Development and Validation of the Engineering Design Metacognitive Questionnaire

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Development and Initial Validation of the Engineering Design Metacognitive Questionnaire

Abstract

Metacognition is the process of thinking about thinking, which refers to students' ability to control cognition to ensure that learning goals are achieved or a problem is solved. It is a complex process that depends on and influences students' understanding about themselves as thinkers and learners, and usually precedes and follows cognitive activity. Metacognitive skill plays a particularly critical role in real-life or open-ended tasks, such as solving ill-structured design problems. While there is growing interest in metacognitive research, few assessment tools have been developed in the context of engineering design, particularly within classroom environments. The objective of the present paper is to discuss the process of Engineering Design and Metacognitive Questionnaire (EDMQ) development and initial validation, specifically the process of face and content validity.

The instrument development is grounded in Butler and Cartier's self-regulated learning (SRL) model which describes the interplay between motivation, cognition, and metacognition within academic activities such as design. The questionnaire is adapted from their works include the Inquiry Learning Questionnaire and the Learning through Reading Questionnaire. A rubric matrix combined Butler and Cartier's SRL features and the Dym and Little's design process and team management components was used in the instrument development. Dym and Little contended that the design process consists of five phases: problem definition, conceptual design, preliminary design, detailed design, and design communication.

The EDMQ include items that address cognitive strategies both in design process and team management activities. Three subsections of the EDMQ were designed to capture students' perception of metacognition at the early, middle, and final stages of the design task across design processes, respectively; the first subsection of EDMQ captures task interpretation and planning strategies; the second subsection captures cognitive actions and monitoring and fix-up strategies; the third subsection captures students' judgment of their design outcomes.

Six undergraduate engineering students were invited in the face validity process. Moreover, the content validity involved two engineering professors and two experts in self-regulated learning. The resulting survey instrument contains 127 questionnaire items assessing five SRL features: task interpretation, planning strategies, cognitive actions, monitoring and fix-up strategies, and criteria of success. This survey instrument may be useful for cognitive and metacognitive research and assessing design processes in the context of engineering design project.

Keywords: engineering design, instrument development, metacognitive, questionnaire

INTRODUCTION

Metacognition is the process of thinking about thinking, which refers to students' ability to control cognition to ensure that learning goals are achieved or a problem is solved. It is a complex process that depends on and influences students' understanding about themselves as thinkers and learners, and usually precedes and follows cognitive activity. Butler found that a student's understanding of a learning activity is grounded in productive metacognition about tasks associated with students' thoughtful planning, self-monitoring, and selection of appropriate strategies to accomplish task objectives [1]. Metacognitive skill plays a particularly critical role in real-life or open-ended tasks, such as solving ill-structured design problems.

Metacognition is critical to the self-evaluation of one's knowledge and abilities [2], which is essential in mathematics [3, 4], science [5, 6], technology [7, 8], engineering [9-11], and instructional design [12-14]. Studies suggest that metacognition not only enhances learning outcomes; it also encourages students to be self-regulated learners who are "metacognitively, motivationally, and behaviorally active participants in their own learning process" [15, p. 329]. A recently completed STEM Talent Expansion Program (STEP) project [16], which implemented a number of projects in first-year engineering courses at Texas A&M University, found that students lacked the abilities needed to manage learning and problem-solving.

While there is growing interest in metacognitive research, few assessment tools have been developed in the context of engineering design, particularly within classroom environments. The objective of the present paper is to discuss the process of Engineering Design and Metacognitive Questionnaire (EDMQ) development and initial validation, specifically the process of face and content validity. No statistical test was conducted at this initial validation process.

METACOGNITIVE AND COGNITIVE STRATEGIES IN ENGINEERING DESIGN

The influence of metacognition in learning and problem solving has been demonstrated extensively [5, 10, 17-22]. A student uses good metacognitive skills to oversee his or her learning process, plan and monitor ongoing cognitive activities, and compare cognitive outcomes with internal or external standards. The dynamic and iterative interplay between metacognitive and cognitive activity is described by Butler and Cartier [23-25] in the Self-Regulated Learning (SRL) model, which characterizes SRL as a complex, dynamic, and situated learning process [26]. This model involves six central features that interact with each other: (1) layer of context; (2) what individuals bring; (3) mediating variables; (4) task interpretation and personal objectives; (5) self-regulating strategies; and (6) cognitive strategies.

First, layers of context may include learning environments such as school, classroom, teachers, instructional approaches, curricula, and learning activities. In engineering education, contexts include learning expectations in engineering as a field of study, the nature of engineering design tasks, and the expectations of particular instructors in different settings. The second feature is what individuals bring to the contexts (e.g., strengths, challenges, interests, and preferences). Third, mediating variables include students' knowledge, perceptions about competence and control over learning, and perceptions about activities and tasks. The fourth feature is student task interpretation and personal objectives. Interpretation of task demands is a key determinant of the goals set while learning, strategies selected (i.e., the fifth feature) to achieve those goals, and the criteria used to self-assess and evaluate outcomes [24-26]. Students set personal objectives such as achieving task expectations to direct their engagement in learning. Sixth, students manage their engagement in academic work by using a variety of self-regulated learning: planning, monitoring, evaluating, adjusting approaches to learning, and managing motivation and emotions.

Design, a central part of engineering education, helps students develop problem-solving ability, critical thinking, and creativity. Design may have numerous solution paths and be bound by constraints, which are not always presented with the problem. Because students engage in ubiquitous, complex and ill-structured problem-solving, the SRL features dynamically interact and influence how they solve a design task. Engineering design tasks require effective self-regulation.

Solving an engineering design problem is a structured and staged process. The ways in which students use strategies, observe what transpires, and search for alternative solutions are rich examples of how metacognition is applied in design activities. Dym and Little [27] contended that the design process consists of five phases: problem definition, conceptual design, preliminary design, detailed design, and design communication. Similar models were proposed by Christiaans [28] and Cross [29]. These design phases are considered as high-level overall views of design processes. They involve a sequence of actions or strategies that are self-contained cognitive approaches and relate to the current state of the design process.

The survey development uses Dym and Little's [27] five-stage prescriptive model to categorize and code cognitive engineering design strategies and evaluate students' metacognitive activities during the five design phases (i.e., problem definition, conceptual design, preliminary design, detailed design, and design communication). This design model was selected for two reasons. First, it categorizes the design process into five main phases with specific cognitive strategies in each phase. Second, the model offers clear coding categories for student cognitive strategies in engineering design. Each survey item was developed to indicate student activity associated with Dym and Little's design process and relevant SRL features.

QUESTIONNAIRE DEVELOPMENT AND INITIAL VALIDATION

The instrument development is grounded in Butler and Cartier's self-regulated learning (SRL) model which describes the interplay between motivation, cognition, and metacognition within academic activities such as design. The questionnaire is adapted from their works include the Inquiry Learning Questionnaire and the Learning through Reading Questionnaire [25]. A rubric matrix combined Butler and Cartier's SRL features and the Dym and Little's design process was used in the instrument development (see Tables 1 and 2). Dym and Little contended that the design process consists of five phases: problem definition, conceptual design, preliminary design, detailed design, and design communication. The SRL columns capture essential SRL features: task interpretation, planning strategies, cognitive actions, monitoring and fix-up strategies, and criteria students associated with success.

The survey instrument consists of three subsections to capture students' perception of self-regulated learning features (i.e., task interpretation, planning strategies, strategic actions, monitoring & fix-up strategies, and criteria of success) at the early, middle, and final stages of the design task, respectively. It means that during the data collection, students will be asked to complete three different sets of survey instrument. The first subsection of EDMQ will capture students' strategies during Problem Definition and Conceptual Design stages. The second subsection will capture students' strategies during Preliminary and Detailed Design stages. The last, the third subsection will capture students' strategies during Design Communication stage. Measurement scales of items for both instruments ranged from 1 to 4 (i.e., 1 = almost never, 2 = sometimes, 3 = often, 4 = almost always). For data analysis, comparison between mean values of all SRL items for each feature across design phases may be conducted to evaluate gaps among SRL features (similar to data analysis method used in [30]).

Table 1. A Design Process Rubric Matrix of Butler and Cartier's SRL Features and the Dym and Little's Design Phases

		Self-Regulated Learning Features				
		Task interpretation (TI)	Planning strategies (PS)	Cognitive actions (CA)	Monitoring and fix-up strategies (MFU)	Criteria of success (CS)
Dym and Little's Design Phases	Problem definition (Pdf)	5 items (TI-Pdf)	6 items (PS-Pdf)	6 items (CA-Pdf)	7 items (MFU-Pdf)	5 items (CS-Pdf)
	Conceptual design (Cde)	7 items (TI-Cde)	7 items (PS-Cde)	8 items (CA-Cde)	9 items (MFU-Cde)	7 items (CS-Cde)
	Preliminary design (Pde)	2 items (TI-Pde)	2 items (PS-Pde)	2 items (CA-Pde)	2 items (MFU-Pde)	2 items (CS-Pde)
	Detailed design (Dde)	2 items (TI-Dde)	2 items (PS-Dde)	2 items (CA-Dde)	2 items (MFU-Dde)	2 items (CS-Dde)
	Design communication (Dcom)	2 items (TI-Dcom)	2 items (PS-Dcom)	2 items (CA-Dcom)	2 items (MFU-Dcom)	2 items (CS-Dcom)

Table 2. A Team Management Rubric Matrix of Butler and Cartier's SRL Features and the Team Management Components

		Self-Regulated Learning Features				
		Task interpretation (TI)	Planning strategies (PS)	Cognitive actions (CA)	Monitoring and fix-up strategies (MFU)	Criteria of success (CS)
Team Management Components	Time	1 item (TI-Time)	1 item (PS-Time)	2 items (CA-Time)	2 items (MFU-Time)	1 item (CS-Time)
	Resources (e.g., materials/tools, information, skills, funding) (Cde)	1 item (TI-Resources)	1 item (PS-Resources)	3 items (CA-Resources)	5 items (MFU-Resources)	1 item (CS-Resources)
	Teamwork	1 item (TI-Teamwork)	1 item (PS-Teamwork)	5 items (CA-Teamwork)	4 items (MFU-Teamwork)	1 item (CS-Teamwork)

Questionnaire validation in the current paper consists of face and content validity. The validity process began with inviting two SRL experts to review the questionnaire and provide comments about the use of SRL constructs on each item. This was an iterative process to evaluate the proper wording on each item for identifying specific SRL feature being assessed. As a result of this process, revisions were made. The evaluation of face and content validity were then conducted by inviting students and engineering design instructors to read the questionnaire items and briefly describe their interpretation of each item. Six undergraduate engineering and three instructors who teach engineering design capstone project were invited in the face and content validity process. While the students focused their attention on the improvement of wording, the instructors focused their evaluation beyond the wording issues such as whether each of those survey items was relevant in their capstone design project. Interview sessions were later conducted for further inquiries and clarifications of their comments about the survey. Revisions were made based on their feedback and the revised questionnaire was returned back to the same students and instructors for their final comments. Final revision was then made based on their final comments.

The resulting survey instrument contains 127 questionnaire items assessing five SRL features: task interpretation (21 items), planning strategies (22 items), cognitive actions (30 items), monitoring and fix-up strategies (33 items), and criteria of success (21 items). Data associated with these five SRL features may be collected at different stages of the design project (e.g., early, middle, final stages of the design project). Examples of the questionnaire items can be read in Tables 3-7.

Table 3a. An Example of *Task Interpretation* Questionnaire Items Across Design Phases

Design phase	Questionnaire item example
Problem definition	When I am defining my design problem, I need to identify the design goals.
Conceptual design	When I am generating solution ideas, I need to look for possible design alternatives.
Preliminary design	When I am working on my selected design, I need to build and analyze the chosen design model.
Detailed design	When I am finalizing my design, I need to refine and optimize the investigated design.
Design communication	When I am communicating my design solution, I need to communicate the processes and outcomes of my final design in detail.

Table 3b. An Example of *Task Interpretation* Questionnaire Items Across Team Management Components

Design phase	Questionnaire item example *When I am working with my team…*
Time	I need to ensure that my contribution to the team will deliver the design tasks in a timely manner.
Resources	I need to seek relevant resources (e.g., materials/tools, information, skills, funding) needed.
Teamwork	I need to do my fair share in an overall team's effort to complete the project.

Table 4a. An Example of *Planning Strategies* Questionnaire Items Across Design Phases

Design phase	Questionnaire item example
Problem definition	As I start defining my design problem, I read the design description (or brief) to identify design goals.
Conceptual design	As I start generating solution ideas, I identify my options to come up with a better design solution.
Preliminary design	As I start working on my selected design, I collect the design requirements, assumptions, or specifications for functions and the chosen design to develop a design model.
Detailed design	As I start finalizing my design, I identify necessary adjustments needed to optimize the chosen design.
Design communication	As I start thinking about how to communicate my design solution, I identify, gather, and organize the information that needs to be communicated to various audiences such as my client, teacher, friends.

Table 4b. An Example of *Planning Strategies* Questionnaire Items Across Team Management Components

Design phase	Questionnaire item example *As I start working with my team,*
Time	I ensure that I have a working schedule to follow throughout the design process.
Resources	I identify potential resources (e.g., materials/tools, information, skills, funding) to complete the design project.
Teamwork	I identify and clarify my part in the team's effort to arrive at a solution.

Table 5a. An Example of *Cognitive Actions* Questionnaire Items Across Design Phases

Design phase	Questionnaire item example
Problem definition	When I am defining my design problem, I am collecting relevant measurements (or quantifications) of the design goals.
Conceptual design	When I am generating solution ideas, I am searching for potential ways to better solve my design problems.
Preliminary design	When I am working on my selected design, I am developing and using physical (or mathematical) models (representations) that represent the actual chosen design.
Detailed design	When I am finalizing my design, I am fine-tuning the design to produce better performance.
Design communication	When I am communicating my design solution, I am drafting a final design report, creating drawings, or developing an oral presentation.

Table 5b. An Example of *Cognitive Actions* Questionnaire Items Across Team Management Components

Design phase	Questionnaire item example *When I am working with my team,*
Time	I am estimating the time needed to accomplish each part of the design tasks.
Resources	I am searching for, selecting, and using working materials/tools, information, and funding sources we need.
Teamwork	I am negotiating the role that I have to play and tasks that I have to do with my teammates.

Table 6a. An Example of *Monitoring and Fix-Up Strategies* Questionnaire Items Across Design Phases

Design phase	Questionnaire item example
Problem definition	While I define my design problem, I am clarifying the design goals with design team/client.
Conceptual design	While I generate solution ideas, I am determining whether I need to look for alternative design solutions.
Preliminary design	While I work on my selected design, I am judging whether my design model reflects my final design.
Detailed design	While I finalize my design, I am judging whether further adjustments are needed to improve the design performance.
Design communication	While I communicate my design solution, I am thinking about how I could improve the design communication and finalize the delivery of those communications.

Table 6b. An Example of *Monitoring and Fix-Up Strategies* Questionnaire Items Across Team Management Components

Design phase	Questionnaire item example *While I work with my team,*
Time	I am thinking about how much time is left, what I still have to do.
Resources	I am asking myself if I have found and selected appropriate resources.
Teamwork	I am asking myself whether the negotiation I made to determine my role in my team is fair and making necessary adjustment if needed.

Table 7a. An Example of *Criteria of Success* Questionnaire Items Across Design Phases

Design phase	Questionnaire item example
Problem definition	After defining my design problem, I know that I have done a good job when I am able to develop a list of final design goals.
Conceptual design	After generating solution ideas, I know that I have done a good job when I am able to consider all possible design solutions.
Preliminary design	After working on my selected design, I know that I have done a good job when I am able to develop a model that reflects the actual final design.
Detailed design	After finalizing my design, I know that I have done a good job when I am able to come up with a detailed and optimized design.
Design communication	After communicating my design solution, I know that I have done a good job when I am able to produce a final written design report, final drawings, or oral presentation to the client containing design information.

Table 7b. An Example of *Criteria of Success* Questionnaire Items Across Team Management Components

Design phase	Questionnaire item example *After working with my team, I know that I have done a good job when…*
Time	I ensure that my contribution had helped my team finish our design tasks on time.
Resources	I find and use relevant resources (e.g., materials/tools, information, skills, funding).
Teamwork	I am able to do my fair share in my team's accomplishments.

CONCLUSION AND FURTHER WORK

In this paper, we have outlined and described the process of engineering design metacognitive questionnaire development and initial validation. A rubric matrix combined Butler and Cartier's SRL features and the Dym and Little's design process and the team management components in the instrument development. While engineering students were invited to evaluate the questionnaire items for face validity, SRL experts and engineering professors were invited to conduct content validity of the questionnaire. The resulting survey instrument contains 127 questionnaire items assessing five SRL features. Despite of several challenges in the survey development process, the researchers believe that this survey will benefit not only engineering instructors and policy makers, but also the students. This developed survey instrument may be useful for cognitive and metacognitive research and assessing design processes in the context of engineering design project such as senior capstone design course. Further data collection effort will be carried out for a construct validity process by inviting approximately 300 senior engineering students who are working on their capstone design projects across nation (e.g., Colorado, Indiana, Texas, Utah).

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