacobson 2001; Wolff et al. 2016), the learning environment included questions to guide learners' meaning-making and reflection of the case. Specifically, we supplemented cases with the following prompts based on Ge and Land's (2003a) problem-solving model: problem-representation, solution generation, justification, and evaluation of a solution. We anticipated that applying the multi-level scaffolding strategy in our learning environment would better facilitate indexing of cases so students could better retrieve them upon transfer.

Integrating case libraries: three studies

Synopsis of Meso-Cycles 1 and 2: toward understanding case design and scaffolding

Meso-Cycle 1 began with the development of an alpha-level prototype case library (Fig. 2). The case library was situated in the domain of sales management. The main problem to solve requires learners to navigate through the complexities involved in making a difficult hiring decision with no clear or predefined solution. The *Nick's Dilemma* unit lasts three weeks and is aligned with the overarching objectives of the Sales Management course, including learners (1) increasing their understanding of the five different areas of the hiring process, (2) enhancing their awareness of the complexities of the hiring process, and (3) supporting their ability to justify

Nick stepped into work Monday morning with his boss, Sheila. She scheduled this meeting to discuss a series of applicants that were being considered to fill a medical device sales position at AdvancedHeal left open after someone recently left to pursue another opportunity at another company. The company was small, but had interesting growth prospects.

"Nick", she begins, "we need to stop having to fill this position. It is us in terms of time and money to have to hire and train a new person every six months. We've had a lot of turnover in this medical sales position that needs to be stopped. As you know, we've missed on some of the previous hires. The three people we have had come in and out have cost us $90,000 over the last year in terms of revenue and training. That's $30,000 per person! The last individual hired for the position seemed pretty good in terms of technical expertise, but it was pretty clear that the sales aspect of the job wasn't a great fit. Let's go through some of these together and see if we can find someone with that right mix between **technical expertise and social skills**".

After going through the applicants, it becomes evident that it was difficult to find a great deal of qualified applicants.

"Oh man," Nick exclaims. "I didn't realize it would be this hard to find one person to fill a position. A lot of these people look really good on paper, but they just don't have the sales experience needed. They have decent schooling, but I want to make sure we bring in the right people. We could try to **retry posting a job ad in the St. Louis newspaper**, but that costs us about $1,500 per month. It's a risk shelling out all that money, but I think it's worth it if we get the right person rather than continuing to lose market share and have to constantly train new people. How about that list you have in front of you? Do you see any resumes that you like in particular?"

Sheila thumbs through some applicants. "Actually, here is one that seems pretty interesting. This individual, Lewis, has a decent GPA. It is about a 3.1 overall, but a 3.8 in classes related to his major. He also has **somewhat related experience** when he worked as a marketing intern for a children's hospital. Another option is try to **try to promote from within.** That might only cost us $15,000 to train a new person. I've heard great things about one employee in particular. This one employee, Terry, gets great telemarketing numbers in one of the worst territories for selling smaller medical devices. Plus, I know the supervisor in that department raves about Terry's character and leadership in that role. Although the experience isn't totally equivalent, it sounds like Terry has a chance to connecting with customers face-to-face."

Fig. 2 Alpha version of *Nick's Dilemma* from Meso-Cycle 1

hiring recommendations within a dilemma-type problem. Within Meso-Cycle 1, Study 1 sought to establish the degree to which success or failure cases engendered higher order learning in terms of argumentation construction (initial argument, counterargument, rebuttal, overall holistic score). In the context of *Nick's Dilemma*, learners worked through a series of five cases, each focusing on a different aspect of the hiring process, after which they make a hiring decision. For example, learners read related cases about how management employees should weigh both technical and sales acumen when evaluating candidates. In another narrative within the case library, the learners read how a loyal employee is overlooked for a promotion and the impact of this on morale and workforce retention. Study 1 found that learners with access to failure cases outperformed the success condition on counterargument and overall holistic argument scores (see Tawfik and Jonassen (2013) for further details). Further, Study 1 uncovered generally positive receptions of the learning environment; however, questions remained regarding the efficacy of the environment to support learning and the degree to which learners relied on the case (Table 1).

Meso-Cycle 2 sought to incorporate findings from Study 1 and expand them by focusing specifically on appending scaffolds to the cases. The goal was to understand the extent to which additional scaffolds are needed for learners to understand and apply the cases. In Meso-Cycle 2, we measured argument scores between the following conditions: (1) failure cases only, (2) failure cases with retain prompts,

Table 1 EDR cycles and corresponding design conditions

Meso-cycle	Design conditions
Meso-cycle 1	Success versus failure cases
Meso-cycle 2	Failure cases combined with question prompts
Meso-cycle 3	Success versus failure cases, each appended with a question prompt for scaffolding

and (3) failure cases with retrieval/reuse prompts. In the cases with retain prompts, we appended the cases with prompts derived from Ge & Land (2003b). For example, "What do you think are the primary factors of this case?", "How is this approach presented in this case similar or different compared with the main problem?", and "Do you have evidence to support your proposed solution?" The other scaffold condition included retrieval/reuse prompts whereby learners were asked to consider how the case related back to the main problem to solve on prominent indices (e.g. "How is Janice's story similar to Nick's Dilemma in terms of employee morale?"). This study found that learners with the retain prompts outperformed the retrieval/reuse conditions on argumentation scores. Based on these results, we thus concluded that learners needed to engage in individual meaning-making of the case rather than be prescribed a set of indices based on the expert's perspective (See Tawfik and Jonassen (2013); Tawfik (2017) for further details).

Meso-Cycle 3: exploring impact of case design on alternative representations of knowledge

Meso-Cycle 3, which is the primary focus of this article, sought to further understand the case-based reasoning process of novices as they are scaffolded by case libraries during PBL. In Meso-Cycle 3, Iteration 1, we sought to measure student learning outcomes using other forms of knowledge representations (concept maps) when learners are presented with success or failure cases. Based on findings from the first iteration as well as the design principles that emerged related to interacting with the cases, the case library was redesigned in Meso-Cycle 3, Iteration 2 using a game-based format, after which another iteration of research was performed. We describe the impetus for these studies in the below sections.

Synopsis of meso-cycle 3, Iteration 1

Findings from Meso-Cycles 1 and 2 led to questions about the degree of interactivity of the case library as well as the limited multimedia employed to convey case narratives. A pattern began to emerge of how novices engage in case-based reasoning. The prior studies suggested that learners do not solely understand and apply the cases as-is; instead, there is an additional element of being able to understand the potentially latent indices within the case. Questions also focused on the knowledge structures that students were developing. In Meso-Cycles 1 and 2, we investigated how learners were able to translate their understanding of the case and reuse it to

construct an argument about how to solve the new problem. However, problem-solving theorists advocate for alternative forms of representation are needed in PBL, such as concept maps. Concept maps differ from arguments in multiple ways. First, concept maps provide a more visual representation of understanding, which many argue resembles internal knowledge structures (Si et al. 2018). Second, the visual nature of concept maps affords a more holistic representation of how ideas relate to one another (Fitzgerald et al. 2009; Olney et al. 2012). While argumentation is focused on the written articulation of a solution rationale, concept maps visually represent the degree to which learners are able to organize their knowledge and conceptual relationships. Hence, the focus of Meso-Cycle 3, Iteration 1 was (a) to incorporate more interactivity into the design of the *Nick's Dilemma* online case library and (b) to investigate the use of concept mapping instead of argumentation to assess student learning.

Methodology: Meso-Cycle 3, Iteration 1

Given that we had found evidence to suggest failure supported elements of argumentation in prior design cycles (counterargument; holistic scores), we sought to determine if the same results could be found in other forms of knowledge representation. Thus, for Study 3, Iteration 1, we replicated certain elements of Study 1, but with a different representation of knowledge—concept maps. We also added a control group. As in the case of the previous meso-cycles, this case library was implemented in an undergraduate sales marketing program located in the Midwestern university. Students (N = 39) were asked to read a version of *Nick's Dilemma* that looked very similar to Fig. 1 with their peers and later independently generate concept maps about germane elements of the problem. To assess the quality of the concept map, two researchers independently coded the artifacts using the Concept Map Quality Scoring Rubric and Protocol (Fitzgerald et al. 2009). The scores ranged from 0 (minimal development of the concept) to 4 (expert representation of the concept) (see Table 2).

Table 2 Concept map quality scoring rubric categories (Fitzgerald et al. 2009)

Score	Value	Description
0	None	Zero or one node; represents no development of concept
1	Minimal/little	Represents a novice/beginning level of development of concept
2	Fair/moderate	Represents an emerging level of development of concept
3	A lot	Represents a great deal of development of concept
4	All parts of concept	Represents an expert level of development of concept

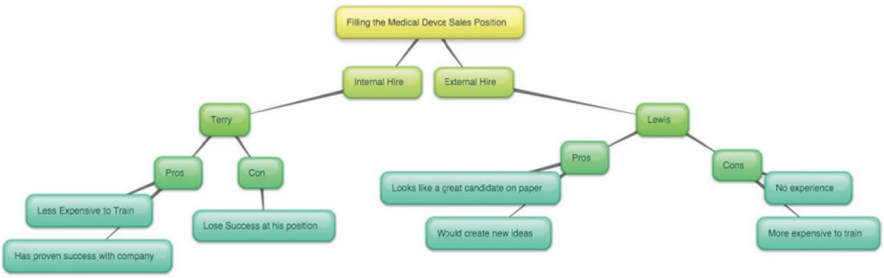

Fig. 3 Example of an underdeveloped student concept map

Results: Meso-Cycle 3, Iteration 1

No statistically significant differences were found between conditions ($p = 0.586$). Upon further review, results showed that nearly half of the concept maps were scored at a minimal level (49%) and another 33% scored as fair. Only 19% were categorized as higher scores (Score 4 = 12%, Score 3 = 7%). Many of the concept maps were underdeveloped and included very few of the primary indices from the cases. In those instances when the lessons from the cases were included, they were only minimally connected by nodes and lines. The concept maps were also very sparse, with little clustering of related concepts (see Fig. 3).

To understand actual interactions with the case library, this study also collected Google Analytics data. The below chart shows the paths that users took to explore the website designed for Meso-Cycle 3, Iteration 1 (see Fig. 4). The data found the average number of pages viewed per session was 4.35. Of note is that nearly all interactions alternate between the Nick's Dilemma page and the assignment description. Therefore, the analytics showed very little interaction with the case libraries that were designed to support learners' problem-solving.

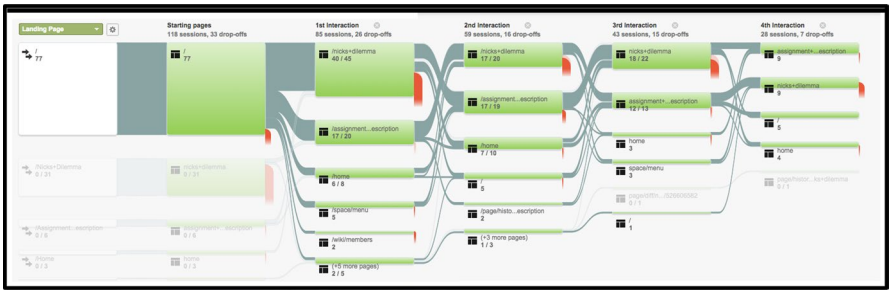

Fig. 4 Uneven click stream data as participants progressed through case library

Revisions after meso 3, Iteration 1

Conjecture maps as reflective design practice

Proponents of EDR laud the approach for its ability to connect research and practice (Barab and Squire 2004; Reeves et al. 2005). However, critics point to perceived methodological weaknesses with EDR in terms of its ability to blend concurrently design, research, and practice (Phillips and Dolle 2006). Others contend that EDR lacks clear standards and should shift its focus to generalization of results (Anderson and Shattuck 2012). Sandoval (2014) maintains, "responding to such criticisms demands moving beyond reflections about the kinds of knowledge design research can produce to develop systematic approaches to the conduct of design research" (p. 19). The systematic approach that Sandoval advocates is conjecture mapping, which provides a means for researchers to consider design elements (including theoretical and practical elements, as well as how they are connected) by explicitly mapping out their connections. By creating an explicit representation of the interconnectedness of design elements and their underlying processes, a means for interpreting EDR outcomes is realized.

For our project, we developed a map based on the high-level conjecture that learners require scaffolds in order to: (1) be able to identify salient features of cases, (2) draw connections between cases, and (3) support decisions in a decision-making problem (Fig. 5). This conjecture was derived from our analysis of the decision-making problem, including relevant literature, and experience from prior design cycles. As suggested in the figure, the design centered around the tools and materials and discursive practices of the online learning environment.

Design insights from conjecture mapping Our conjecture map allowed us to reflect on design in terms of high level learning objectives, embodiment, mediating

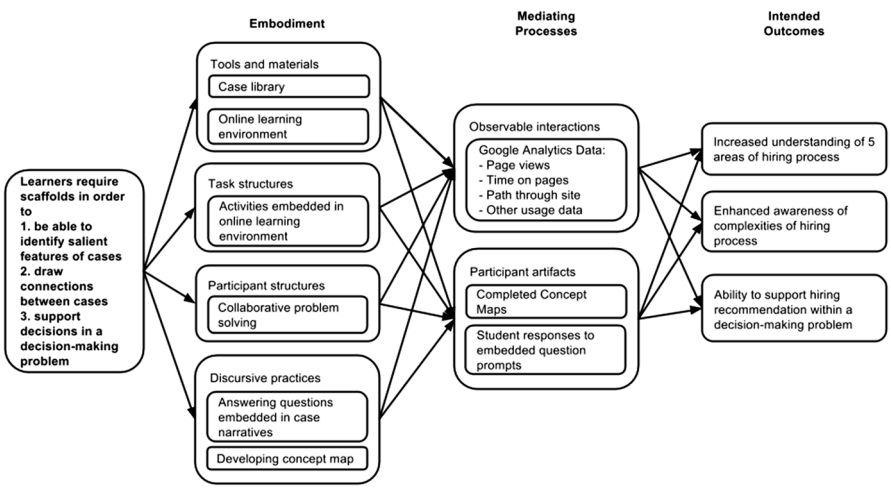

Fig. 5 Conjecture map of a design to promote problem-solving using a case library

process, and intended outcomes. In terms of embodiment, the conjecture map required us to assess our goals and then articulate the embodiment of those goals in terms of tools, tasks, participant structures, and discursive practices. As we reflected on how to accomplish this, we then engaged in discussions about the requisite mediating process and participants artifacts that would support our intended embodiment. Finally, this led us to consider how our outcomes and needs of the subject matter would be supported. The process of developing the conjecture map led to a number of design questions and tensions. In particular, we wondered if (a) cases were written at a level appropriate to the audience (b) students had read the initial and supporting cases and (c) had students perhaps missed key information? We address these questions in the following sections and how they were considered in our redesign.

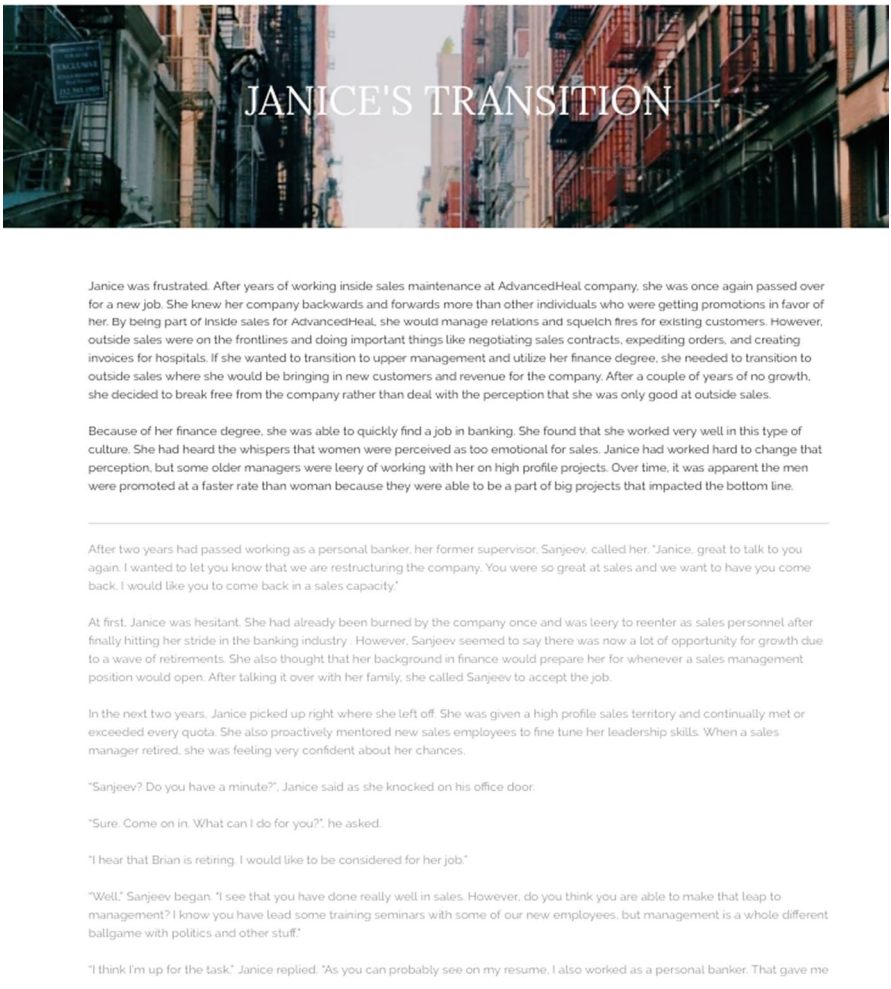

Fig. 6 Concerns about the case presented as a "wall of text."

Design query 1: Were the cases written at a level appropriate to the audience?

As we reflected on our design, our discussions focused on the readability of the cases. While reading level did not appear to be problematic, we became concerned about the average length of the narratives in our case library, which was 811 words, with the shortest being 529 words and the longest being 1055 words (see Fig. 6). While no specific design guidelines exist about case length, related literature suggests that length can impact case retrieval due to cognitive load (Aha et al. 2005; McSherry 2001). Hence, we questioned how case length might impact how cases are retained. That is, if the amount of text in a case was overwhelming, might this preclude students from properly retrieving a case? Might this, in turn, impact students' ability to interact, retain, reuse the case when solving the problem?

Design query 2: Did students read the initial and supporting cases?

To determine whether students had read the initial and supporting cases we designed, we used Google Analytics' behavior overview to investigate usage patterns across all conditions. The behavior overview section provides information such as number of page views, unique page views, and average time spent on a given page. Results indicated that, on average and across conditions, users accessed 5.2 pages per session. These were not necessarily unique pages, but the total number of times separate pages were accessed. The average amount of time per session was 00:10:47. This suggests that, on average, students in all conditions spent around 50 seconds on each page. This seemed to be far too little time to read each page, let alone comprehend and reflect on what was read. To verify this assumption, we calculated how quickly students would have to have read each page in order to complete it in 50 seconds. We used word counts for all cases in the case library (811 words, on average). Our results indicate that students would have needed to read 960 words per minute in order to complete a page in just 50 seconds. Hence, it is highly unlikely that students were reading all of the information presented to them in the case library. Additional questions emerged around case presentation such as (a) what do students do if the design of a case does not lend itself to web-based reading patterns? And (b) do they still retrieve the case, do they abandon the case, or something else if they are not satisfied with the design?

Design query 3: Did learners miss key information?

After we discussed the readability of the cases, our discussions focused on how learners navigated to the cases and the reasons for selecting a case. Although the cases we designed were clearly linked, it was not explicitly clear to students what information they would encounter when they clicked the link. This led us to question whether our design sufficiently made it clear that students were intended to visit the cases linked from the primary case. In other words, the indices, as indicated by hyperlinks in the primary case, might have been insufficient to prompt case retrieval.

Do students ignore hyperlinks if it is not clear that they lead to supporting cases? What cues might better prompt case retrieval?

Meso-Cycle 3, Iteration 2: promoting intentionality and usability by means of interactive and multimedia-rich elements

Synopsis of meso-cycle 3, Iteration 2

Meso-Cycle 3, Iteration 1 ultimately led to useful design principles about how to support novices as they engaged with case libraries during problem-solving; however, what led to the identification of these design principles was the outcome of no statistically significant differences between study conditions in the prior design

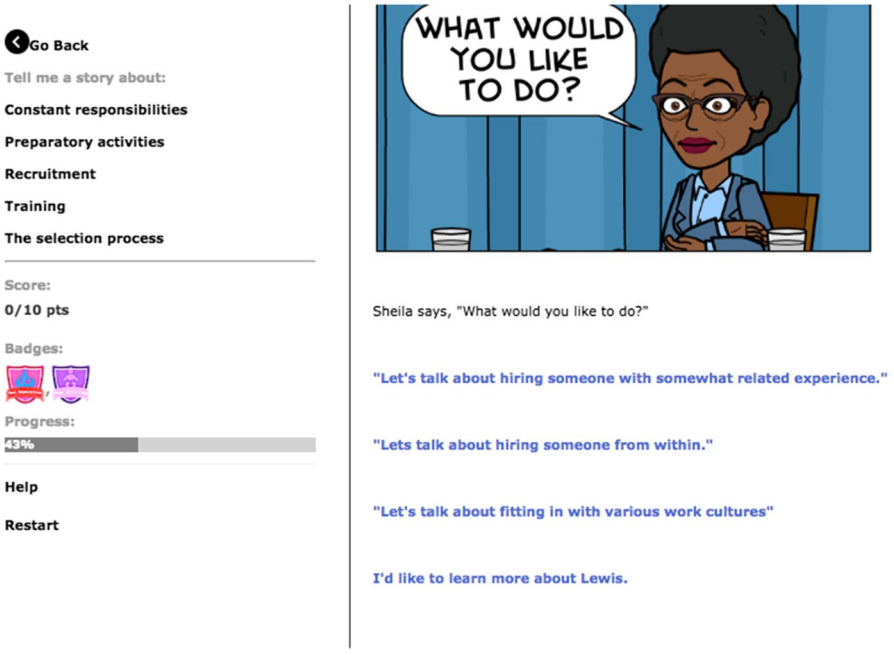

Fig. 7 Redesigned case library based on game-based learning principles

cycle (Meso-Cycle 3, Iteration 1) (see Schmidt and Tawfik (2018) for further detail). As a result, we used our findings to rethink our approach in terms of both theory and design. As we described above, we used a conjecture map to reflect on how to best instantiate case-based reasoning in a digital environment, which led to insights in terms of index generation and decision-making. We also discussed how our case narratives conveyed cause-effect, which might have been misaligned with the more holistic representation of knowledge that is afforded by concept maps. We thus shifted our assessment from concept mapping to causal mapping. To this end, we adopted Coggle (https://coggle.it), a freemium online causal mapping tool. In terms

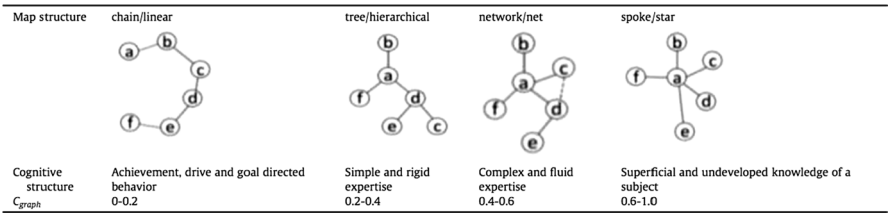

Fig. 8 Topological features of learners' causal maps, as outlined in Clariana and colleagues (2013)

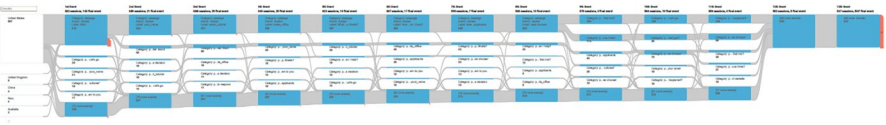

Fig. 9 Click stream data as participant's progressed through redesigned case library

of interface design, we developed a game-based learning strategy for the case library that incorporated both deep elements of gaming (non-linear narrative, role-playing, etc.) and shallow elements (achievement badges, points, etc.), as well as a variety of endings to engender more explicit interaction with the concepts embedded within the narrative (see Fig. 7).

Methodology: Meso-Cycle 3, Iteration 2

The final phase of our study was conducted in a similar sales management course as in prior design cycles, with a total of 64 students. To better align with the cause-effect afforded by case libraries, the overall goal was to generate a causal reasoning map that articulated the various solutions and their effects. Participants used the game-based learning approach, which provided an unfolding narrative of Nick's Dilemma using key decision-points. As Nick interacts with his boss (Sheila) and co-workers, he reads related cases about the decision-making point that he is considering. To make the lessons learned more salient, badges are also embedded to highlight when an important index is encountered.

In contrast to our prior protocol that described the concept maps by their development, we used the approach outlined in Clariana and colleagues (2013) for Meso-Cycle 3, Iteration 2. This approach provided a typology about how the map represents learners' internal knowledge structure (Fig. 8). Researchers independently coded the causal reasoning maps, with an initial inter-rater reliability of 54% and a final reliability of 100%.

Results: Meso-Cycle 3, Iteration 2

As described earlier, we completed changes in our approach to study case-based reasoning in terms of the learning environment (game-based learning) and assessments

(causal reasoning maps). To explore the differences that emerged from the redesign, we compared the maps from Meso-Cycle 3, Iteration 1 and Meso-Cycle 3, Iteration 2, categorized using the topological features outlined in Clariana and colleagues (2013). Ordered logistic regression was used, the results of which found statistically significant differences between the maps from Meso-Cycle 3, Iteration 1 and Meso-Cyle 3, Iteration 2 (Chi Squared = 5.725; DF = 2; Significance = 0.5; R squared = 0.68). A further investigation found that significant differences emerged between the groups on measurements of network/net ($p = 0.021$). That is, learners using the game-based learning environment were more likely to generate more network/net designs in their maps.

As in Meso-Cycle 3, Iteration 1, we also gathered Google Analytics data to better understand how the design impacted participants' interaction with the cases. Whereas the analytics showed the prior design was focused on two pages (main page, assignment), this design yielded a much more uniform interaction across all pages (see Fig. 9).

Discussion of Meso-Cycle 3, Iterations 1 and 2

The redesign process started with an acknowledgment of the flaws in our design and reflective discussions on the early design decisions that led to these issues. A recurring theme in our discussions was an assumption that if students were presented with a case library, they would use it as designers intended. Continued discussions further led us to realize that many early design decisions were focused primarily on applying case-based reasoning theory rather than on the overall design of the learner experience.

These realizations led to a shift in our focus to how to improve learner experience, while also designing for CBR. We brainstormed to generate ideas, which were considered in terms of their perceived merit related to our conjecture map, as well as our limited development capacity of just two people. In the course of our discussions, a tension emerged in that the more we considered how we could rework our existing case library, the more apparent it became that the form of our current design was at odds with the function suggested by our refined design ideas. For example, we considered splitting up existing case descriptions on the same page or across pages. However, there was concern this would result in a very disconnected presentation of materials to the learner. We also considered having students answer questions prompts on each page, having them create their own case indices, or even having them create their own cases. Once again, we were unclear how the additional interactivity would impact understanding of the case and inadvertently serve as a source of cognitive load. Ultimately, our design discussions pointed to general dissatisfaction with the current design of the case library and led us to the realization that simple tweaks and visual updates would be insufficient remedies to underlying design flaws. This, in turn, led to the identification and implementation of new design principles to support learners' problem-solving, which we discuss in the following sections.

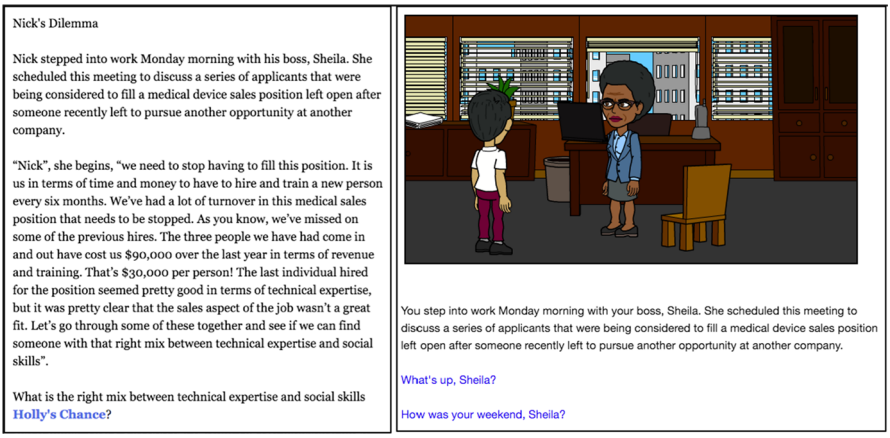

Fig. 10 Rapid prototypes developed in Twine, with a text-based version on the left and a multimedia version on the right

Emergent design principle 1: design for visual presentation

We opted to take a rapid prototyping (RP) approach for our redesign, given our uncertainty as to which direction the new version of the learning environment should take. According to Tripp and Bichelmeyer (1990), RP is particularly useful in complex situations that make predictions difficult, situations that have not produced satisfactory results using other methods, and "new situations where there is not an abundance of experience from which to draw" (p. 9). The second author of this paper was teaching a course on educational game design and had been using a tool for creating text adventures in his classes called Twine (http://twinery.org). We decided to use this tool to prototype a single case from the case library, with each team member prototyping the case independently. Figure 10 provides examples of the outcomes of our rapid prototyping process.

Developing prototypes in Twine proved to be a productive way to move our design forward. One prototype was similar to prior versions of the environment, but had embedded questions within the case descriptions instead of at the end. The other prototype was divergent from other versions of the environment, and had reworked the case descriptions into more of a graphic novel format as a way to support interactivity, improve aesthetics, and promote engagement. In terms of supporting case-based reasoning, we reasoned that the more active approach would allow learners to embody the lessons learned as they interacted with the cases. We used these prototypes to discuss the pros and cons of both approaches. We both shared a preference for the prototype that had a graphic novel feel, noting an appreciation for the fluidity of the design, the feeling of page turning as opposed to page loading, the comic book style, and how questions were embedded as something the learner had to click on to move forward, similar to an ASK system (Ferguson et al. 1992; Jonassen 2011a; Schank 1999). In the end, we focused on a design that utilized a

graphic-based approach. We felt as though this better supported conveying the context of *Nick's Dilemma*, while also affording a game-based aesthetic.

Emergent design principle 2: design for optimal case length

Our redesign was also informed by Nielsen's (2006) assertion that users read web content largely in an F-shaped pattern. That is, users do not read through the page in a linear fashion, but rather that they skim information, such as reading the first two paragraphs while the rest are skimmed. This was problematic for the earlier version case library because we relied on large chunks of text, so it was likely that learners are not reading the case library as intended.

In the latest design, we utilized the multimedia principle of chunking as a way to advance the narrative. As can be seen in Fig. 10, we attempted to limit each page to a maximum of two paragraphs, with most pages providing just a few sentences. This design approach promoted three benefits in our learning environment. First, by limiting the on-screen text, it mitigated the F-shaped pattern that comes with long pages of text. Second, the shorter approach was more in line with users' cognitive load and working memory requirements. Finally, the short pages required users to click, and thus be more engaged, to progress the narrative.

Emergent design principle 3: design mechanisms to prompt case retrieval and decision-making

Findings from Meso-Cycle 3, Iteration 1 suggested a fundamental re-imagining of the learning environment was needed. In particular, the conjecture map led us to revisit the element of decision-making inherent in our learning environment. We also wanted confirmation that learners had made the right decisions. While our original design asked learners to utilize the cases, we failed to support decision making sufficiently. Alternatively, a decision-making approach requires one to reexamine the various decisions along the solution paths and how the variables interact with each other to influence an outcome. In our design that utilized a game-based strategy, we restructured the interface around three primary decision-points: (1) hiring the external candidate, (2) hiring the internal candidate, and (3) restarting the search using advertisements. Moreover, it was important to consider the permutations of the decisions. For instance, it is possible that hiring an internal candidate is the right choice, but it will likely result in a failure if s/he is not properly mentored. This required us to revisit the placement of the case library in our design as a way to understand the outcomes of student choices.

Based on the design tensions that emerged from development of the conjecture map, our focus for the new version looked more specifically at the interplay of design and theory as embodied in the learning environment. We were also interested in promoting more active reading of case descriptions. In particular, one design tension focused on how to leverage the indices towards decision-making in the learning environment. For example, we included a case entitled "Janice's Story" and the

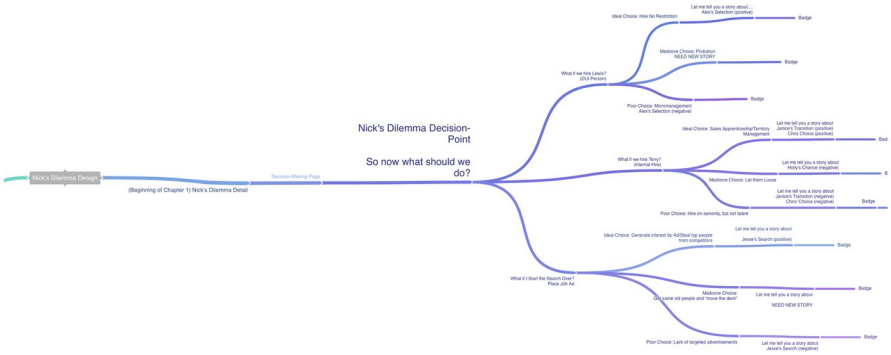

Fig. 11 Nonlinear Branching Narrative using Coggle

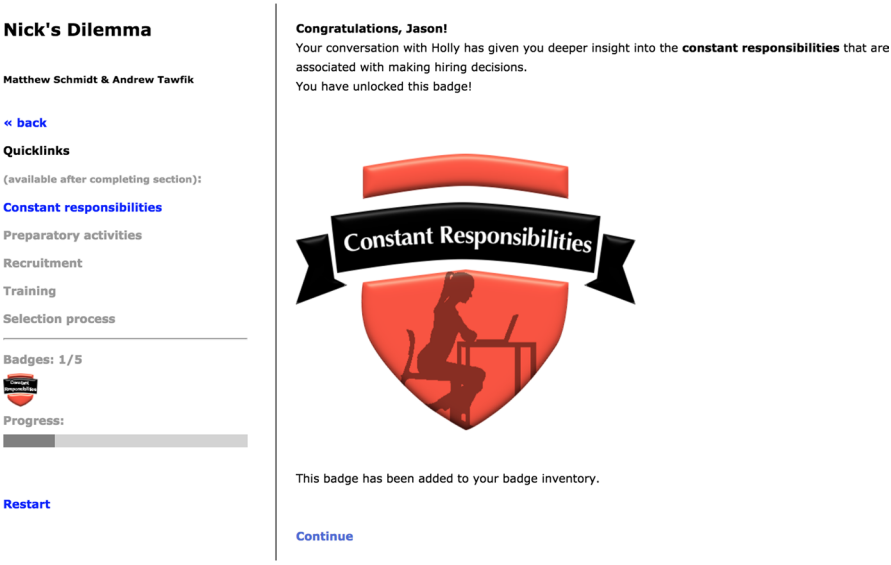

Fig. 12 Badges as advanced organizers for cases

learner reads about how an individual was passed in favor of a man. While we used the term "retention" to drive our index, there were other related indices such as "morale" and "equity" that others might employ to label the case. As we began to rethink our learning environment, we found that the permutations quickly became difficult to manage. With each decision-path, there were multiple subsequent decisions that the learner could progress, which quickly became unwieldy from a design perspective. To support our design process, we utilized concept mapping to visualize the various solution paths our learning environment could take (see Fig. 11). This allowed us to better construct the non-linear narrative structure of our learning environment.

The cases were reimagined as a way to convey key lessons learned, such as improving employee morale and clear responsibilities. To do this, we utilized a badging structure (Davies et al. 2015). This served two purposes. First, it served as an advanced organizer to show learners what the primary objectives were. Second, badges were awarded to reinforce when learners had made the optimal decisions. Once again, our causal mapping visual aid helped outline when the badges would appear in our nonlinear storyline (Fig. 12).

Implications for theory and practice

Based on case-based reasoning theory, many argue that PBL is a way to meaningfully engender problem-solving in classroom contexts (Hmelo-Silver et al. 2007; Jonassen 1997). Theorists assert that as learners solve problems posed in PBL settings, they are able to understand how the concepts are applied across a variety of contexts (Kim et al. 2017; Lazonder and Harmsen 2016). It is further argued that wide-ranging exposure to problem-solving experiences allows individuals to develop more refined and robust knowledge structures based on the characteristics of a given phenomenon (Clariana et al. 2013; Eseryel et al. 2013). However, one of the challenges of PBL is that learners are posed with the types of complex problems that practitioners must solve, despite not having prior experience with the subject matter. Related to this, CBR has implications for how to scaffold learners during PBL. Indeed, CBR theorists contend that learners can be given multiple cases as a type of problematized scaffold (Kolodner et al. 2012). As learners reference the appropriate case or cases, they are able to overcome the experiential gap that critics of PBL often cite (Tawfik and Kolodner 2016). Moreover, the narrative format of cases uniquely affords opportunities for rich meaning-making, causal reasoning, and learning transfer as learners engage in PBL (Jonassen 2011a).

In line with expert-novice studies (Jacobson 2001; Wolff et al. 2016), many theorists have suggested CBR theory can be used to guide the design of scaffolds embedded in learning technologies (Jonassen 2011a; Kolodner et al. 2012). When compared with other forms of scaffolding, some studies discuss how case libraries are beneficial for understanding alternative perspectives (Bennett 2010; Goeze et al. 2014), promotion of reflection (Blomberg et al. 2014), and decision-making (Gartmeier et al. 2015). While these studies have established case libraries as a viable scaffolding strategy, literature has yet to empirically validate specific design principles that foster problem-solving, causal reasoning, and sound knowledge structures. To address this gap, this study employed a multi-year, longitudinal EDR effort across 3 meso-cycles. As an overarching methodological framework, EDR is particularly appropriate for the research reported here, given that this approach allows for the development of a consistently maturing intervention while simultaneously contributing to theoretical understanding (Amiel and Reeves 2008). Moreover, EDR is especially useful when existing understanding is limited or insufficient, as many contextual variables are not known a-priori when designing for learning in complex systems (Barab and Squire 2004). Our EDR approach embraced incomplete knowledge and allowed us to iteratively advance our intervention so as to promote

relevance and impact in our implementation. Ultimately, this approach allowed us methodically to explore the theoretical assumptions of CBR, while also identifying relevant design principles that serve to guide how CBR theory might be applied in future learning technology research and development.

At the outset of our project (Meso Cycle 1), we identified and implemented initial design principles derived from CBR theory, including (a) leverage case libraries to scaffold problem-based learning (Jonassen 2011a); (b) apply case libraries as vicarious memory (Kolodner 1991; Kolodner et al. 2004); and (c) scaffold learners through reflection on cases (Tawfik and Kolodner 2016). In the early vision of our project, this was applied in terms of static "success versus failure" case libraries with hyperlinks to cases embedded within a main problem to solve. In light of the literature about how novices and experts process experiences differently (Jacobson 2001; Wolff et al. 2016), a follow-up study focused on better supporting retention of the cases through appended reflection questions as learners constructed argumentation essays (Meso-Cycle 2).

In Meso-Cycle 3, Iteration 1, we sought to understand how findings from earlier studies could be applied using alternate forms of representation, i.e., concept maps. Interaction data were also collected to garner insight into how learners utilized and retained cases. In contrast with prior findings, we found no statistically significant differences between concept maps when comparing the success and failure conditions. Moreover, Google Analytics showed that learners rarely interacted with any cases and instead were more focused on the assignment requirements. These findings caused us to question some of the purported benefits of failure cases described by CBR theory (Lin-Siegler et al. 2016; Schank 1999), as well as the efficacy of our case library design. We then engaged in development of a conjecture map that allowed us to explicate holistically how CBR theory was embodied in our learning environment, and specifically focus on how theory was associated with our intended learning outcomes. This process laid bare the underlying theoretical architecture of our design, the processes that were necessary to promote the intended outcomes, as well as the absence of some necessary processes. Questions were identified related to how novices employ case libraries, especially as they relate to reading level of the cases, interaction with the linked cases, and overlooked indices. Specifically, conjecture mapping led us to refine our understanding of CBR theory and design so as to better retain, retrieve, and reuse the cases. Insights that arose from conjecture mapping led to identification of emergent design principles that focused on optimal case length, mechanisms to prompt case retrieval and decision-making, and visual presentation. These principles, in turn, had significant ramifications for how our design conjecture was embodied in the learning environment in Meso Cycle 3, Iteration 2.

A major theme in our reevaluation of CBR theory and related design principles was how to make the indices of the related cases more prominent so that lessons learned could be transferred to the main problem to solve. Whereas the initial design principles of Meso Cycle 1 were largely driven by the literature (e.g. cases as vicarious experience), insights from the conjecture map led to embedding game-based features, decision-making opportunities, and badging. While we reduced the amount of text on each page and improved visual presentation, the current game-based design required learners to click through multiple pages to complete a case.

In addition, we implemented questions at the bottom of each page to replace hyperlinks that were embedded in the narrative in prior versions of the learning environment. Once again, this game-based strategy was designed to avoid some of the passive interaction patterns we had identified in the earlier meso-cycles of our project. The design made the indices less opaque within the problem, which supported learners' decision-making. Finally, the badges were included as an additional measure to visually reinforce the indices and support their knowledge construction. Indeed, it appears as though making the questioning and decision-making more salient for students played a role in the learners' causal reasoning, as evidenced by the statistically significant higher scores in the causal maps.

Conclusion

The purpose of the current article centers on how we, as learning designers, came to recognize tensions between the extant design approach and supporting theory. As highlighted in this design case, conjecture mapping played a unique role in how we were able to overcome those tensions and ultimately transform *Nick's Dilemma* from a more traditional hypertext-based learning environment into a DGBL environment that is multimedia-rich and interactive. Design problems are notoriously difficult because they are ill-structured, do not have a single correct solution, and typically lack a clear solution path (Jonassen 2011b), as is evident in the example we have described here. Our experience highlights how conjecture mapping supports reflective practice and elucidates important insights about how the theory can inform design. Using a rapid prototyping approach, we were able to generate new ideas that have led to established improvements to our case library and have contributed to new directions for theory and design.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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