Development and Validation of the Uncertainty Management in Problem-Based Learning Scale in Postsecondary STEM Education

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Abstract
In problem-based learning (PBL), individual differences in students' use of metacognition and self-regulation skills exist and calls for extensive research in postsecondary STEM education. This study focuses on students' uncertainty management in PBL. A scale of the uncertainty management in PBL (UM-PBL) was developed. Exploratory factor analysis was conducted and showed that the UM-PBL has substantial reliability and a total of 14 items across three constructs of a) perception of uncertainty in learning to solve problems, b) self-efficacy in and c) strategy for uncertainty management. Gender differences in the first two constructs were found, confirming its known-group validation. Students' problem-solving scores were positively correlated with scores of the first two constructs, suggesting its predictability of its relationship with academic performance.

1. Introduction

In postsecondary STEM education, problem-based learning (PBL) has shown its effectiveness in promoting students' higher-order thinking skills, academic achievement, as well as students' motivation (Wahono et al. 2020). PBL is a student-centered instructional method where students can construct their content knowledge and acquire problem-solving skills through the experience of solving authentic complex problems (Hmelo-Silver, 2004). Central to this productive learning in PBL is "student use of metacognition and self-regulation skills" (Marra et al., 2014, p.230). Students need to be aware of what they are certain and uncertain, what they do and do not understand, and what they can and cannot do in learning processes. Also, students become more responsible for regulating their problem-solving and/or sensemaking strategies and actions when compared to the classes where teachers regulate or help students regulate their learning (Marra et al., 2014). However, nonnegligible individual differences in students use of metacognition and self-regulation skills as well as problem-solving skills exist and calls for extensive research on this issue. A large volume of studies have highlighted that several learner characteristics across (meta-)cognitive (Lee & Chen, 2009), regulative (Meyer et al., 1997), and self-efficacy (Dunlap, 2005) can greatly influence the effectiveness of PBL on individual learning outcomes.

Among the learner characteristics that influence student learning in PBL is the students' *uncertainty management in PBL* this paper focuses on. Uncertainty management has been rarely explored but can be understood closely related to one's metacognition and regulation. Uncertainty refers to "a subjective experience of being aware that one has incomplete knowledge, information, ability or skills" to understand relevant knowledge and solve problems (Park et al., 2022, p. 1118). By uncertainty management, we refer to intentional activities that involves recognizing the fact that one is uncertain and regulating one's learning and thinking process by using strategies of increasing, maintaining, reducing, and postponing one's uncertainty (Chen et al., 2019; Chen & Techawitthayachinda, 2021). Given that management of uncertainty starts with recognition of it and requires regulation of one's actions during the process of it, uncertainty management can be understood in relation to metacognitive and regulative aspects of student learning.

However, little research has explored how (well) students manage their uncertainty in PBL and how such characteristic can be measured since the concept of uncertainty management is relatively new to the educational research field (Chen et al., 2019). Even though there is increasing number of research that addresses the benefits and roles of uncertainties (Beghetto, 2021; Chen et al., 2019; Jordan & McDaniel, 2014; Lamnina & Chase., 2019), there is an obvious lack of empirical data that show how students believe in the role of uncertainty in acquiring knowledge, how they perceive their struggling experiences of uncertainty, how much they are confident in managing the recognized uncertainties, and what and how well th*ey* use strategies to manage uncertainties in PBL setting. Authors believe that these aspects of epistemic beliefs, perceptions, self-efficacy and strategy use are all closely related to students' competency of uncertainty management. To the best of our knowledge, however, there is no survey questionnaire that investigates uncertainty management in PBL in postsecondary STEM education. Thus, the goals of this paper were to:

a) develop and validate the scale of the uncertainty management in PBL (UM-PBL),
b) test the known-group validation
c) test the relationship between the level of uncertainty management and academic performance

2. Theoretical framework

This paper assumes that the uncertainty management in PBL involves learner characteristics regarding epistemic beliefs and perceptions of uncertainty and self-efficacy in and strategy for uncertainty management (see Table 1 and Figure 1).

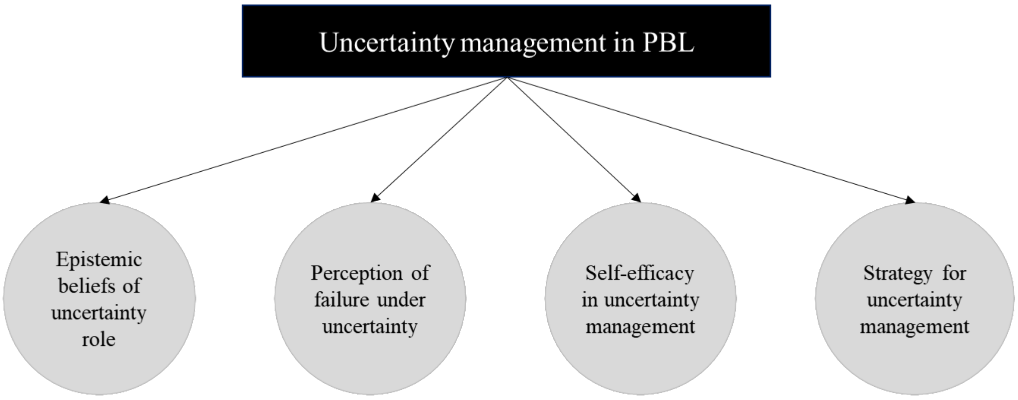
Table 1

Theoretical constructs and rationale for each construct

Theoretical construct	Rationale
1. Epistemic beliefs of uncertainty role	● Epistemic beliefs operate at the metacognitive level and help students regulate their learning processes (Hofer, 2004; Mason et al., 2010) ● Students' epistemology (e.g., "knowledge is complex") takes places in and affects students' metacognitive and regulative actions such as planning and/or monitoring one's understanding. ● Students' *beliefs in the role of uncertainty* can also affect students' monitoring of comprehension, planning for further learning process, and thus the management of uncertainties they encounter.
2. Perception of failure under uncertainty	● How students perceive their struggling or failure experiences under uncertainty is also believed to affect students' intention to deal with the recognized uncertainty that they encounter during their learning. ● Once students recognize the value of the struggling experience under uncertainties, they can keep their motivation and curiosity to grapple with and resolve the uncertainties (Lamnina & Chase, 2019; Manz, 2018).
3. Self-efficacy in uncertainty management	● Students' belief in their abilities in handling such uncertainties in a productive way can also greatly impact whether student engage with managing the recognized uncertainties. ● As the level of self-efficacy in specific tasks has shown to affect students' engagement in those specific tasks (Bandura, 1982), grappling with uncertainties require students' confidence in managing uncertainties.
4. Strategies for uncertainty management	● The strategies students bring into action when they face such uncertainties (i.e., uncertainty management strategies) can also determine the level of students' uncertainty management in PBL. ● Students who are equipped with learning strategies that are helpful for overcoming the struggling moments are likely to productively manage their uncertainties. ● For example, students can manage their uncertainties by trying to reflect on their solutions, incorporate or integrate multiple

	perspectives to come up with a better solution, and discuss the possible solutions with peers (Authors, 2022).

Figure 1
Conceptualization of the uncertainty management in PBL



3. Study 1: The development and validation of the scale

3.1. Item development
A total of 16 items were developed for the initial draft of UM-PBL by authors based on theoretical framework (see Appendix A). The content of the items was then reviewed by five researchers: Three were from science education department and two were from computer science department and had previously taught PBL sessions for several years.

3.2. Participants and data screening
A total of 239 undergraduate and graduate students from diverse departments (computer science, physics, electrical engineering, biochemistry, and science education) at a large public university in US participated in the survey. 38 responses were excluded after the outlier detection analysis using Z-score with cutoff value of 3.0. As a result, data from 201 responses were used in the exploratory factor analysis.

3.3. Result: Construct validity, internal consistency (reliability), and known-group validation
3.3.1. Exploratory factor analysis of the structure of UM-PBL

Even though the parallel analysis suggested a three-factor solution as the best fit for the data, authors also explored one- and two-factor solutions (See Table 2). Authors compared and discussed the results of each factor solution in terms of both factor loading and theoretical examination and concluded that the three-factor solution had the best fit as a UM-PBL model and also best represent the theoretical constructs.

Table 2
One-, two- and three-factor solutions of the UM-PBL

Item #	One-factor solution	Two-factor solution		Three-factor solution		
	1	1	2	1	2	3
1	0.705	0.692		0.783		
2	0.816	0.825		0.775		
3	0.668	0.799		0.855		

4	0.619	0.663		0.592		
6	0.822	0.790		0.624		
8	0.688	0.636		0.513		
5	0.550	0.469			0.574	
9	0.713	0.692			0.449	
11					0.673	
12	0.605	0.628			0.707	
13			0.578			0.566
14	0.537		0.794			0.800
15	0.571		0.621			0.637
16	0.521		0.430			0.462
10	0.612	0.564				
7	0.555					

With a three-factor solution, 14 items retained in the final questionnaire of the UM-PBL. Decisions made regarding construct integration and item deletion and relocation were described in Table 3.

Table 3

Decisions on and rationale for item retainment

Decisions made through EFA	**Rationale**
1. Integrate the two constructs, *epistemic belief of uncertainty role* and *perception of failure under uncertainty*, into a new construct of *perception of uncertainty in learning to solve problems*	● Items under epistemic beliefs of uncertainty role and perception of failure under uncertainty were loaded to the first factor together, except two items (item 7 and 5; Discussed below). ● Even though one's beliefs in uncertainty role can be, in theory, distinguished conceptually from the perception of failures under uncertainty, but authors could not deny that our questions for both constructs were recognized similar enough to hang together in practice by respondents. ● It is partly because authors phrased the items for the *perception of failure under uncertainty* without using the term 'failure' to avoid the negative effects of students' preconception of failures in their responses. The items thus rather seemed to ask how students perceive the *uncertainty* that comes with their learning activities. ● Also, it seems valid to ask one's beliefs in the role of uncertainty to assess a (new) construct of *perception of uncertainty in learning to solve problems*. ● For example, when one has positive (or negative) beliefs in the role of something (e.g., uncertainty role), he/she is accordingly highly likely to perceive positively (or negatively) their experiences of it (e.g., perception of uncertainty in learning). ● Thus, along with Item 4, 6, and 8 discussed above, items 1, 2, and 3 can functionally achieve a joint goal

	of assessing the perception of uncertainty in learning to solve problems.
2. Remove item 7 and 10	• Both items were not classified into any of factors, yielding the factor loading values under 0.4
3. Relocate item 5 into the second factor, which is *self-efficacy in uncertainty management*	• Even though it was intended to ask whether students perceive failing experiences under uncertainty as a barrier, it turned out to assess students' confidence or efficacy in handling the situations when they face. • Thus, authors agreed that item 5 can achieve the same goal of other items under self-efficacy in uncertainty management
4. Retain all items under strategy for uncertainty management, which was the third factor	• All items under the theoretical construct of strategy for uncertainty management (item 13, 14, 15, and 16) hanged together under the third factor.

The three-factor model accounts for 52.6% of the variance and the internal consistency of each construct was adequate: Cronbach's α=.855 for the first factor, α=.732 for the second factor, α=.637 for the last factor, and α=.851 for the overall model. See Table 4 and Appendix B for the revised constructs and final items of the three-factor model of UM-PBL.

Table 4

The revised constructs and items for the UM-PBL

Label	Original item #	Items	Original construct	Revised construct
PU1	1	I believe understanding and handling uncertainty can enrich my problem-solving skills.	Epistemic belief of uncertainty role	Perception of uncertainty in learning to solve problems
PU2	2	Uncertainty advances my problem-solving skill because it motivates me in further research.		
PU3	3	When I encounter uncertainty, I believe it helps me to reflect my problem-solving skills.		
PU4	4	I see no point in exploring uncertainty in a class as long as I can get tasks done.	Perception of failure under uncertainty	
PU5	6	I view uncertainty as an opportunity to grow my knowledge and learn more practical problem-solving skills.		
PU6	8	I feel that uncertainty in assignments can be highly interesting once I get into them.		
SE1	5	Failure stops me from finding a better solution to solve the problems		Self-efficacy in uncertainty management
SE2	9	I am not afraid of exploring uncertain situations during assignments to gain more knowledge.	Self-efficacy in uncertainty management	
SE3	11	Handling uncertainty during assignments is not one of my strengths.		
SE4	12	I can remain calm when I'm facing uncertainty because I know that I can rely on my abilities to overcome the challenge.		
MS1	13	When I encounter uncertainty during an assignment, I discuss it with other students trying to find a better way of solving the problem.	Strategy for uncertainty management	Strategy for uncertainty management

MS2	14	I try to relate the uncertainty I encounter during assignments to what I learnt in other subjects/courses or my experience to solve the problem.		
MS3	15	I try to integrate multiple different feedbacks or information together to explore alternative explanations and other possibilities before I come up with the final solution		
MS4	16	I regularly check ideas/solutions against my uncertainties during an assignment and adjust my problem-solving/learning plan if needed.		

3.3.2. Known-group validation

After the exploratory factor analysis, we conducted another test for construct validity: known group validation was explored with the same responses of the final 14 items. For the known group validation, authors reviewed prior research on gender differences in aspects related to the constructs to draw assumptions.

Numerous studies have explored different characteristics that are assumed to account for gender gaps such as self-efficacy or self-concept (Sax et al., 2015), disciplinary cultures (Seymour & Hewitt, 1997) and occupational plans/aspirations (Morgan et al., 2013). Also, researchers have shown that male students exhibit higher ability in the aspects related to the problem-solving strategy, such as problem-solving and reflection patterns (Zhu, 2007), retrieval ability in solving problems (Royer et al., 1999), and flexible strategy use (Gallagher et al., 2000). Building upon this discussion, authors believed that perceptions of uncertainty in PBL, self-efficacy in uncertainty management, and strategy for uncertainty management would be at different levels among STEM students by gender.

198 responses were included in the analysis as three responses which reported their gender as 'not prefer to say' were excluded. Independent t-tests showed that men's perception of uncertainty in learning to solve problems was significantly higher than that of women (mean difference = 0.227; $t(196)=2.45$, $p=.015$, Cohen's $d=.386$), that men's self-efficacy in uncertainty management was significantly higher than that of women (mean difference = 0.474; $t(196)=4.09$, $p < .001$, Cohen's $d=.631$), and that the total average score was also significantly higher in the score of men than that of women (mean difference =.245; $t(196)=3.06$, $p=.003$, Cohen's $d = .470$; see Table 5).

Table 5
Results of independent t-tests of gender differences in scores of each construct and total

Variable	Group	*n*	*M(SD)*	Mean diff.	*t*	*p*	ES(d)
PU	M F	59 139	4.11 (0.58) 3.88 (0.61)	.227	2.45	.015	0.386
SE	M F	59 139	3.69 (0.74) 3.22 (0.75)	.474	4.09	< .001	0.631
MS	M F	59 139	3.97 (0.62) 3.93 (0.63)	.040	0.416	.678	
Total	M F	59 139	3.95 (0.50) 3.71 (0.52)	.245	3.06	.003	0.470

4. Study 2: Further validation of the scale in computer science course

With the UM-PBL which consists of 14 items of three constructs (see Appendix B), we further tested the predictability of its relationship with the academic achievement. Building on the previous research which argued for the potential relationships between uncertainty management and learning outcomes

(Chen, 2022; Forrest et al., 2012; Lamnina & Chase, 2019), authors assumed that the survey score would be positively correlated with the score of problem-solving.

4.1. Contexts and participants

To test the predictability of the relationships, the survey was implemented in a Cybersecurity course in a large private university located in Southwest US. The course implemented three sessions of problem-based learning in the Fall 2021 semester. In each PBL session, students were required to perform computer programming skills to solve a complex real-world problem (e.g., to develop a network which can detect cyber-attack using *snort*, an open-source network intrusion detection system). As a scaffolding, the Knowledge Graph, visual representation of concepts related to the problem and relationships between each concept, was developed by authors and offered to students. Out of 55 students enrolled in this course, 23 students were included in the analysis process because others did not complete PBL sessions and/or surveys.

4.2. Result: Correlation between uncertainty management and problem-solving score

Pearson correlation coefficients were computed to assess the linear relationship between scores of uncertainty management and problem-solving. As can be seen in the Table 6, there were significant positive correlations between the scores of the last PBL session and of the PU ($r(21) = 0.454$, $p = 0.029$) , SE ($r(21) = 0.471$, $p = 0.023$), and total average ($r(21) = 0.434$, $p = 0.039$) of the post-survey of the uncertainty management in PBL.

Table 6

Correlation between uncertainty management and problem-solving score

	S1	S2	S3	PrPU	PrSE	PrMS	PrT	PoPU	PoSE	PoMS	PoT
S1	1	.606**	.422*	-.051	-.151	-.020	-.094	.032	-.093	.167	.045
S2		1	.619**	.095	-.121	-.060	-.024	.139	.050	-.003	.102
S3			1	.409	.006	.042	.214	.454*	.471*	-.018	.434*
PrPU				1	.544**	.560**	.892***	.427*	.645***	.004	.482*
PrSE					1	.341	.789***	-.133	.156	-.106	-.066
PrMS						1	.739***	.000	.225	.197	.140
PrT							1	.152	.451*	.023	.252
PoPU								1	.759***	.097	.907***
PoSE									1	.174	.862***
PoMS										1	.449*
PoT											1

Note. S = PBL session, T = Total, Pr = Pre-, Po = Post-; * $p < .05$, ** $p <.01$, *** $p <.001$

5. Discussions

5.1. Uncertainty management that involves perception, self-efficacy and strategy use

With the UM-PBL validated through EFA, this study explored the dimensions of students' uncertainty management in PBL. Three dimensions were identified in terms of perception, self-efficacy, and strategy use. In the process, items that originally belonged to either epistemic beliefs of uncertainty role or perception of failure under uncertainty were grouped together under a new construct of *perception of uncertainty in learning to solve problems*. Despite the practical difficulties of distinguishing the two constructs and the issues of item phrasing, the result of this study offers plausible assumptions that epistemic beliefs in learning challenges (e.g., uncertainty) and perceptions of the challenges are closely related with each other in theoretical perspective.

The UM-PBL also assess dimensions of self-efficacy in and strategy for uncertainty management. Related to each construct of the UM-PBL are there numerous studies that developed and validated some measurements (e.g., Attitudes Towards Mistakes Inventory (ATMI), Leighton et al., 2014; College Academic Self-Efficacy Scale (CASES), Owen & Froman, 1988; Motivated Strategies for Learning Questionnaire (MSLQ), Pintrich et al., 1991). However, these measures assess the constructs in either too broad contexts (e.g., attitudes toward mistakes or self-efficacy in educational setting rather than that of uncertainty management) or too general scopes (e.g., general learning strategies rather than strategies in managing uncertainties) to be adopted for the uncertainty management assessment. Thus, the UM-PBL does add unique contributions to assessment of learner characteristics that affect students' tendency or competency of dealing with uncertainties.

5.2. Contribution of the development of the UM-PBL

This paper also confirmed the known-group validation of UM-PBL in terms of gender differences in the perceptions of uncertainty in PBL and self-efficacy in uncertainty management. While strategy for uncertainty management was not found to be significantly different by gender, UM-PBL can be effectively used in research on gender differences in STEM education. As addressed earlier, several studies investigated different learner characteristics to provide explanations and suggest interventions for gender differences. With the result of known-group validation, the UM-PBL can also provide significant explanations for and suggest different interventions for gender differences in STEM. For example, it would be meaningful intervention to encourage female STEM students to have positive beliefs in the role of uncertainty in building knowledge by explicitly letting them go through uncertainties (e.g., Productive Failure; see Kapur, 2014 for more details). In a recent study by Palominos and colleagues (2022), after students went through simulation of productive failure, they recognized the usefulness and productiveness of struggling experiences. Positive correlations that PBL score has with perception of uncertainty and self-efficacy in uncertainty management can further corroborate the potential advantages of such interventions for encouraging uncertainty management. However, due to the short of sample size, this study was not able to conduct regression analysis for PBL score with UM-PBL scores as independent variables. Given the significant correlations mentioned above, it is expected that future studies with a larger sample size can confirm the potential predictability of UM-PBL score for learning outcomes.

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Appendix A: The initial version of UM-PBL implemented for data collection (16 items)

Constructs	#	Item
Epistemic beliefs of uncertainty role	1	I believe understanding and handling uncertainty can enrich my problem-solving skills.
	2	Uncertainty advances my problem-solving skill because it motivates me in further research.
	3	When I encounter uncertainty, I believe it helps me to reflect my problem-solving skills.
Perception of failure under uncertainty	4	I see no point in exploring uncertainty in a class as long as I can get tasks done.
	5	Failure stops me from finding a better solution to solve the problems
	6	I view uncertainty as an opportunity to grow my knowledge and learn more practical problem-solving skills.
	7	I like to identify what I don't know during an assignment so that I can improve my learning performance in class.
	8	I feel that uncertainty in assignments can be highly interesting once I get into them.
Self-efficacy in uncertainty management	9	I am not afraid of exploring uncertain situations during assignments to gain more knowledge.
	10	I believe I can overcome uncertainty in assignment if I spend more time and effort on it.
	11	Handling uncertainty during assignments is not one of my strengths.
	12	I can remain calm when I'm facing uncertainty because I know that I can rely on my abilities to overcome the challenge.
Strategy for uncertainty management	13	When I encounter uncertainty during an assignment, I discuss it with other students trying to find a better way of solving the problem.
	14	I try to relate the uncertainty I encounter during assignments to what I learnt in other subjects/courses or my experience to solve the problem.
	15	I try to integrate multiple different feedbacks or information together to explore alternative explanations and other possibilities before I come up with the final solution
	16	I regularly check ideas/solutions against my uncertainties during an assignment and adjust my problem-solving/learning plan if needed.

Appendix B: The final version of UM-PBL used for study 2 after validation

Survey on your experiences in Problem-Based Learning (PBL)

Problem solving is a challenging activity and may cause uncertainty. Uncertainty here is defined as an unsure situation that causes a learning struggle. They may include, but not limited to, a) being uncertain what the expectations are in the given task, what the problem is, what I do and do not know, what I should know, how I can move on to next steps, and/or what is relevant or not, and b) being confused with ambiguous or unclear instruction.

The following survey questions can help us advance in research of this area. Your participation in this survey is greatly appreciated and help us make improvements to science/engineer education. The survey should only take 5-10 minutes.

Your name?	( )
Your gender?	Male / Female / Prefer not to say
Your major?	( )
Degree program	Undergraduate / Graduate / Other
Program Year	1st Year / 2nd Year / 3rd Year / 4th Year / Other
Have you ever learned cybersecurity with a problem-based learning approach before this course?	Yes / No / Not sure

Please read the questionnaires and answer them based on your experience of problem-solving.
(1 = Strongly disagree, 2 = Somewhat disagree, 3 = Neither agree nor disagree,
4 = Somewhat agree, 5 = Strongly agree)

	1	2	3	4	5
I believe understanding and handling uncertainty can enrich my problem-solving skills.					
Failure stops me from finding a better solution to solve the problems					
When I encounter uncertainty during an assignment, I discuss it with other students trying to find a better way of solving the problem.					
Uncertainty advances my problem-solving skill because it motivates me in further research.					
I am not afraid of exploring uncertain situations during assignments to gain more knowledge.					
I try to relate the uncertainty I encounter during assignments to what I learnt in other subjects/courses or my experience to solve the problem.					
When I encounter uncertainty, I believe it helps me to reflect my problem-solving skills.					
Handling uncertainty during assignments is not one of my strengths.					
I try to integrate multiple different feedbacks or information together to explore alternative explanations and other possibilities before I come up with the final solution					
I see no point in exploring uncertainty in a class as long as I can get tasks done.					

I can remain calm when I'm facing uncertainty because I know that I can rely on my abilities to overcome the challenge.					
I view uncertainty as an opportunity to grow my knowledge and learn more practical problem-solving skills.					
I feel that uncertainty in assignments can be highly interesting once I get into them.					

Note. In this final version, two items (items 7 and 10) from the initial version were excluded by the result of EFA. Those were: “I like to identify what I don’t know during an assignment so that I can improve my learning performance in class.” and “I believe I can overcome uncertainty in assignment if I spend more time and effort on it.”