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Prompting students to make socioscientific decisions: embedding metacognitive guidance in an e-learning environment

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ABSTRACT
This study aimed at improving the decision-making (DM) skills of 11th graders by incorporating a DM framework, visualisation tools, collaboration, and metacognitive guidance into a socioscientific issue context. Two classes, the experimental group (embedded metacognitive guidance, $N = 42$) and the comparison group (no metacognitive guidance, $N = 32$), were involved in the implementation of the experimental methodology. An open-ended test and worksheets were developed to assess the students' DM skills. The results indicated that the two versions of the DM learning modules had similar effects on the improvement in the students' DM skills, but there were significant differences in their overall skills in DM ($Z = -6.410$, $p < .001$), generating criteria ($Z = -6.956$, $p < .001$), and evaluating DM results ($Z = -2.533$, $p < .011$) based on the student responses on the worksheets. These findings indicate that further studies need to explore the mechanism of metacognitive guidance for students with different socioscientific issue DM skills in e-learning environments.

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Introduction

Socioscientific issues (SSIs) such as climate change, shortages of food and energy, and decreased biodiversity and sustainable development are complex issues related to society, science, and technology. These SSIs need to be addressed by providing decision-making (DM) instruction that improves the scientific literacy of students so that they are able to participate effectively in complex debates (Callan et al., 2009; Halpern-Felsher & Cauffman, 2001). Moreover, the science curriculum standards in many countries aim to cultivate responsible and literate citizens who will actively participate in public affairs and debates, and make deliberate and informed decisions that will improve the lives of both individuals and society as a whole (National Research Council, 2012; North American Association for Environmental Education, 2000). Wals, Brody, Dillon, and Stevenson (2014) suggested that convergence between science

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education and environmental education is necessary to engage students in integrative thinking and linking between scientific knowledge and local (place-based) understanding.

SSIs frequently involve competing relationships and people with conflicts of interest embedded in these environmental, social, ethical, economic, political, and scientific problems. Incorporating SSIs with science instruction provides students with the opportunity to construct knowledge about ill-structured issues and to practise making decisions about multifactorial issues (Levinson, 2006). SSI DM is a complex and multifaceted process that requires students to assess and weight the advantages and disadvantages of each argument, evaluate diverse evidence in support of the arguments, consider trade-offs or cut-offs among competing solutions, reveal conflicts of interest held by stakeholders, and appropriately weight the factors involved in the issues (Eggert, Ostermeyer, Hasselhorn, & Bögeholz, 2013). Therefore, making decisions about SSIs requires many advanced skills and strategies that most people do not develop naturally.

According to the literature, DM can be defined from two different perspectives: a process involving a series of steps for making a decision (e.g. Lee & Grace, 2012) and a variety of abilities that learners need to be equipped with for performing high-quality DM processes (e.g. Gresch & Bögeholz, 2013). This study perceives 'decision-making' in the broad sense that involves a process of and a variety of abilities for DM. In addition, it is imperative for decision-makers to use metacognition to reflect on how to work through the DM process using which strategies (Böttcher & Meisert, 2013; Gresch & Bögeholz, 2013). Some researchers have suggested that it is important to assist students in developing the ability to systematically and effectively process complex data involved in SSI; thus, they advised teachers to introduce DM strategies explicitly in SSI contexts so as to enhance the quality of the students' decisions (Nicolaou, Korfiatis, Evagorou, & Constantinou, 2009; Papadouris, 2012).

It is no surprise then that several studies have revealed the difficulties and failures of students in making decisions about SSIs (Kortland, 1996). Previous studies have found that students were not able to develop criteria for evaluating alternatives (Papadouris & Constantinou, 2010), did not know how to select a strategy (Seethaler & Linn, 2004), made decisions intuitively without comparing the pros and cons of alternatives (Hong & Chang, 2004), and were easily influenced by prejudice and emotion (Betsch & Haberstroh, 2005). Most students were not familiar with evaluating the reliability of evidence, were not able to use evidence properly, and failed to provide sufficient evidence to support their claims (Lin & Mintzes, 2010; Nicolaidou, Kyza, Terzian, Hadjichambis, & Kafouris, 2011; Sandoval & Millwood, 2005). Students often find it difficult to argue based on the available evidence (Sampson & Clark, 2008), and few of them are able to show multiple perspectives in their thinking when they are dealing with SSIs (Pedretti & Nazir, 2011). One of the main reasons for these problems is that school science instruction emphasises science content and solving well-structured questions instead of engaging students in scientific processes embedded in authentic problems (Rose & Barton, 2012) in which students are required to coordinate knowledge and skills simultaneously when making decisions about SSIs.

Therefore, many science educators and environmental educators have suggested incorporating SSIs into the curriculum and instruction so as to promote the abilities of students in higher level thinking when making arguments (Lin & Mintzes, 2010; Venville & Dawson, 2010), judging evidence (Roberts & Gott, 2010), and DM (Lee & Grace, 2012;

Papadouris, 2012). Researchers have suggested the necessity of structuring learning tasks carefully when students are learning about complex issues, especially those involving SSIs for which the outcomes are uncertain (Ottander & Ekborg, 2012; Zeidler, Sadler, Simmons, & Howes, 2005). Providing a DM framework for learners has been seen as an effective approach for teaching DM related to SSIs (Gresch, Hasselhorn, & Bögeholz, 2013).

Using evidence is also critical for multi-perspective reasoning in context, especially for how students select available evidence to make their decisions (Lee & Grace, 2012). Evidence is one of the important components of DM (Inch & Warnick, 2010); a reasonable and scientific approach requires claims or arguments to be supported by suitable evidence (Zimmerman, 2007). Therefore, it is crucial to teach students how to use and judge evidence for successful DM. However, few empirical studies have examined the effect of incorporating the usage and judgement of evidence in teaching on the development of DM skills. Regarding this issue, Nicolaidou et al. (2011) proposed the 'Credibility Assessment Framework' and designed web-based instructional materials based on this framework.

Meanwhile, metacognitive guidance in instruction is important for students to make SSI decisions (Eggert et al., 2013). It enables them to think more deliberately about the appropriateness of supportive evidence, of the criteria for selecting the solutions, and of weighting the advantages or disadvantages of each decision, especially when learning to use compensatory and/or noncompensatory strategies for making decisions. Colombo, Iannello, and Antonietti (2010) also suggested that metacognitive questioning and meta-reflection would encourage students to much more recursively consider the decisions they make. Chiu, Chen, and Linn (2013) also suggested that metacognitive guidance includes applying visualisation tools to provide students with structural support to experience the process of making decisions, and making revisions to their decisions in e-learning contexts. A well-designed e-learning environment would be helpful for students to learn how to make decisions through experiencing a series of metacognitive scaffolding processes (Huffaker & Calvert, 2003). In other words, integrating metacognitive guidance into the instructional design of an e-learning environment is expected to lead to better quality SSI DM on the part of students.

The following evidence-based three-phase process was adopted in the present study as the DM framework for the learning module: (1) recognising the decision problem, (2) differentiation, and (3) post-decision consolidation (Svenson, 1996). The use of a DM framework supports students' discussion of their competing ideas during the DM process and the development of the required skills, while also assisting teachers in reviewing the engagement of students in the process (Ratcliffe, 1997). Such a DM framework emphasises guiding students to experience the DM process and to develop their DM skills, such as generating criteria, analysing alternatives, applying a DM strategy, and evaluating the DM results.

Therefore, the present study was designed to embed metacognitive guidance into a DM e-learning environment and explore if the guidance would exert significant effects on the students' DM skills related to an SSI.

Research questions

In accordance with the purpose of this study, the following specific research questions were addressed:

1. Were the students' DM skills significantly improved after the instructional intervention?
2. Did the students' DM skills related to SSIs differ significantly between the experimental group (EG; embedded metacognitive guidance) and the comparison group (CG; no metacognitive guidance) in the e-learning environment?

Methodology

An experimental design was employed in the current study to investigate the impact of metacognitive prompts on the students' DM skills related to an SSI. The designed e-learning environment and the research instruments used by the authors for the purpose of this study are described below.

Instructional design: SSI DM in an e-learning environment

The DM learning module applied in this study focused on making and justifying decisions about where to locate a reservoir in northern Taiwan within a real context that involved geographic, geological, biological, and socioeconomic information about the area and society. Contexts are a mediator of DM related to SSIs that influence the procedures, sources, and rationales that students use to collect evidence, gather DM criteria, and make post-activity decisions (Lee & Grace, 2012). Also, posing a realistic problem or issue to students is important since this helps them to understand the problem space, and provides multiple forms of data or information for analysing alternatives (Nicolaou et al., 2009). Therefore, we selected a realistic SSI – 'where to build a dam' – as an interesting and compelling problem space. A three-phase learning module incorporating a DM framework to promote the efficacy of the students' DM was then designed (Zeidler, Osborne, Erduran, Simon, & Monk, 2003).

Before applying the DM activity (Activity 3 in Figure 1), two training activities (Activities 1 and 2) were used to focus on the prerequisite skills. Activity 1 comprised a 1-hour whole-group lesson designed to enhance the students' understanding of the concept of evidence, especially the reliability and validity of the evidence. We provided text that included five pieces of evidentiary text supporting the claim that the process of global warming is accelerating. Each piece of evidence in the text consisted of its source (the Weather Bureau, the *Scientific American* magazine, and scientific research reports) and content (personal experiences and the results of investigations, observations, or scientific experiments). The teacher asked the students to read the text, and then guided them to discuss the validity and reliability of the evidence and its relevance to the claim. Activity 2 was also a 1-hour whole-group lesson which modelled DM strategies for the students. In this training activity, the teacher demonstrated how to apply DM strategies for choosing an appropriate bicycle, considering the conditions of the biking path and budget limitations. After introducing three different DM strategies (cut-offs, scoring, and weighting and trade-off), the teacher guided a whole-class discussion about the pros and cons of these strategies, and when and how they might be best adopted.

Following the training activities, Activity 3 (the DM activity) – which consisted of a 3-hour small-group task using a visualisation tool – was designed following the three-phase DM framework. In the phase of recognising the decision problem, students explored a visualisation tool called 'Reservoirs in Taiwan' (as shown in Figure 1) to acquire information about the functions of water reservoirs and their possible impacts on the environment. The students were expected to synthesise the prerequisites of building a reservoir from the aspects of geology, meteorology, ecology, population, factory distribution, and cultural heritage. Recognising these prerequisites for building a reservoir helped the students to generate the criteria for the decision problem of 'where to build a water reservoir.' They were guided by a worksheet to generate the criteria for their decision about the problem.

In the differentiation phase, the students used the 'Jing-Si Reservoir' (JSR) visualisation tool to decide where to build the reservoir (see Figure 2). The tool allowed the students to

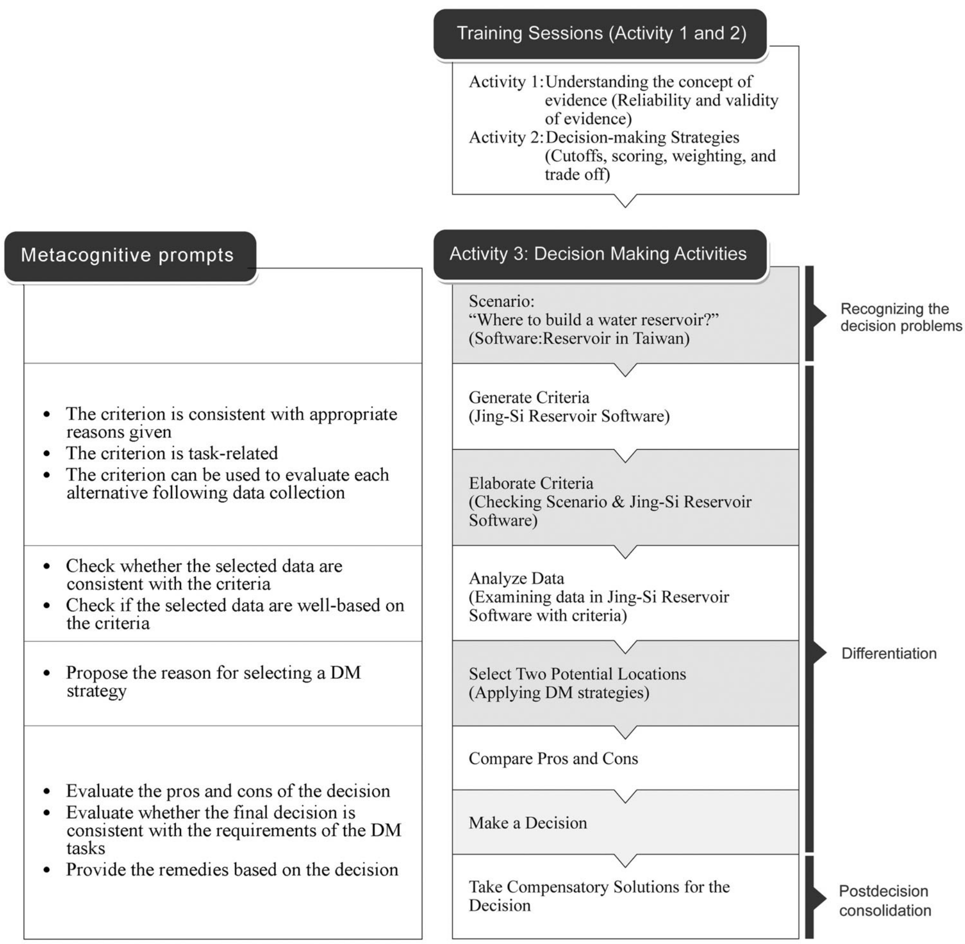

Figure 1. Framework of a learning module for DM in an SSI context.

search for and evaluate data related to six locations along a river. They refined the criteria that they had generated after browsing the information provided by the JSR tool, and then examined the data of the six locations based on their criteria and chose two potential candidate sites for building a reservoir. After carefully evaluating these two sites, they made a decision as to which would be the best, and discussed its impact on future water supplies and the surrounding environment. The visualisation tool allowed the students to visualise the complex information and keep it manageable by enabling the necessary data layers and disabling the other data layers in the JSR tool (see Figure 3). Specifically, the interface of the tool includes several main functions, namely 'Tips,' 'About reservoirs,' and 'Data center' (Figure 3 shows a screen capture of the tool interface). The students could find information about how to use the tool in the 'Tips' interface, and look for relevant information about the construction costs of reservoirs, calculations of water supplies based on rainfall, and the geological conditions of the river and catchment area in the 'About reservoirs' interface which serves as the knowledge bank. The 'Data center' interface allows students to query the data of the six locations and to judge which is suitable to build a reservoir based on their own criteria. The students were required to organise the data they found using the tool in the worksheet, which guided them to reason based on the available data. After choosing a location for the reservoir, the students could use the 'Simulation' interface to visualise a three-dimensional bird's-eye view of the area that would be

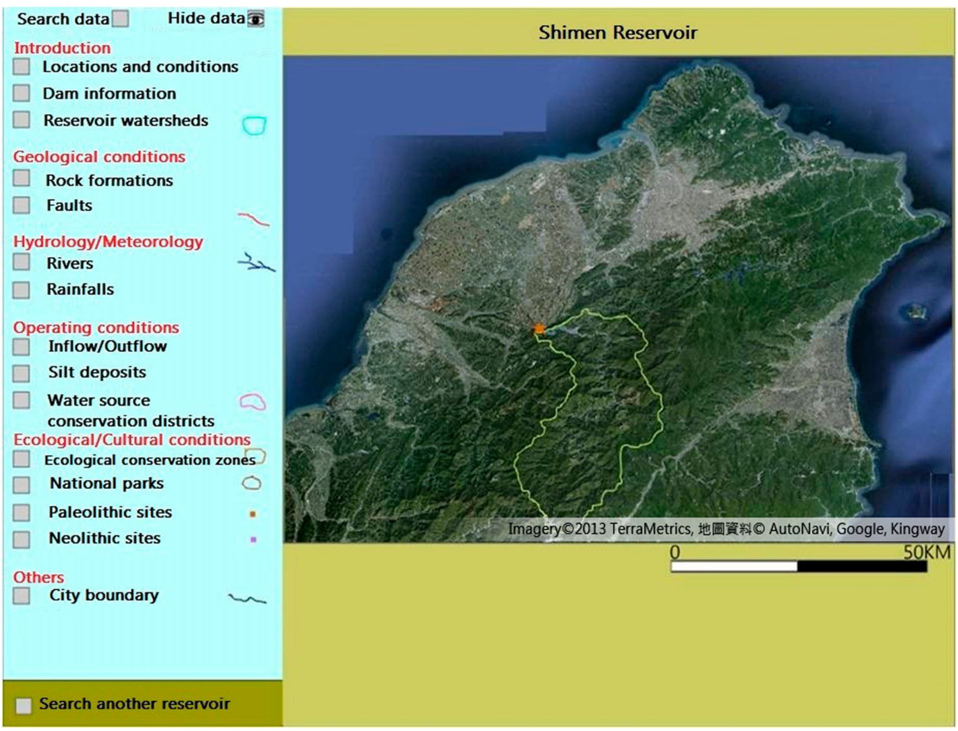

Figure 2. Screenshot of the 'Water Reservoirs in Taiwan' software embedded with information about two water reservoirs in northern Taiwan that was used to help students understand the factors related to building a water reservoir on a river. (The copyright of the map belongs to Google.)

Figure 3. Screenshot of the 'Jing-Si Reservoir' software.

covered by water after building a reservoir in that location, which helped them evaluate the impact of their decision on the surrounding environment. The learning activities that we designed along with the visualisation tool guided the students to learn how to select suitable data as evidence, make judgements, reason based on evidence, apply DM strategies, and evaluate their decisions based on their own criteria.

Finally, the post-decision consolidation phase guided the students to ensure that the decision they made was the most appropriate through sharing their decision and justifications with peers and writing compensatory solutions for their decision from a reflective viewpoint. The students had a chance to review their DM process and reflect on their understanding of the concept of evidence and DM strategies.

The students in the EG learned with the DM learning module that included metacognitive guidance, which had been developed to support understanding, planning, monitoring, and reflection of a DM task by students (Quintana, Zhang, & Krajcik, 2005) (see exemplar metacognitive guidance in Table 1). First, providing metacognitive guidance for generating criteria focused on guiding students to judge the quality of the self-generated criteria by examining the criteria with a list of standards for high-quality criteria. Second, providing metacognitive guidance for analysing alternatives guided the students to compare the strengths and weaknesses of the various alternatives. Third, providing metacognitive guidance for applying a DM strategy facilitated students' reflection on why they should use a particular DM strategy in making their decision. Finally, providing metacognitive guidance for evaluating the DM results led the students to evaluate the quality of their decision based on their own criteria and to propose the remedies for the decision. The students in the CG received the version of the DM learning module that did not contain metacognitive guidance. It should be noted that the EG and CG received

Table 1. Possible learning difficulties and the corresponding prompting across DM tasks.

DM task	Difficulties of learning DM	Descriptions of metacognitive guidance	Metacognitive guidance in the worksheets
Generating and elaborating criteria	Most students are not able to develop criteria to evaluate alternatives (Papadouris & Constantinou, 2010)	Judge the quality of the self-generated criteria	• The criterion is consistent with appropriate reasons given • The criterion is task related • The criterion can be used to evaluate each alternative following data collection
Analysing alternatives	Students are not familiar with evaluating the reliability of evidence and fail to provide sufficient evidence to support their claims (Lin & Mintzes, 2010; Nicolaidou et al., 2011; Sandoval & Millwood, 2005)	Guide to verify the consistency between the selected data and the criteria	• Check whether the selected data are consistent with the criteria • Check if the selected data are well based on the criteria
Applying a DM strategy	Students do not know how to select a strategy to make a decision (Seethaler & Linn, 2004)	Prompt to propose the reason for selecting an appropriate DM strategy	• Propose the reason for selecting a DM strategy
Evaluating DM results (comparing pros and cons, and taking compensatory solution)	Students usually lack meta-reflection on the result of making an SSI decision (Eggert & Bögeholz, 2010)	Prompts to evaluate the pros and cons of the decision, and the DM process	• Evaluate the pros and cons of the decision • Evaluate whether the final decision is consistent with the requirements of the DM tasks • Provide the remedies based on the decision

the same content and the same assignments, and the two groups had equal opportunities and instructional time to achieve their learning goals.

Several researchers have suggested that students' DM skills are cultivated better in a collaborative learning environment (Baumberger-Henry, 2005; Chasek, 1997; Pata & Sarapuu, 2001). Students need to exchange their thoughts and gain multiple perspectives about SSIs through peer discussions in small groups. Therefore, the DM learning module was provided in a collaborative learning environment in order to support students in developing appropriate criteria, analysing alternatives, applying suitable DM strategies, and proposing compensatory solutions while choosing a location for building a dam.

Participants

Two classes of 11th graders (aged 16–17 years) from a senior high school in Taipei city, Taiwan, participated in this study. The normal class grouping and random assignment of students to the classes were conducted when students entered the school. These two classes were randomly assigned to the CG ($N = 43$) and EG ($N = 43$) to implement the experimental methodology. After eliminating incomplete work samples due to absence from either the pre-test or the post-test, the effective sample size of the study was 74. The final analysis involved 42 samples for the EG and 32 for the CG. The students were randomly divided into nine small groups in each class, each of which had a laptop computer for performing the DM activities during the instructional intervention.

None of the students had received instruction on DM related to SSI contexts prior to this study. The two groups were taught by the same teacher who had taught earth science in a senior high school for 21 years. She had a strong undergraduate background in earth science, and participated in several team meetings to discuss the learning module with the researchers involved in this study. She was familiar with the rationale and instructional strategies of the learning module and the visualisation tools.

Instruments and data analysis

It took 7 hours to administer the pre-test and post-test and to complete the DM learning module for both the CG and EG. To deeply examine the students' DM skills, the decision-making test (DMT) consisted of three open-ended questions based on DM subskills including generating criteria, analysing alternatives, applying a DM strategy, and evaluating the DM results. The first question was designed to explore the ability of generating criteria by asking the students to describe what their considerations were when choosing a bicycle, and also the underlying reasons. The second question sought to identify how students collected and analysed data on the alternatives, and how they used a strategy to make the decision by asking them to describe the DM process. The final question asked the students to reflect on their decisions. The interrater reliability between the two coders (one with a Ph.D. in science education and the other a high-school science teacher with a master's degree) was .82 in the DMT, which indicated that the interrater reliability of scoring students' answers in DMT reached an acceptable level.

In order to examine the overall effect of the DM learning module and the impact of metacognitive guidance on the students' DM skills, we collected data from two sources: the DMT and the worksheets. We coded the students' answers in the DMT and the worksheets using the same scoring rubric, except for the analysing-alternatives task. The developed rubric was constructed through repeatedly examining student answers until the score categories reached saturation. It scored the students' DM subskills from 0 to 2 points (see Table 2). For the DMT, student answers related to analysing alternatives were coded using the rubric given in Table 2. It should be noted that the performance of the students in analysing alternatives in the embedded assessment (worksheets) were coded in a different way since there were six alternatives. Students received 1 point when they analysed each alternative correctly in the worksheets, and so the maximum score was 6. Since some of the data did not satisfy the assumption of normality (see Appendix), we decided to use the Wilcoxon signed-rank nonparametric statistical test, which was implemented using SPSS 19.0. The effect size (index r; Field, 2009) was obtained by dividing the Z values by the square root of N (the total number of participants).

We compared the scores in the pre- and post-DMTs for examining the effect of the DM learning module on the students' DM skills for the EG and CG separately. In order to compare the effect of the metacognitive guidance on the students' DM subskills for the EG and CG, we compared the improvements in DMT scores of these two groups. Also, we attempted to investigate the DM practices of the students while learning by comparing the coded scores for the worksheets in the EG and CG.

Table 2. Scoring rubrics for skills in performing DM tasks.

DM skills	Definition	Score of 0 points	Score of 1 point	Score of 2 points
Generating criteria	Skill in generating high-quality criteria with appropriate reasons	• The criterion is not task related • The criterion is not measurable	The criterion is task related and is not measurable, but no appropriate reasons were given	The criterion is task related, measurable, and appropriate reasons were given
Analysing alternatives	Skill in considering each alternative following the data analysis	Did not provide any results in analysing the alternatives	• Provided the results in analysing partial alternatives • Provided the results in analysing the alternatives with errors, such as lacking the unit of measurement	Provided the complete results in analysing each of the alternatives without errors
Applying a DM strategy	Skill in applying an appropriate DM strategy to SSIs	• Did not use any DM strategies • Used invalid DM strategies	Used DM strategies along with a noncompensatory approach	Used DM strategies along with a compensatory approach
Evaluating DM results	Skill in proposing the statements or remedies for the decision	Did not provide any statements or remedies based on the decision	Provided statements that did not address the advantages and disadvantages of the decision	Provided statements that adequately addressed the advantages and disadvantages of the decision

Findings

In this section, we first compare the two versions of the DM learning module (EG and CG) in terms of how the students' DM skills improved, based on an analysis of the improvements in DMT scores and worksheet scores.

The students' DM skills were measured based on their answers on the worksheets and in the pre- and post-DMTs. The improvement in DM skills achieved by embedding metacognitive guidance was determined by comparing the pre-test and post-test scores of the CG and EG using the Wilcoxon signed-rank test. Table 3 indicates that the intervention of the DM learning module had similar effects on students' DM skills in both the CG and EG. Students in both groups exhibited much better overall DM skills ($Z = -2.490$, $p < .013$ for the CG and $Z = -3.757$, $p < .001$ for the EG) after the intervention.

The results of the comparison of the students' DM skills for the two versions of the DM learning modules (EG and CG) from the analysis of the DMT and worksheet scores using the Mann–Whitney U test are summarised in Tables 4 and 5. Table 4 gives the descriptive statistics of the improvements in scores of the students and the results of the Wilcoxon signed-rank test for each DM subskill. None of the improvements in scores for the DM subskills differed significantly between the two groups. These results indicate that the two versions of the DM learning modules had the same effect on the improvement in

Table 3. Results of Wilcoxon signed-rank tests of the pre- and post-DMT scores.

	Pre-test		Post-test				
	Mean	SD	Mean	SD	Z	p	*Post hoc*
CG	4.49	2.097	5.44	2.196	−2.490**	<.013	post > pre
EG	5.37	2.012	6.60	0.877	−3.757**	<.001	post > pre

$^{**}p < .01$.

Table 4. Results of Mann–Whitney *U* tests of improvements in DMT scores in the CG and EG.

	CG			EG				
DM skills	Mean of gain scores	SD	Mean rank	Mean of gain scores	SD	Mean rank	*Z*	*p*
Generating criteria	−0.19	−0.140	42.50	−0.14	0.639	44.50	−0.43	<.669
Analysing alternatives	0.77	0.740	43.97	0.74	1.093	43.03	−0.19	<.846
Applying a DM strategy	0.74	1.020	40.76	1.02	1.012	46.24	−1.17	<.900
Evaluating DM results	−0.37	−0.400	43.80	−0.40	0.660	43.20	−0.13	<.900
Total	.954	2.478	41.88	1.233	2.034	45.12	−0.609	<.543

Table 5. Results of Mann–Whitney *U* tests of scores for the worksheets in the CG and EG.

	CG			EG				
DM skills	Mean	SD	Mean rank	Mean	SD	Mean rank	*Z*	*p*
Generating criteria	8.84	1.111	25.02	13.05	1.825	61.98	−6.956**	<.001
Analysing alternatives	4.52	0.729	47.79	4.38	0.612	39.21	−1.604	<.109
Applying a DM strategy	1.81	0.394	41.50	1.91	0.294	45.50	−1.238	<.216
Evaluating DM results	3.14	0.710	37.27	3.51	0.668	49.73	−2.533*	<.011
Total	18.31	1.750	26.28	22.84	2.410	60.72	−6.410**	<.001

*$p < .05$.
**$p < .01$.

the students' DM skills based on the DMT scores. However, the descriptive statistics of the students' scores for the worksheets and the results of the Mann–Whitney *U* test for the CG and EG, as presented in Table 5, indicated that there were significant differences not only in their overall skills in DM ($Z = -6.410$, $p < .001$) but also in generating criteria ($Z = -6.956$, $p < .001$) and evaluating DM results ($Z = -2.533$, $p < .011$). The results revealed that the DM performance for the worksheets was better for the EG than for the CG. This indicates that adding metacognitive guidance facilitated the students' DM skills related to an SSI context. Especially, the students in the EG benefitted mainly by the provision of metacognitive guidance in generating criteria and evaluating their DM results.

Discussion

In summary, the EG's DM performance in the worksheets was significantly better than that of the CG regarding the overall skills of DM, generating criteria, and evaluating their DM results. It revealed that the improvement in the students' DM skills was mainly influenced by metacognitive guidance when prompting the students to accomplish DM tasks in selecting the location to build a reservoir. The results echoed the findings of previous studies which verified that students' DM skills and DM quality could be significantly improved with the aid of metacognitive guidance (Eggert et al., 2013; Gresch et al., 2013). Obviously, these 11th graders benefited from embedding metacognitive guidance in constructing DM skills (e.g. generating criteria and evaluating DM results) in an e-learning environment.

First, generating criteria and evaluating DM are regarded as two relatively difficult DM skills. These two skills are also crucial components for making high-quality decisions (Papadouris, 2012). Especially, generating criteria is one important step in making a decision in SSIs as the development of criteria is closely related to the analysing alternatives (Jimenez-Aleixandre, 2002). Most of the students might have never experienced the systematic process of learning DM. Therefore, they were unfamiliar with these two skills. Through providing metacognitive guidance in the form of written prompts, which were goal-oriented questions or instructions that made the students much more focused on their tasks, the students in the EG had more chances to clearly and reflectively think over what they would do, and had fewer instances of trial-and-error while performing the task. This is why the students in the EG had significantly better performance in terms of generating criteria and evaluating their DM results.

Second, Bloom's taxonomy (1956) classified evaluating as one of the higher order thinking skills, so it is necessary to guide students with sufficient learning supports for developing their evaluation skills (Alford, Herbert, & Frangenheim, 2006). In this study, the visualisation tools allowing students to visualise the complex but manageable information played an important role in developing their evaluation skills by supporting their selection of the best options through recursive practices of generating criteria and evaluating the appropriateness of evidence (the data selected from the 'Data center' of the visualisation tool) for their DM in SSI contexts. In addition, we guided the students to experience the compensatory DM process by prompting them to evaluate the pros and cons of the decision and to make the final decision considering their own generated criteria. Therefore, the students had many opportunities to become familiar with and/or to internalise these DM skills.

Third, the prerequisite learning experiences before the DM task were needed so that the students were equipped with understanding of the reliability and validity of evidence, and of three different DM strategies (cut-offs, scoring, and weighting and trade-off) through the training sessions (Activities 1 and 2). These two training activities helped the students realise how to weight and evaluate the data regarding the criteria and options for DM. Besides, Sadler and Zeidler (2005) found that, when students had more knowledge of a task, they would be more likely to incorporate and apply it in the DM tasks. The knowledge bank ('About reservoirs' in the visualisation tool) provides the necessary background knowledge of building water reservoirs to facilitate the students' search for useful information for their DM. With the aid of metacognitive prompts (using why and how questions to prompt students to apply knowledge), the EG had more chances to integrate more knowledge into their DM, so they exhibited better DM practices than did the CG.

Learning in terms of small groups is common in science classrooms, especially when learning complicated topics such as SSIs. Albe (2008) pointed out that small-group discussion allowed students to actively engage in discussion and to cooperatively deal with SSIs. The discussion process in a small group would foster students' multiple perspectives and learn how to weigh alternatives regarding the socioscientific issue they are working on (Ratcliffe & Grace, 2003). The small-group learning was employed in this study to promote students' DM in the CG and EG. During the period of the DM instruction, the students interacted with each other but were assessed individually in the pre- and post-tests. It should be noted that the learning effects shown in the post-test also included the cooperation within the small group and were not all from the DM learning module and metacognitive prompts. However, since the CG and EG both had the same learning environment setup, except for the metacognitive prompts, the results of the comparison study in fact indicate the effect of the metacognitive prompts in the EG; this is especially noticeable in the group difference for the worksheets (see Table 5).

Conclusions and implications

This study shows that integrating the evidence-based and three-phase DM framework into a module in an e-learning environment was effective in terms of improving grade 11 students' SSI DM skills; in particular, the metacognitive guidance played a key role in the teaching intervention.

Therefore, we suggest that teachers and curriculum designers should be aware of the following design components for promoting students' SSI DM: the prerequisite learning experiences for training students to learn how to develop, weight and evaluate evidence, the criteria and options for DM, incorporating a DM framework, using visualisation tools, collaborative learning, and providing metacognitive guidance for generating criteria and evaluating DM results.

However, it remains unclear how metacognitive guidance influences students with different SSI DM skills in an e-learning environment. Hence, it is worth exploring the learning mechanism in order to develop different metacognitive guidance for the teachers to enhance the DM skills of different students in SSI contexts. Moreover, the present study did not examine how the students developed the abilities of participating in social debates or of communicating the consistency of the criteria and decisions in a collaborative learning environment. Further discourse analysis within small groups and interview data need to be collected and analysed to determine how group members interact with each other when making SSI decisions.

Finally, one limitation of this study was that we did not consider how personal value judgement affected the students' SSI DM (Hogan, 2002; Sadler & Zeidler, 2004). Although we trained the students to make decisions on SSI in terms of adopting metacognitive guidance with systemically rational thinking, we still could not ignore that personal value judgements potentially affected their formulation and choice of criteria as well as their final decisions. That is to say, it may be necessary for us to further clarify the role of personal value judgement in SSI DM. It would be beneficial for researchers and teachers to understand the influence of instruction on students' DM.

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Appendix

Testing for conformity to a normal distribution using the Shapiro–Wilk test.

		DM skills	Statistics	*df*	*p*
CG	Pre-test	Generating criteria	.662	43	<.001
		Analysing alternatives	.613	43	<.001
		Applying a DM strategy	.613	43	<.001
		Evaluating DM results	.700	43	<.001
		Total	.842	43	<.005
	Post-test	Generating criteria	.732	43	<.001
		Analysing alternatives	.551	43	<.001
		Applying a DM strategy	.544	43	<.001
		Evaluating DM results	.798	43	<.001
		Total	.867	43	<.003
EG	Pre-test	Generating criteria	.527	43	<.001
		Analysing alternatives	.649	43	<.001
		Applying a DM strategy	.635	43	<.001
		Evaluating DM results	.527	43	<.001
		Total	.813	43	<.001
	Post-test	Generating criteria	.613	43	<.001
		Analysing alternatives	.479	43	<.001
		Applying a DM strategy	.140	43	<.001
		Evaluating DM results	.752	43	<.001
		Total	.777	43	<.001