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Detangling the Interrelationships Between Self-Regulation and Ill-Structured Problem Solving in Problem-Based Learning

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Detangling the Interrelationships Between Self-Regulation and Ill-Structured Problem Solving in Problem-Based Learning

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Abstract

One of the goals for problem-based learning (PBL) is to promote self-regulation. Although self-regulation has been studied extensively, its interrelationships with ill-structured problem solving have been unclear. In order to clarify the interrelationships, this article proposes a conceptual framework illustrating the iterative processes among problem-solving stages (i.e., problem representation and solution generation) and self-regulation phases (i.e., planning, execution, and reflection). The dynamics of the interrelationships are further illustrated with three ill-structured problem-solving examples in different domains (i.e., information problem solving, historical inquiry, and science inquiry). The proposed framework contributes to research and practice by providing a new lens to examine self-regulation in ill-structured problem solving and offering guidelines to design effective tools and strategies to scaffold and assess PBL.

Keywords: self-regulation, ill-structured problem solving, problem-based learning

Introduction

Problem-based learning (PBL) is an instructional method that was first implemented in medical education and later applied widely in various domains and disciplines (e.g., Barrows, 1986, 1996; Schmidt, 1989). It is aimed at providing a focused, experiential learning experience to students. PBL is organized around an inquiry process of investigation, explanation, and resolution of real-world problems that are often messy, fuzzy, ill-defined, ill-structured, and interdisciplinary (Barrows, 2000; Hmelo-Silver, 2004; Savery, 2006; Torp & Sage, 2002). Such problems are typically situated in and emerged from a specific context (Jonassen, 1997) and may take the form of a problem scenario, a case study, or a project, which is often open-ended in terms of goals or means to pursue goals or both goals and means (Hannafin, Land, & Oliver, 1999; Jonassen, 1997).

One of the essential skills for students to develop in PBL is self-regulated learning, which is a critical component of self-directed learning (Loyens, Magda, & Rikers, 2008). In order to implement PBL successfully, we need to address at least the following issues: (1) understanding experts' processes in solving ill-structured problems, (2) examining how experts regulate their mental processes during ill-structured problem solving, and (3) providing scaffolding to help learners self-regulate their processes in solving ill-structured problems. In this article, we take a closer look at the first and second issues, especially the interrelationships between the ill-structured problem-solving process and the self-regulation process. It is our hope that the investigation of these issues can help us to develop instructional design models, prescribe specific strategies, and create effective scaffolding tools to support PBL.

Background

Over the past three decades, researchers have been examining experts' mental models in ill-structured problem-solving processes (e.g., Sinnott, 1989; Voss & Post, 1988). The results led to the conceptualization of several models, including those of Sinnott (1989), Voss and Post (1988), and Jonassen (1997),

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which were built upon one another. All of these models indicate the involvement of both cognitive and metacognitive processes in ill-structured problem solving. Cognitive processes in ill-structured problem solving refer to the mental activities of applying domain-specific knowledge to solve a problem (Chi & Glaser, 1985; Jonassen, 1997; Voss & Post, 1988; Voss, Wolfe, Lawrence, & Engle, 1991). Metacognitive processes refer to both self-awareness of individuals' cognitive processes and self-regulation of the ongoing cognitive processes during problem solving (Zimmerman & Campillo, 2003).

Further, Ge and Land (2003, 2004) consolidated the previous ill-structured problem-solving models into four main processes: (1) problem representation, (2) generating solutions, (3) constructing arguments, and (4) monitoring and evaluation. For each of these processes, Ge and Land (2003, 2004) further specified its cognitive and metacognitive requirements based on Jonassen's (1997) work. Although Ge and Land's (2004) framework has been applied as a conceptual tool to examine the relationships between ill-structured problem solving and other variables such as different types of scaffolds (Bixler & Land, 2010; Bulu & Pedersen, 2010; Wu & Looi, 2012), knowledge integration (Chen & Bradshaw, 2007), and motivation (Song, 2005), it is rather limited due to a lack of clarity regarding the relationships among various cognitive and metacognitive processes involved in ill-structured problem solving. For example, monitoring and evaluation in Ge and Land's (2003, 2004) model should not be a standalone process in ill-structured problem solving; similarly, the process of constructing arguments should occur simultaneously during, instead of after, the generation of solutions. As research has evolved and developed, Ge (2013) suggested that the four ill-structured problem-solving processes (i.e., problem representation, generating solutions, constructing arguments, and monitoring and evaluation) are not merely didactic, sequential processes proceeding from one to the next; rather, they were dynamically intertwined and complexly acting upon each other as the problem solver manipulates problem space, represents and transforms problems, and generates or develops solutions. Literature suggests that self-regulation, an essential component of metacognition, runs through the entire duration of problem solving rather than just operating at the stage of monitoring and evaluation (Zimmerman & Campillo, 2003). Ge and Land's (2003) work was an attempt to understand the interactive relationships between self-regulation and ill-structured problem solving, yet it does not clearly or explicitly address the interrelationships between the two important processes.

Purpose

Although extensive research has focused on self-regulation, the literature does not provide much insight into how exactly the two processes—namely, self-regulation and ill-structured problem solving—interact with each other. Questions remain regarding the interrelationships: Do self-regulative processes of planning, monitoring, and evaluation manifest differently during different problem-solving processes? Does the construction of argument take place in both problem representation and solution processes? How does self-regulation support ill-structured problem solving? Is self-regulation an iterative process throughout problem solving? If so, how does each iteration lead the problem-solver closer to the solution? Does ill-structured problem solving drive the development of self-regulation? How do motivation and beliefs affect self-regulation in ill-structured problem solving? We believe that it is worthwhile to pursue these questions in order to create a robust and supportive PBL environment that develops learners' ill-structured problem-solving skills. By expanding our repertoire about self-regulation to the context of ill-structured problem solving, we also expect to contribute to the PBL literature through an improved understanding of ill-structured problem solving.

Therefore, the purpose of article is to detangle the complex relationships between two essential processes in PBL: self-regulation and ill-structured problem solving. We first start the discussion with a general literature review on ill-structured problem solving, and then we specifically examine the role of self-regulation in ill-structured problem solving. Next, we propose an ill-structured problem-solving framework accounting for self-regulation. Subsequently, we illustrate the new framework by examining self-regulation processes in three different contexts of ill-structured problem solving. With the clearer and deeper understanding of the relationships between self-regulation and ill-structured problem solving, we conclude the article with theoretical and practical implications for PBL in light of the updated conceptual framework.

Ill-Structured Problem-Solving Processes

In order to understand the relationships between ill-structured problem solving and self-regulation processes, we must first understand the nature of ill-structured problems. According to Sinnott (1989) and Jonassen (1997), ill-structured problems are those we encounter in everyday life. Unlike a well-structured problem that consists of a well-defined initial state, a known goal state, a constrained set of logical operators, and a preferred and prescribed solution path, an ill-structured problem is typically complex and ill-defined, because one or more of the problem elements are unknown or uncertain (Jonassen, 1997), and the goals are vaguely defined or unclear (Voss & Post, 1988). Due to the ill-defined nature, the descriptions of the problems are not clear, and the information needed to solve them is not entirely contained in the problem statements, which subsequently makes less clear or explicit the appropriate means or actions to solve the problem (Chi & Glaser, 1985; Jonassen, 1997). Kitchner (1983) noted that ill-structured problems could involve multiple solutions with multiple solution paths, or there could be no solution at all. Because problem solvers have to make a judgment about the problem and defend their solutions, other internal elements, such as personal opinions or beliefs, may often play a role in the ill-structured processes.

Jonassen (1997) echoed Schön's (1990) argument that ill-structured problem solving is a design process instead of a search process, which is very different from the goal-searching process in solving well-structured problems. Although ill-structured problem solving also goes through processes of problem representation and solution generation, the cognitive and metacognitive activities involved in solving ill-structured problems are much different from those in solving well-structured problems. Ill-structured problem solving is more dialectic in constructing problem space, generating solutions, and monitoring and applying strategies in solving a problem. The dialectic nature of ill-structured problem solving requires problem solvers to be able to reconcile their conflicting conceptualizations of the problem and construct arguments to defend their selection of problem space and solutions. Constructing arguments involves identifying alternative views or perspectives about the problem, which is often based on problem solvers' personal beliefs. Furthermore, because the outcomes of ill-structured problem solving could involve multiple solutions, metacognitive processes such as monitoring and evaluation become particularly important, because problem solvers must execute their metacognitive strategies based on personal beliefs when faced with alternative solutions. Therefore, ill-structured problem solving involves not only the processes of problem representation and generating solutions, as found in well-structured problem solving (although with different nature), but also, most critically, the processes of constructing arguments as well as monitoring and evaluating, whether explicitly or implicitly.

In summarizing Jonassen's work, Ge and Land (2003, 2004) identified four most distinctive cognitive and metacognitive processes in ill-structured problem solving: (1) problem representation, (2) developing solutions, (3) making justifications and constructing arguments, and (4) monitoring and evaluation (Ge & Land, 2003, 2004; Jonassen, 1997). *Problem representation* involves understanding the problem state and goal state and the path from the initial to the goal state through manipulation of the problem *space* or *schema* (Jonassen, 1997). In the PBL context, students are expected to work in groups through the problem space by defining the problem, identifying learning issues and goals (Barrows & Tamblyn, 1980), narrowing down project scope, identifying factors and constraints, and determining sources of needed information (Nelson, 1999). Due to the complexity of the ill-structured problem, students are required to construct and move across multiple problem spaces in order to decide which problem space is the most relevant and useful (Sinnott, 1989). This is when students' brainstorming, sharing of multiple perspectives, and negotiating a common understanding of the problem (Barrows & Tamblyn, 1980; Schmidt, 1989) would become crucial for ill-structured problem solving (Voss & Post, 1988). The expected result of problem representation is the transformation of an ill-structured problem from an initially fuzzy problem state into a clearer problem state and from vague goals into well-defined goals. The problem representation process is a necessary prerequisite for effective solutions development.

Generating solutions is a natural process in problem solving that follows an elaborative problem representation (Chi & Glaser, 1985). It is a process when problem solvers acquire needed information and resources to address the problem and implement feasible procedures or plans to develop solutions to the problem (Voss et al., 1991). Since ill-structured problem solving involves multiple problem spaces and representations, generating solutions becomes a process of identifying various positions and figuring out how people with different positions would select solutions differently (Jonassen, 1997). In an ideal PBL environment, students are expected to be open to different input and feedback as well as other sources and to negotiate meaning to reach a consensus instead of relying on one single view (Ge & Wang, 2016). The optimal solution is often reached through iterative discussions with peers and through refinements based on the outcome of problem representation as well as formative evaluations of the solution or problem-solving output (Schmidt, 1989).

The iterative process of generating or selecting a solution, as described above, inevitably involves *justifications and construction of argument* (Jonassen, 1997; Kitchner & King, 1981). In PBL, students not only must make informed decisions and select the most viable against alternative solutions but also must support their decisions with defensible and cogent arguments (Jonassen, 1997; Voss & Post, 1988). In doing so, students must be able to examine and evaluate the selected solutions. In this regard, the solution process also involves monitoring and evaluation (Sinnott, 1989).

Monitoring and evaluation are part of the metacognitive activities in ill-structured problem solving (Jonassen, 1997; Voss & Post, 1988). The process of monitoring and evaluation involves both knowledge and regulation of cognition (Brown, 1987; Flavell, 1979; Pressley & McCormick, 1987). *Knowledge of cognition* refers to acquired knowledge about cognitive processes, which can be used to control cognitive processes; *regulation of cognition* refers to active, ongoing monitoring of individuals' cognitive processes based on their knowledge of cognition (Flavell, 1979). Evaluation goes hand in hand with monitoring the solver's cognitive process during problem solving. It is a process of systematic and objective examination concerning the relevance, effectiveness, efficiency, and impact of the solution activities based on problem representation. The evaluation result helps individuals self-regulate their problem-solving processes. In the context of PBL, the final stage of problem solving involves finalizing the solution or project. This should be the stage when students are engaged in conducting the final evaluation or test or revising and completing the final versions of the solution or project (Nelson, 1999). Evidence (e.g., Ge & Wang, 2016) indicates that when students skip the final stage of monitoring and evaluation, the quality of their solutions may suffer.

The Role of Self-Regulation in Ill-Structured Problem Solving

As noted above, self-regulation plays an active role in ill-structured problem solving in PBL, which requires problem solvers to constantly monitor, evaluate, and regulate their problem-solving processes until a feasible, viable, and defensible solution is reached (Ge & Land, 2003; Lynch, Ashley, Pinkwart, & Aleven, 2009). Self-regulation "is an active, constructive process whereby learners set goals for their learning and then attempt to monitor, regulate, and control their cognition, motivation, and behavior, guided and constrained by their goals and the contextual features in the environment" (Pintrich, 2000, p. 453). Pintrich (2000) identified four phases of regulation: *forethought*, *planning, and activation*; *monitoring; control;* and *reaction and reflection*. Each of these phases addresses cognition, motivation/affect, behavior, and context. Drawing from social cognitive theory, Zimmerman and Campillo (2003) identified three phases of self-regulation during problem-solving processes: *forethought* (task-analysis and self-motivating beliefs), *performance* (self-control and self-observation), and *self-reflection* (self-judgment and self-reaction). These key self-regulation processes were evident in Ge and Land's (2003) study on students working on ill-structured problem-solving tasks.

Ill-structured problem solving starts with a problem representation, which involves self-regulative processes of planning, goal setting, and monitoring. The self-regulation process helps learners navigate uncertain problem states, fuzzy situations, and unclear goals in search of solutions (Jonassen, 1997). In the meantime, evaluation skills must be executed to determine whether obtained information is effective for a solution, and it is also necessary to weigh the importance of the selected goals in a given situation (Kluwe, 1987; Kluwe & Friedrichsen, 1985), examine various perspectives, and evaluate the viability of the selected solutions. The evaluation process is also a process of reflection on how the proposed solution would alleviate the causes of the problem, what should be done when a challenge arises, and what values imply if alternative solutions are selected (Voss et al., 1991). Arguably, different phases of self-regulation influence problem-solving processes and outcomes.

Although the majority of the problem-solving literature highlights the cognitive aspects of the problem-solving process, motivation and individual beliefs, which have not been sufficiently addressed, also influence the self-regulation of problem solvers (e.g., Zimmerman & Campillo, 2003). The importance of motivation and beliefs in self-regulation is supported by some self-regulation literature. For instance, Butler and Winne (1995) argued that individual beliefs such as motivational beliefs play an important role in individual goal settings. Pintrich (2000) further argued that self-regulators adopt certain goal orientations and judge their own efficacy. Therefore, we posit that a comprehensive ill-structured problem-solving framework should incorporate motivational and epistemic aspects of self-regulation.

Toward a Theoretical Framework of Self-Regulation in Ill-Structured Problem Solving

In order to capture the dynamics of self-regulation throughout ill-structured problem solving, we propose a framework that integrates ill-structured problem-solving models (Jonassen, 1997; Sinnott, 1989; Voss & Post, 1988) with a self-regulation model (Zimmerman & Campillo, 2003) (Figure 1). We posit ill-structured problem solving as a series of self-regulation processes that feed from one phase to another. Because there are two unique but interrelated stages during the problem-solving processes, namely *problem representation* and *solution generation* (Ge & Land, 2003), the proposed framework identifies two self-regulation cycles—one for *problem representation* and the other for *solution generation* (as demonstrated by the two boxes in Figure 1). The relationship between the two cycles is circular, not linear: a *problem representation* cycle can lead to a cycle of *solution generation*, and the *solution generation* cycle may return to start a new *problem representation* cycle. The relationships between the two cycles are illustrated by the two red dotted-line arrows that connect the two boxes in Figure 1. Within each of the two cycles, there are three self-regulation phases—*planning, execution*, and *reflection* (Zimmerman & Campillo, 2003). Through the iterations of the three phases within each cycle, a plausible problem representation or solution is developed and evaluated, which in turn serves as the input to the

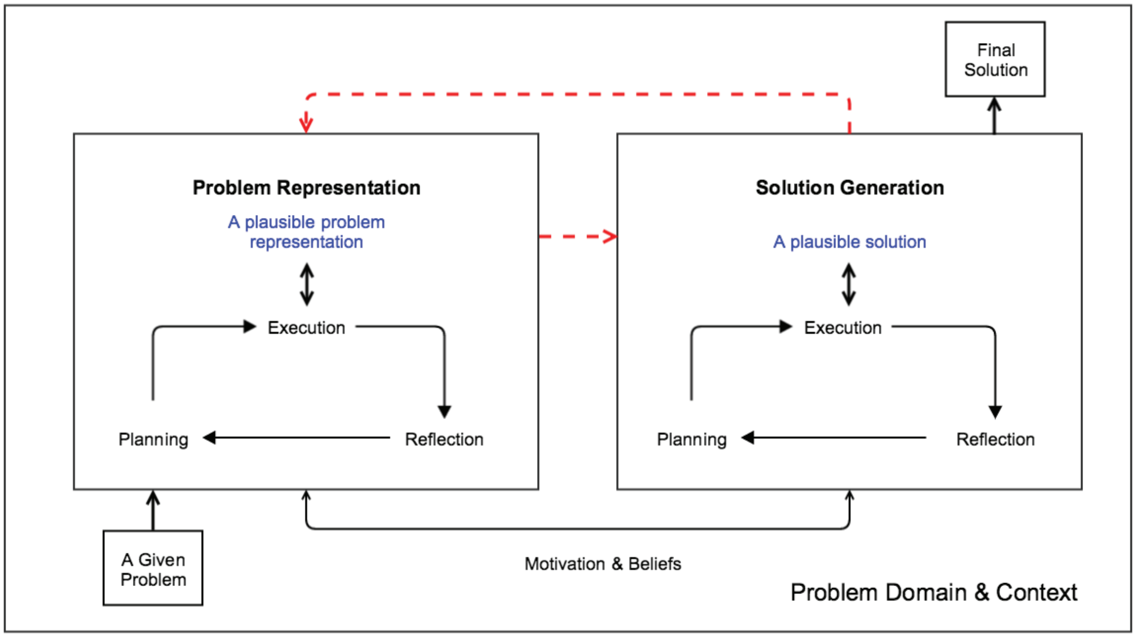

Figure 1. A conceptual framework of self-regulated ill-structured problem solving.

subsequent cycle or stage of problem solving. The iterations continue until a satisfactory solution is reached.

To further identify details of the proposed framework, we purposely selected three different domain contexts that demonstrate similar problem-solving processes and subprocesses: information problem solving (IPS), historical inquiry, and science inquiry. For each of these contexts, we synthesize key literature and a few empirical studies, with the purpose of applying and operationalizing the proposed framework in different contexts, examining detailed self-regulation processes in problem representation and solution generation across the contexts, and drawing common themes for each self-regulation phase illustrated in Figure 1. It should be noted that our accounts here are descriptive of how experts would carry out the tasks in the three naturalistic contexts without any instructional interventions. For clarity, we use *stages* to represent the two key problem-solving processes or cycles (problem representation and solution generation) and *phases* to refer to self-regulation subprocesses (planning, execution, and reflection).

The three contexts, IPS, historical inquiry, and science inquiry are all representative of ill-structured problem solving with key PBL elements and processes. IPS tasks usually present the learner with a problem or a need to address, which requires the learner to identify information needs and search, extract, evaluate, and integrate information to address the problem or need (Brand-Gruwel, Wopereis, & Vermetten, 2005). While an IPS task can range from well-structured to ill-structured, our focus in this article is on ill-structured IPS tasks, such as explaining the relationship between psychological factors and stress or burnout (Wopereis, Brand-Gruwel, & Vermetten, 2008). Brand-Gruwel, Wopereis, and Vermetten (2005) provided a detailed account of IPS processes through empirical studies. Although self-regulation has been highlighted in their model as an integral component, the model does not clearly specify how self-regulation is manifested in different IPS subprocesses. Nonetheless, the empirical account provided us with a window to examine problem solving and self-regulation through our framework.

One form of historical inquiry asks learners to identify the causes of historical events. When a learner is presented with a historical document, there are often events of which the causes are unknown, uncertain, or unreported. In other words, a state of coherence is lacking in the learner's understanding of the causes that explain why an event occurred (Poitras & Lajoie, 2013). In such a case, performing inquiries into the causes of a historical event is an ill-structured problem-solving task with the purpose of reinstating coherence in understanding (Greene, Bolick, & Robertson, 2010; Poitras & Lajoie, 2013). Through their conceptualization and review of empirical studies, Poitras and Lajoie (2013) presented a detailed account of the self-regulatory processes in historical inquiry, which enabled us to analyze historical inquiry processes according to our model.

In science inquiries, learning often begins with a phenomenon, a topic, or a learning challenge that requires scientific investigations to provide explanation, discovers properties of a given domain, or address a certain challenge (Pedaste et al., 2015). To proceed, learners need to conceptualize the problem by questioning and generating hypotheses; design and conduct experiments; record, analyze, and evaluate data; and infer or induce conclusions from data (Pedaste et al., 2015; van Joolingen & de Jong, 1997). Science inquiries often end with communication as well as reflections of findings (Pedaste et al., 2015).

In the sections that follow, we take a closer look at how self-regulation is manifested in the planning, execution, and reflection phases within the problem representation and solution generation stages, respectively. We illustrate the processes across the three contexts while using a particular IPS task as a continuous example. In the example IPS task, learners are asked to investigate how to handle expired food. To do this IPS task, learners have to use the Internet to conduct research and then write a short essay to report their findings (Brand-Gruwel, Wopereis, & Walraven, 2009).

Self-Regulation in Problem Representation

In the stage of problem representation, problem solvers develop a plausible representation of the given problem by performing a task analysis through phases of planning, execution, and reflection. The *planning* phase is characterized by (1) reading task materials, (2) activating prior knowledge and motivational beliefs, and (3) forming initial goals for problem representation. For each of the three problem-solving contexts, the learner would first engage in an attempt to closely read an IPS task (Brand-Gruwel et al., 2005), a historical document (Poitras & Lajoie, 2013), or a challenge or topic in science (Pedaste et al., 2015). Based on the readings, the learner may recall relevant prior knowledge, which may include both content knowledge related to the task and learner's conceptualization of domain standards. In the case of historical inquiry, a domain standard can be the criterion of causality; that is, "consequent activities should logically follow from their antecedents" (Poitras & Lajoie, 2013, p. 219). In addition to recalling prior knowledge, the learner also activates personal motivational beliefs, such as epistemic beliefs, self-efficacy beliefs, goal orientations (Zimmerman & Campillo, 2003). By relating prior knowledge and personal beliefs to the task at hand, the learner may form some initial, implicit goals for problem representation that may include an anticipation of what the goal state of the problem would look like (Lazonder & Rouet, 2008).

To illustrate the *planning* phase with the IPS example, we describe how a ficticious individual named John, who has expertise in IPS, goes about performing the task. John would first read the specific task requirements, which include (1) the questions to be responded (How should one handle food that is expired? Can you continue to eat them?), (2) the expected procedure (Internet research), and (3) the product (an essay to report findings). Upon reading the task, John may recall that he had always been told not to eat expired food and had always thrown it away. While believing that he may not know the entire truth, John implicitly decides to find out whether there is something more to his current understanding.

With the initial goals, the learner moves to the *execution* phase. In this phase, the learner (1) applies prior knowledge and sometimes refers to additional information or resources provided by the task to further interpret and analyze the problem at hand, (2) identifies key components of the problem, and (3) formulates a problem representation. In historical inquiries, learners may apply prior knowledge or refer to additional resources on hand to examine the historical document and may identify events depicted in the document that has unknown, uncertain, or unreported causes (Poitras & Lajoie, 2013). In the case of science inquiry, learners may apply prior knowledge to identify the variables involved in a science problem and subsequently formulate preliminary research questions and hypotheses regarding the relationships among the variables (Pedaste et al., 2015; van Joolingen & de Jong, 1997). While such execution processes may not be externalized or observed from the outside, the identified key components of the problem and their interrelationships become "an internal model of the task or problem at hand" (Lazonder & Rouet, 2008, p. 755), or the representation of the problem.

In the example IPS task, the individual, John, may apply his prior knowledge to the problem to identify information gaps (Brand-Gruwel, Wopereis, & Vermetten, 2005). By considering his prior knowledge and experience, John may determine what is currently unknown to him. For example, he may wonder that although he always throws away expired food, he does not really have any scientific evidence to support this decision. Consequently, John may conceptualize the IPS task as a search for scientific evidence regarding the handling of expired food.

The problem representation developed through the first planning-execution iteration may not be fixed, especially when a problem is complex and ill-defined. Instead, the representation is subject to the learner's mental deliberation. While a novice learner may simply move to the solution generation stage with the first problem presentation, a skillful problem solver is likely to stay longer in the problem representation stage by engaging in *reflections* (Brand-Gruwel, Wopereis, & Vermetten, 2005; Brand-Gruwel, Wopereis, & Walraven, 2009). In this phase, learners evaluate the completeness and accuracy of the problem representation. To do this, they often need to go back to reread the task, recall additional prior knowledge, or consult additional information and resources. In science inquiry, learners may revisit the original challenge or task to ensure that the initial research questions and hypotheses are indeed aligned with the problem. When it is deemed that the initial conceptualization does not adequately represent the problem, another round of planning, execution, and reflection may begin. The iterative phases of planning-execution-reflection help the learner develop a more complete problem representation. Although this process may take several iterations, it can be a relatively fast process in many cases, which often takes place without the construction of any tangible artifacts and with only a mental schema of the problem.

To illustrate the process with the IPS example, after forming the initial conceptualization of the IPS task as a result of the *execution* phase, John, as a skilled problem solver, decides to revisit the task description to find out if his current understanding fully captures what the task entails. He may identify additional details he overlooked previously, or he may recall additional prior knowledge (e.g., Zhou, 2013a). For example, he may recall incidences he read about food poisoning due to spoiled food. Through another iteration of planning and execution, he may add food safety as an important dimension to his initial conceptualization of the IPS task. When John believes that he has a good understanding of the problem, the problem representation then feeds to the subsequent solution generation stage.

Self-Regulation in Solution Generation

Problem solving moves to the *solution generation* stage when learners are satisfied with their representation of the problem. In a sense, the mental representation of the problem feeds into and serves as an input to solution generation (see the shorter red dotted-line arrow in Figure 1). Similar to the problem representation stage, the solution generation stage starts with *planning*. Based on the problem representation, the learner (1) plans for strategies for solutions, (2) identifies resources and tools for developing solutions, and (3) recalls procedural knowledge required to execute solutions. For IPS and historical inquiry, the planning may involve the formulation of specific questions and subquestions, the identification of information sources and search tools, and planning for search strategies such as query terms. For science inquiry, the planning often involves the design of experiments. Learners may identify equipment and materials needed for an experiment as well as specific variables to be investigated and strategies to manipulate the variables (van Joolingen & de Jong, 1997). Problem representation plays an instrumental role in solution planning. For example, in the context of IPS, planning for appropriate query terms hinges on an adequate understanding of the problem (Argelagós & Pifarré, 2012).

Continuing the IPS example, as John plans for the task solution, he may recall the procedures for Internet searching and identify a particular browser and search engine as tools for the search. Based on the problem representation formulated earlier, he plans a few query terms such as "handling expired food" and "food safety." Since he intends to find scientific evidence about the topic, he may decide to pay more attention to the source of the information from his search. In the meantime, he may also start to consider how the beginning of the report, or even the structure of the report, should look.

In the *execution* phase, learners apply domain-specific procedural knowledge and task strategies to perform a series of tasks. For IPS, the tasks include implementing queries, scanning search results, identifying relevant websites, close reading, organizing and integrating information, and compiling a response or presentation (Brand-Gruwel et al., 2005). For historical inquiry, the tasks may involve searching and reading information, formulating explanations, and corroborating information (Greene et al., 2010; Poitras & Lajoie, 2013). In science inquiry, the learner needs to systematically manipulate variables, make observations, and gather, analyze, and interpret data (van Joolingen & de Jong, 2007). In addition to performing procedural steps, learners may also apply task strategies such as highlighting, note taking, and systematic data recording (de Jong & van Joolingen, 1998; Zhou, 2013b). *Execution* is the most clearly observable phase among all the three phases in both problem representation and solution generation stages. It is also a phase that varies the most in different problem-solving contexts.

Learners do not perform all the procedures in the *execution* phase before reaching the *reflection* phase. While performing an execution task at any time, they may feel the need to monitor and evaluate the progress. Thus, the foci of the reflection phase include two aspects: the process and the results of a solution. In IPS, while scanning and reviewing search results or the content of a website, learners may evaluate the trustworthiness of the information or judge the relevance of the information to their problem representation (Lazonder & Rouet, 2008; Walraven, Brand-Gruwel, & Boshuizen, 2009). If the search is deemed not fruitful, the learner may go back to the *planning* phase to identify new search tools or formulate new query terms. In historical inquiry, learners need to constantly monitor their state of understanding in light of new information to evaluate whether the new information helps answer the questions and whether the coherence between an event and causes has been achieved in the inquiry process. In science inquiry, the learner may continuously engage in a mindful coordination between hypotheses and evidence gathered from experiments and draw evidence-based conclusions (Klahr & Dunbar, 1998; Zhang, Chen, Sun, & Reid, 2004). At times, the process may lead back to the planning and execution of another experiment (Pedaste et al., 2015).

In the IPS example, John's *execution* and *reflection* phases are closely intertwined. While entering query terms in a search engine, scanning the search results, reviewing particular websites from the search results, or drafting the report, John continuously evaluates and monitors the progress, with his problem representation acting as a guiding factor. For example, among the search results, he may be more inclined to visit a Centers for Disease Control and Prevention website due to its credibility; he may pay more attention to the results and information related to food safety due to their relevancy to his problem representation. If he finds it difficult to locate the needed information, he may go back to the *planning* phase to adjust his original queries.

In addition to returning from the *execution* to the *planning* phase upon reflection in the solution stage, learners may also return to the *problem representation* stage to adjust their mental representations of the problem (Argelagós & Pifarré, 2012), which is indicated by the longer red dotted-line arrow in Figure 1. Even in the final stage of IPS—information organization and presentation—the learner may still revisit the problem representation stage in an effort to align the compiled response or presentation with the task requirements (Argelagós & Pifarré, 2012). From time to time in historical inquiry, learners may need to go back to the original document to reevaluate inquiry questions, identify additional pieces of information that may enrich the problem representation, or even formulate new problem representations. In conducting science inquiries, learners may need to revisit the original research questions and hypotheses to ensure that the conclusions drawn from an experiment adequately address the problem. If necessary, new research questions and hypotheses may be generated, and new experiments may be planned and executed. The return from solution generation to problem representation stage is usually triggered by the learner's judgment that the solution progress or result is inadequate and that replanning of solution does not lead to productive improvement. Thus, ill-structured problem solving involves iterative cycles of processes (problem representation and solution generation) and subprocesses (planning, execution, and reflection), with each cycle potentially bringing the learner closer to the problem solution (Poitras & Lajoie, 2013).

To illustrate with the IPS example, as John reviews his search results, he may find that handling of expired food varies by types of food. Upon reflection, another round of problem-solving processes and subprocesses may begin. He may return from the problem solution stage to the problem representation stage (illustrated with the longer red dotted-line arrow in Figure 1) by revisiting the original IPS task and adjusting his understanding, or representation, of the problem to incorporate types of food as an additional dimension. Accordingly, he may travel back to the problem solution stage again to conceptualize and search with new query terms such as "dairy products," which indicate another type of food, to locate more specific information.

The Role of Motivation and Beliefs

Motivation and beliefs have been identified as crucial components in self-regulation (Boekaerts, 1997; Pintrich, 2000). Zimmerman and Campillo (2003) argued that underlying the problem solvers' goal setting and strategic planning activities are their self-motivational beliefs. In our model with two separate self-regulation cycles for problem representation and solution generation, respectively, we posit that motivation and beliefs act on different phases of both problem-solving stages. For example, in the planning phase of problem representation, learners' motivation and beliefs may influence their anticipated goal state of the problem, which in turn may influence subsequent phases in problem representation and solution generation. In the reflection phase, learners' epistemic beliefs may influence how they conceptualize a problem, evaluate new information or data, and incorporate the new information or data into the final solution. We use IPS and science inquiry as two contexts to illustrate the effects of motivation and beliefs in problem solving.

When a learner reads an IPS task, he recalls his prior knowledge related to the task and activates his motivation and beliefs. Suppose that his achievement goals are oriented toward performance-avoidance—that is, avoiding demonstration of incompetence in an undesirable situation (Elliot & Church, 1997); he may reduce the goal state of the problem to the search for a perfect website with the answer to the IPS problem (Wallace, Kupperman, Krajcik, & Soloway, 2000). This anticipation of the goal state may influence his subsequent self-regulative behaviors in solving the IPS problem. For instance, Zhou (2013b) found from students' information search trace data that performance-avoidance-dominant students were less capable of constructing effective search queries in their information search. Interestingly, she found that 19 out of 28 students in this group started their search by using the entire IPS task question as the query term. Further, these students tended to extract information from searches to compile responses without sufficient evaluation of the information.

In science inquiry, learners often face anomalous data that do not align with their understanding or hypotheses. While an appropriate response would be to evaluate the alignment between experimental findings and hypotheses, reflect on causes, and make necessary adjustments, Chinn and Brewer (1993) found that learners would discount anomalous data in various ways to defend their original theory. Researchers have linked such behaviors to learners' epistemic beliefs (e.g., Pintrinch, Marx, & Boyle, 1993; Qian & Alverman, 1995; Windschitl & Andre, 1998). Recent research has identified epistemic beliefs as a mechanism that influences the goal standards a learner adopts in self-regulated learning (Muis, 2007; Muis & Franco, 2009). Relating to the proposed model, we conjecture that personal beliefs may have predisposed learners in their approaches to the planning, execution, and reflection across the two problem-solving stages.

Implications for Research and Practice in PBL

Implications for Research

The proposed framework contributes to the theoretical development of ill-structured problem solving and self-regulation in multiple ways. Problem solving is considered a goal-oriented activity from the perspective of self-regulation (Pintrich, 2000). Traditional models (e.g., Zimmerman & Campillo, 2003) depict problem solving as a single-loop process in which problem solvers aim at one single goal—finding the correct solution. However, the proposed framework suggests that in solving an ill-structured problem, problem solvers have to iteratively achieve two goals: defining the problem and finding a solution. In fact, ill-structured problem-solving literature suggests both problem representation and solution as iterative processes that go through constant monitoring, evaluation, and modifications throughout problem-solving activities (e.g., Hong, & Choi, 2011; Stepich & Ertmer, 2009). Thus, we expanded Zimmerman and Campillo's (2003) self-regulation model to incorporate multiple goals within a self-regulation framework.

Another contribution of the new model is the integration of motivation and beliefs in the conceptualization of self-regulated ill-structured problem solving. Although motivation and individual beliefs are important components in the existing self-regulation models (e.g., Boekaerts, 1997; Butler & Winne, 1995; Muis, 2007; Pintrich, 2000; Zimmerman, 1995), they have received little attention in the problem-solving literature. Mayer (1998) suggested that motivation concerns such as interest, self-efficacy, and attribution are important factors in problem solving. Unfortunately, it was not clear how motivation and beliefs fit into a problem-solving model. By utilizing a self-regulation lens to examine problem solving, the proposed framework allows us to explicitly integrate motivation and beliefs as antecedents influencing problem solvers' representation and solution processes. There were some studies examining the relationship between epistemic belief and self-regulation using questionnaires (e.g., Muis, 2007; Muis & Franco, 2009). However, those studies did not focus on the complex and dynamic relationships between epistemic beliefs and self-regulation in an ill-structured problem-solving context. Therefore, future research can refer to this proposed model to empirically test the relationship between epistemic beliefs and self-regulation in the context of ill-structured problem solving.

Implications for Designing PBL Environments

The current conceptual framework will help us to design scaffolding specifically aimed at facilitating self-regulation in PBL, which also helps us to develop assessment for self-regulation in PBL. The current PBL literature suggests various tools and strategies to scaffold PBL, such as question prompts, expert modeling, concept mapping, and peer interactions (e.g., Ge & Land, 2003; Pedersen & Liu, 2002; Cho & Jonassen, 2002; Lai & Law, 2006). However, it is unclear what, when, and how various tools are used to scaffold learners in PBL (Ge, Law, & Huang, 2012). With an illustration of the dynamic interrelationships between ill-structured problem solving and self-regulation and highlights of major characteristics of self-regulation in each of the problem-solving stages, this framework provides us with guidelines to design scaffolds that address the "what," "when," and "how" questions.

This framework reveals specific self-regulation activities in each of the ill-structured problem-solving stages. For instance, planning during problem representation includes activating prior knowledge, understanding tasks, and formulating goals, while planning during solution generation involves strategic planning and identifying resources. Therefore, it is necessary to consider providing contextualized scaffolds for a particular problem-solving stage during PBL.

In addition, this framework also emphasizes the importance of scaffolding students for the iterative self-regulation phases across different problem-solving stages, especially from solution generation back to problem representation. Novice problem solvers tend to stick to their initial problem representation and try to figure out a solution based on the initial representation, while expert problem solvers would reflect on and revise their problem presentations before reaching a solution (e.g., Hong & Choi, 2011). Therefore, PBL practitioners should help students to develop more sophisticated self-regulation skills, such as continuously and purposely reflecting on plausible solutions and updating problem representations accordingly.

Finally, the self-regulation phases identified in the framework would help educators and researchers map out various assessment points for evaluating students' self-regulation and problem-solving competence. This evaluation process would inform the instructional design of PBL and provide both educators and researchers with rich learning analytics data to identify ways to improve learners' PBL experience.

Conclusion

In this article, we have proposed a conceptual framework demonstrating the dynamic nature of self-regulation in ill-structured problem solving. In addition, through three domain contexts we have also described problem solvers' self-regulation phases during different stages of ill-structured problem solving. We hope that this conceptual framework can be used as a research tool to provide insight into (1) self-regulation activities that emerge in different problem-solving processes and subprocesses, (2) designing effective instructional scaffolds to support self-regulation in PBL, and (3) developing valid and reliable instruments to measure both self-regulation and ill-structured problem-solving skills.

This framework only addresses ill-structured problem solving by a solo problem solver, whereas problems are often solved collaboratively in PBL (Hmelo-Silver, 2004). Therefore, we recognize the limitation of this framework. As the context of learning moves from individual to collaborative learning, the nature and processes of self-regulation also change. The goals and the processes of self-regulation become more complicated with the involvement of multiple self-regulators. In the future, we hope to extend our PBL research from examining self-regulation to investigating coregulation and socially shared regulation in the context of ill-structured problem solving, with insights gained from previous research (e.g., Efklides, 2008; Malmberg, Järvelä, Järvenoja, & Panadero, 2015; McCaslin, 2009; Volet, Summers, & Thurman, 2009; Winne, 2015).

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