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Integrated STEM Learning in an Idea-centered Knowledge-building Environment

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Abstract

STEM learning is an integrated approach to improving learners' problem-solving capacity and 21st-century skills by engaging them in systematic investigation that requires interdisciplinary knowledge. This study aimed to examine whether the design of an innovative knowledge-building environment facilitates STEM learning. Participants were university students engaging in in-depth group projects to design a piece of living-technology product. Data were obtained from student groups' online discussion of their STEM projects. Both quantitative and qualitative analyses of student groups' knowledge-building activities, including fostering a strong sense of community, working productively with ideas, and assuming higher-level agency, provided evidence of students'

deep engagement in the design of their STEM projects. Recommendations for the design of effective STEM learning environments are offered.

Introduction

The lack of professionals in science, technology, engineering, and mathematics (STEM) fields and students' declining interests in pursuing STEM majors (Han 2017) indicate a need to promote STEM subjects. In 2007, the US Congress legislated to promote STEM subjects, followed by various initiatives taken to encourage students to pursue STEM careers in related fields by ensuring that they are equipped with solid STEM knowledge and skills (Kuenzi 2008). There has also been research into the nature, process, and outcomes of STEM education. A search for "STEM education" in Google Scholar carried out on May 15, 2018 retrieved over 202,000 publications and in the past 5 months alone, more than 3400 articles mentioning STEM have been published. Another search for "STEM education" in the Web of Science database yielded 1864 publications for the period 2008–2018 (from 56 in 2008 to 342 in 2017). Apparently, the importance of STEM education is increasingly recognized by educators and policy makers (Ritz and Fan 2015). It is argued that STEM education facilitates the development of important 21st-century skills such as creative, communicative, collaborative, and design skills that are urgently needed to solve today's pressing societal, economical, and environmental problems (Bybee 2010; National Science Teachers Association 2011).

Despite significant support of STEM education in many countries, nonetheless, systematic evidence-based research and practice conducive to STEM-wide educational change have yet to be implemented (Ritz and Fan 2015). More empirical studies are needed to explore ways of promoting STEM education (Chai 2018). This study aims to mitigate the gap, by introducing a learning environment designed to foster STEM education. We start by discussing factors that influence the effectiveness of a STEM learning environment and then argue that knowledge-building environments (KBEs) have the potential to foster STEM learning. We describe our empirical investigation in a higher education context before presenting recommendations for designing effective STEM learning environments.

Literature Review

Factors Influencing Effectiveness of STEM Learning Environments

Existent literature suggests a myriad of factors—e.g., teaching, learning, and social—which may influence the effectiveness of STEM learning environments. First, from a teaching perspective, different from the pedagogy of each subject in STEM, one of the main features characterizing the STEM approach is that it is inherently integrated (Becker and Park 2011; Honey et al. 2014; Wang et al. 2011). In other words, STEM education must be inter- or multi-disciplinary (Becker and Park 2011; English 2016; Stohlmann et al. 2012). But in a deeper sense, this also implies an innovative approach that goes beyond just integrating several academic disciplines and instead involves the integration of other instructional factors such as attitudes, motivation, beliefs, and higher-order cognitive skills into the creative use of content knowledge (Bransford et al. 2000; Bruning et al. 2004). To this end, various design-oriented and project-based approaches to integrated STEM instruction have been proposed (Swap and Walter 2015; Gross and Gross 2016; Han et al. 2016; Kelley and Knowles 2016; Siew et al. 2016). For example, Kelley and Knowles (2016) proposed a conceptual framework for STEM education that includes four elements: (1) scientific inquiry, (2) technological literacy, (3) mathematical thinking, and (4) engineering design, in which engineering design especially plays a major role. Siew et al. (2016) evaluated middle-school students' experience of using an engineering design process approach in an integrated STEM program. They found that this outreach program helped students become more aware of their potential as problem-solvers regardless of the difficulty they encountered when addressing design challenges. Hathcock et al. (2015) found that students could learn effectively through design-based STEM activities supported by question-based scaffolds.

Second, from a learning perspective, effective STEM education demands a learner-centered environment where students interact with interdisciplinary knowledge actively and constructively (Walter et al. 2016). A meta-analysis of 119 studies of students from preK-20 concluded that positive learning outcomes are associated with a learner-centered environment with a positive teacher–student relationship (Cornelius-White 2007). In line with Dewey's (1938) work on experiential education that pivots on student-centered, hands-on activities, research in STEM courses also suggests a positive linkage between student-centered approaches and learner engagement (Deslauriers et al. 2011; Gasiewski et al. 2012). Cantrell et al. (2003) argued that effective STEM learning environments must enable students to learn from first-hand experiences. For example, two middle-school students were found to engage in deep learning through hands-on learning experiences in an out-of-school studio (Evans et al. 2014). Similarly, robotics can also provide an attractive, hands-on learning environment for STEM education that facilitates students' acquisition of knowledge and skills for more complex learning (Barak and Assal 2018). Unfortunately, a survey of teachers from higher education institutions revealed that instructors in STEM-related disciplines were less likely to use student-centered learning approaches than instructors in non-STEM disciplines (Walter et al. 2016), a finding echoed by another survey of 400 colleges and universities (Hurtado et al. 2012). Clearly, fostering student-centered STEM learning environments remains a significant challenge, especially in higher education settings.

Third, from a social perspective, collaboration among learners is essential for an effective STEM educational environment (Sanders 2009). Based on a review of 67 studies, Wilson and Varma-Nelson (2016) found peer-led collaborative learning to be a common practice in STEM education. Research also shows that learning engagement can be enhanced through meaningfully structured collaboration (Gasiewski et al. 2012). Hence, it is desirable to integrate collaboration in STEM learning environments so that learners exercise their higher-order thinking skills to solve interdisciplinary problems collaboratively (Duran and Sendag 2012; Springer et al. 1999; Wells 2016).

In summary, prior literature suggests that to be effective, a STEM learning environment ought to support integrated interdisciplinary knowledge, allow students to engage in design-oriented or project-based tasks, foster a student-centered learning atmosphere, promote experiential learning, and encourage peer interaction and collaboration. Together, these features give rise to an integrated STEM learning experience conducive to the integration of knowledge from multiple disciplines. Previous research, however, has shown that in many classes where an integrated STEM approach is adopted, students may be able to focus on the tasks, problems, or challenges they are assigned, but have problems engaging with disciplinary knowledge in a more consistent and integrated manner (Berland and Steingut 2016). Similarly, a review by Chalmers et al. (2017) indicated that the design of many STEM curriculum units does not allow students to engage in the construction of in-depth STEM knowledge. Addressing this issue would probably require novel approaches to the design of effective STEM learning environments, and here we propose one innovative approach that creates an idea-centered learning environment to encourage students to work innovatively with ideas to solve problems and build knowledge collaboratively (Chalmers et al. 2017; Chen and Hong 2016).

Idea-centered Knowledge-building Environments

As argued above, effective STEM learning requires an innovative learning environment. Here, we posit that KBEs can provide such an environment. A KBE is defined as a physical, virtual, or hybrid space where a knowledge community produces and improves ideas over an extended period to collectively advance knowledge (Scardamalia and Bereiter 2003). A KBE must support three activities: working with ideas, fostering community, and assuming epistemic agency (Lin et al. 2014).

First, with respect to working with ideas, a KBE values the sustained production, development, and improvement of ideas relevant to real-world issues or problems (Bell 2010; Lin et al. 2017). In a KBE, ideas are treated as improvable (just like everyday objects that can be operated), as something that can be developed into more reliable and valid knowledge (Scardamalia and Bereiter 2003; Hong et al. 2015). In order for idea-centered knowledge work to prosper in a KBE, a culture must be in place so that students feel safe in taking risks, and in giving and receiving criticism. Learners are also encouraged to generate diverse ideas to address joint or related problems and to share ideas with other members of the community to improve the communal understanding of the problem at issue and the utility of generated ideas (Lin and Chan 2018; Vokatis and Zhang 2016). Such idea improvement, undertaken by a collective, allows ideas to evolve into more refined and promising problem solutions. Overall, an idea-centered KBE provides students with many opportunities to work with complex ideas in their messiness and diversity, to learn to synthesize ideas, and to achieve a deeper understanding of the problems or issues addressed through integrating and extending disciplinary knowledge such as STEM knowledge (Chalmers et al. 2017; El Sayary et al. 2015; Savery 2006). This idea-centered approach fits naturally with integrated STEM as it centers on authentic ideas that naturally draw from knowledge from multiple disciplines (Chen and Hong 2016). In contrast, non-idea-centered or concept-based learning environments (CLEs) usually use textbook problems or puzzles and problems are often assigned by a teacher rather than chosen by students because they are interesting (Grant and Hill 2006). Students working on a problem in a CLE are often encouraged to review structured, textbook presentations of carefully defined concepts from a specific subject rather than to work with emerging ideas from all potentially relevant disciplines. In a CLE, instead of ideas, concepts are more likely to be valued. They represent the finalized and valid form of knowledge and are regarded as the basic units of knowledge to be evaluated and validated. In a CLE, the main learning objective is usually to master a huge corpus of established knowledge of a particular subject area as effectively as possible in a given time-frame (Lou et al. 2011).

Second, with respect to fostering community, a KBE values collective or group endeavor as much as individual achievements. Students are encouraged to take collective responsibility for advancing knowledge as a community.

It is important, therefore that all members are seen as legitimate knowledge contributors, rather than separated into knowledge haves and have-nots or innovators and non-innovators; similarly, it is important to encourage group pride in advancing collective knowledge. It is equally important to foster distributed expertise (Brown et al. 1993; Looi et al. 2010; Zhang et al. 2011) in a group by valuing and integrating members' different strengths with respect to the knowledge problem at hand, since knowledge advancement is usually best achieved through symmetric knowledge process. Ensuring the symmetrical distribution of expertise also facilitates group-based interdisciplinary learning, which is highly valued in STEM education. In contrast, CLEs are not always designed to support group- or community-based learning. They are commonly designed for individual learning and this is especially true in the case of CLEs designed to support preparation for high-stake examinations. Even when CLEs are designed to support group-based learning, they may only support what has been called learning-in-a-group, i.e., members of the group help each other to learn the target knowledge (e.g., assigned textbook concepts) more efficiently via division of labor (Roschelle and Teasley 1995). For example, a four-member group might divide a book chapter into four portions, then assign each member a portion to learn and then share with the rest of the group (Aronson 1978, 2002). This is very different from learning-by-group, in which the group tries to achieve a top-level collective goal and advance collective knowledge, rather than members using the group or community as a means to achieve individual learning objectives.

Third, with respect to assuming agency, a KBE highlights the importance of community members assuming the role of knowledge workers by exercising epistemic agency. This emphasis is in line with the recognized significance of self-directed learning in STEM education (León et al. 2015). In a KBE, members are encouraged to be metacognitively and motivationally active in setting goals, managing knowledge, and developing strategies. Members of a KBE should not merely generate ideas and share information with their peers; they should actively participate in the community's knowledge discourse to help achieve its ultimate knowledge goals. To advance knowledge, members must not only be aware of the current state of knowledge in the community, but also be able to expand their knowledge in a constructive manner. In short, members need to become autonomous epistemic agents, capable of dealing with all knowledge goals and problems in concert with other members of the community; members' personal learning gains are regarded as a byproduct of the community's collective effort. In contrast, students in a CLE act more like knowledge re-producers, replicating and validating textbook concepts and knowledge, and are usually more passive learners as they tend to rely on teachers or parents when it comes to setting learning goals, planning learning activities, and evaluating learning. Some individual learners may be able to set their own short-term learning goals in order to pass school tests and examinations, but overall they depend on the teachers and curriculum authority to chart the course of their education. How to transform students into actual knowledge workers who are able to engage in sustained knowledge advancement desired by STEM education remains to be further researched. Table 1 shows the key differences between KBEs and CLEs.

Table 1 Differences between KBEs and CLEs

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This Study

Previous studies suggest that KBEs are conducive to (1) pre- and in-service teachers' learning and professional development (Hong and Lin 2010; Chai and Tan 2009), (2) advancing students' thinking and learning skills (i.e., communicative, creative, critical, and collaborative skills) (Gilbert and Driscoll 2002; Lin et al. 2017; Ryser et al. 1995; Scardamalia et al. 2012), and (3) improving their social learning capacity (Hong and Scardamalia 2014; Hong et al. 2015). Given these findings, it is plausible that a properly designed KBE could transform users into knowledge workers—an educational goal shared with STEM education initiatives. Nevertheless, it is clear from a recent review of KB studies over the past 30 years (see Chen and Hong 2016) that studies dedicated to investigating the relationships between KBE and STEM learning remain lacking. The purpose of this study was to fill the gap, by investigating the extent to which a designed KBE could foster STEM learning. Specifically, we designed and implemented a KBE that features a STEM design project and we asked the following related research questions: (1) How would students act and perform in an online KBE? (2) How do students engage in the specific aspects of KB activities of fostering community, working with ideas, and assuming agency in the KBE? (3) What is the overall quality of STEM products designed by students in the KBE? (4) What are the relationships between students' overall online performance, specific KB activities, and final STEM products in a design project? (5) What group processes are used to design a STEM product in a KBE?

Method

Participants and Context

This study was a case study conducted at a university in Taiwan. Participants included 48 teacher-education students who had no formal STEM learning experiences before this study, and took a beginning college course. Building on Kelley and Knowles' (2016) conceptual framework for STEM education, the one-semester course required students to (1) engage in scientific inquiry process in groups; (2) use an online forum and its tools to access/integrate/exchange information (i.e., technology literacy); (3) exercise mathematical thinking to identify problems, analyze underlying patterns, and find solutions; and (4) design or re-design a piece of living-technology product that can help improve human life.

The course activities can be divided into two major parts: face-to-face and online activities. The face-to-face activities, which occurred in classroom, included lectures, presentations, textbook reading, questions and class discussion, and exams. This part of activities was highly teacher-centered and knowledge-based. In contrast, the online activities centered on student-directed inquiry and were independent of the classroom lecturing activities that focus on learning about textbook concepts. The development of the online part of the course was based on knowledge-building (KB) pedagogy (as discussed above) with support from Knowledge Forum (KF) technology (see below for detail). At the beginning of the course, the participants were randomly divided into 10 groups (4 groups of 5 students and 2 groups of 4 students) and they worked in these groups throughout the course. All of their online group activities were recorded in KF, including discussions related to their design projects.

Instructional Design

The instructional design of this course was mainly concerned with two design problems: (1) how to support student collaboration, and (2) how to integrate the online platform (i.e., Knowledge Forum) to support their collaboration. In terms of the first design problem, each group was invited to undertake the following collaborative activities that centered on a shared technology design goal: (1) Problem observation and investigation: discussing everyday technology objects that can be potentially improved. (2) Problem determination: deciding and selecting one particular technology object as the main STEM project for further discussion and evaluation. (3) Solution generation and evaluation: brainstorming as many diversified ideas as possible to address the issues or defects identified from the selected technology object. (4) Solution decision: In-depth discussion and debate comes into reflect, elaborate, and finalize the best solution ideas for improving the target technology object for final improvement

To address the second design problem, this study capitalized on various features of KF designed for three essential dimensions of KB (working with ideas, fostering community, and assuming agency) (see Fig. 1). Within these three KB dimensions, working with ideas allows students to integrate knowledge from different disciplines in order to address problems they identified; fostering community allows them to work in groups and shoulder collective design responsibility; and assuming agency encourages them to take risk and be adventurous for new learning experiences. These KF features are described below.

Fig. 1

Pedagogical design and a screenshot of KF showing a KF note (bottom right) and a KF view and features of the KF design

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Features that Support Working with Ideas

Using KF, learners can contribute a note to express an idea, reference notes when building on existing ideas, and revise a note to improve ideas within it. "Note-contributing" is the function members used for generating ideas. It allows members to contribute ideas to the database in order to address a given problem during a given time period. "Note-referencing" allows users to reference each other and share ideas. "Note-revising" allows members to reflect on his or her ideas.

Features that Help to Foster Community

KF provides functions such as "note-reading," "note-building-on," and "note-linking." The "note-reading" function shows community members' reading activity for a specified time period. "Note-building-on" allows users to revise or improve old ideas, share information or ask questions about ideas within an existing note in a build-on tree.

"Note-linking" includes all notes from building-on-notes, referenced notes, and rise-above notes (i.e., higher-level notes which subsumes all related ideas or notes).

Features that Help Learners Assume Agency

KF provides tools such as "problems-worked-on," "keyword," and "search." The "problems-worked-on" feature records the content and number of problem statements contained in notes authored by the user. The "keyword" tool allows users to exercise extra effort to identify important key concepts when working or reflecting on their ideas in writing. "Search" is a tool to help users take a more directed, focused approach to identifying a given idea or relating one idea to another.

One thing to note is that the tools and functions described here are only a subset of those available in KF. It is also important to note that some tools may serve more than one KB purpose in KF. In this course, students were able to use the majority of tool features such as note-contribution, note-reading, note-build-on, note-revision, reference, search, and problem-worked-on (see Fig. 1).

Data Collection and Analysis

Mixed methods were used to collect data of each group's online discussion in KF. The main data sources were (1) a group's online activity logs, (2) group discourse in KF, (3) the final STEM product designed by a participating group, and (4) analysis of a selected group's project and STEM learning.

Figure 2 illustrates the analytical framework of this study. First, online activities (such as notes-contributed, notes-built-on, and notes-read) were automatically logged in the KF database and descriptive statistics were calculated to provide a general picture of activities in KF.

Fig. 2

Analytical framework

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Second, the content of online discussion was analyzed qualitatively in light of the three KB dimensions—fostering community (FC), working with ideas (WI), and assuming agency (AA)—using the KF note as the unit of analysis. From a knowledge-building perspective, the FC activity is defined as the extent to which a community members' engagement or involvement by interacting or collaborating with others to improve ideas by posting notes in Knowledge Forum. The level of FC activities was classified into three levels: level 1—simple participation through the creation of notes; level 2—deep involvement in group conversation about the design topic/problem/ideas; and level 3—working to synthesize diverse or inconsistent ideas for advancing group or community knowledge. Table 2 summarizes the three levels of community engagement or involvement. To analyze WI, all KF notes were carefully read and re-read and then divided into two types: (1) notes focused on idea-relevant discussion and (2) notes composed of idea-irrelevant discussion. Notes categorized as idea-relevant were further classified according to the level of epistemic agency they displayed (higher vs. lower). Here, epistemic agency reflected a learner's efforts in advancing one's understanding. Hence, notes that merely reported anecdotes of real-life problems, generated new ideas, provided information, made suggestions, or asked questions were classed as lower-agency behaviors, whereas notes illustrating learners' intention to elaborate or integrate ideas, identify potential problems, or provide a solution to a problem were classified as higher-agency behaviors.

Table 2 Coding scheme of three types of knowledge-building activities
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Third, to evaluate the quality of each group's design product (e.g., eyeglasses with a massage function, reusable chopsticks), we used Besemer's (1998) Creative Product Analysis Matrix (CPAM). Each group's design products were evaluated in three dimensions: novelty (i.e., originality and surprise); resolution (i.e., value, logicality, usefulness and comprehensibility); and elaboration and synthesis (i.e., organic qualities, elegance and craftedness). Detailed descriptions of these dimensions are presented in Table 3.

Table 3 Creative product scoring scheme
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Fourth, we computed the correlations between the above measures of (1) online KF activities, (2) KF discussion content, and (3) STEM products. Online KF activities were indexed using the quantitative, behavioral variables recorded in the KF database as frequencies or percentages. To ensure statistical reliability, we first transformed all variables into standardized *z*-scores, which were then summed to yield a single score representing a group's online activity. We used the same approach to generate an overall *z*-score for the three KB activities. Spearman correlations between overall KF activity, combined KB activities, and the final STEM product score (which was not transformed into a *z*-score as there was only one final score) were then calculated to identify associations between these aspects of STEM learning.

Finally, the entire design process was described and explained for one representative group to illustrate how groups approached design work in the designed KBE, using Norman's (2013) conceptual design-thinking framework of two working spaces (i.e., problem and solution spaces).

Inter-coder reliability (Spearman's ρ) was calculated for all the above analyses to check that coders displayed sufficient agreement with one another. The values indicated good, reliable agreement between coders: fostering community $\rho = 0.86$ ($p < 0.01$); working with ideas and assuming agency $\rho = 0.74$ ($p < 0.01$); creative products $\rho = 0.81$ ($p < 0.01$).

Results

Overall Online Performance

Overall online KF performance in this course is presented in Table 4, using the group as the unit of analysis. During the semester, 1461 notes were contributed in KF, a mean of 29.31 per participant (SD = 26.41). The average percentage of notes linked to another note (through replying or referencing) was 79.4% (SD = 17.63%). Each student has read on average 19.6% (SD = 22.41%) of all notes. In addition, the average percentage of notes with keywords was 52.85% (SD = 32%). Overall, these records of KF activities demonstrate that online interaction was fairly interactive in this course, but these interactive behavioral indicators only give a general sense of the extent to which participants acted and took part in group activities in the course. More detailed qualitative analyses were necessary to explore in detail how participants sustained the community, worked with ideas, and assumed epistemic agency.

Table 4 Descriptive analysis of the KF community's online activities
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Knowledge-building Practices

Following the above analysis, we investigated the quality of students' online work and performance of the three essential aspects of KB activities, i.e., fostering community, working with idea, and assuming agency using the group as the unit of analysis. First, we analyzed fostering community, using the community engagement coding scheme based on the three dimensions of participation, discussion, and integration, as described above. As shown in the top portion of Table 5, there was a difference among the three community dimensions ($\chi^2(2) = 10.46$, $p < 0.01$). Post hoc analysis was carried out using Wilcoxon signed-rank tests. There were no differences between the participation and discussion running trials ($Z = -1.224$, $p = 0.221$) or between discussion and integration running trials ($Z = -2.157$, $p = 0.031$). However, there was a reduction in perceived effort in the participation relative to the integration ($Z = -2.555$, $p < 0.05$), indicating that the groups did not demonstrate higher-level integration activities. Nevertheless, these data show that groups did work together to advance group knowledge for the STEM project.

Table 5 Knowledge-building practices
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Second, we analyzed working with ideas by examining *what* were generated in notes to code them into two types: idea-relevant and idea-irrelevant. We then calculated non-parametric statistics to compare the numbers of each type of notes. As shown in the middle portion of the Table 5, a Wilcoxon signed-rank test showed that there were more notes on idea-relevant discussion ($M = 91.9$, SD = 29.85) than on idea-irrelevant discussion ($M = 15.4$, SD = 10.91; $Z = -2.803$, $p < 0.01$). Overall, the findings indicate that groups were able to work productively in KF and discussed ideas related to their design project rather than chatting.

Third, we analyzed assuming agency by looking in detail at the content of all idea-relevant notes. We then compared the frequency of each level of agency using a non-parametric test, the Wilcoxon signed-rank test. As shown in the rest of the Table 5, the results revealed a difference between the numbers of high- and low-agency notes ($Z = -2.803$, $p < 0.01$); there were more notes documenting cognitive behaviors associated with low agency ($M = 4.18$, SD = *0.07*) than notes documenting high agency ($M = 1.64$, SD = 0.16). This was as expected, as it is not possible for students to perform higher-level cognitive activities without the support of lower-level cognitive activities. The important issue is whether activity displaying higher agency improved STEM product design.

STEM Products

We looked into the final STEM products students designed in the KBE. These products were designed based on related products the students encountered in their daily life. For example, one group designed a new kind of umbrella with a detachable, replaceable canopy that would be attached with buttons, a zipper, or Velcro. This can be compared with a standard umbrella, where the canopy is usually stitched to the umbrella's metal ribs. As one group member (Group 2) said "…the canopy of the umbrella is always sewn tightly to the framework of the umbrella and cannot be separated!!…we may be able to address this problem by using buttons…" We used Besemer's (1998) CPAM to code each product design in terms of novelty, resolution, and elaboration & synthesis. As shown in Table 6, non-parametric statistics revealed significant difference among novelty, resolution, and elaboration/synthesis ($\chi^2(2) = 6.20$, $p < 0.05$). We carried out post hoc analysis using Wilcoxon signed-rank tests. There were no significant differences between the novelty and resolution running trials ($Z = -0.564$, $p = 0.573$) or between elaboration/synthesis and novelty running trials ($Z = -0.767$, $p = 0.443$). However, there was a statistically significant reduction in perceived effort in the resolution versus elaboration/synthesis ($Z = -2.405$, $p < 0.05$), indicating that when designing their STEM products, groups focused on value, logicality, usefulness and comprehensibility at the expense of the product's organic qualities, elegance, and well-craftedness. Overall, the findings indicated that students were able to make creative improvements to the product they started with using the KBE and that they were particularly effective in designing practical improvements.

Table 6 Evaluation of groups' STEM products using Besemer's creative product analysis matrix

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Relationships among Online Activities, KB Activities, and STEM Products

Finally, we explored the relationships among overall online interactions, KB activities, and STEM product design. As shown in Fig. 3, online performance was correlated with the score for KB activities ($\rho = 0.77$, $p < 0.01$), indicating that the combined online activities may be used as a measure for understanding how KB activities were practiced in the KF. In addition, the STEM product design score was correlated with the score for KB activities ($\rho = 0.75$, $p < 0.05$), but not with online performance ($\rho = 0.61$, $p > 0.05$). This implies that qualitative measures of the KB activities may be more closely related to the quality of STEM product design than the quantitative, online behavioral variables. From a temporal perspective, it is posited that there is a causal relationship among them because students' group workflow started with their online performance, mediated by the three KB activities, and eventually culminating with the formation of the design of their STEM products. It might, therefore, be interesting to explore the causal relationships amongst the three variables. Nevertheless, the correlations we have documented are sufficient to support our main claim, namely that the designed KBE is conducive to integrated STEM learning. Below, we look more closely at groups' design processes in this KBE using one group as a case.

Fig. 3

Relationships among online activities, KB activities, and STEM products (**$p < 0.01$; *$p < 0.05$)

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A Case Example

Groups' STEM product designs were grounded in real-life issues or problems that they found interesting. To gain a better understanding of the processes by which groups developed their STEM product designs, we used Norman's (2013) conceptual framework of two working spaces (i.e., problem and solution spaces) to examine how groups approached their design problems and eventually came up with solutions, considering the process in terms of the following four phases: problem observation and investigation, problem determination, solution generation and evaluation, and solution decision. Overall, our analysis shows that all groups went through these four phases. Due to constraints on space, we decided to look in more detail at one group, Group 2, to illustrate the design process in detail.

Group 2’s Phase 1 (problem observation and investigation) discussion initially focused on identifying possible everyday objects and products that needed improvement. Eventually, they identified the following eight targets: toothbrush, umbrella, typing, hair spray, washing machine, hair dryer, dining table, and food menu. During the problem investigation phases group members started to discuss all the potential problems of each product. Below, we summarize the main problems and solutions they identified for each potential target: (1) demountable toothbrush (reduce material waste); (2) detachable umbrella (convenience and reuse of materials); (3) voice typing (convenience); (4) cleaning hair spray (for hairstyling and hair-cleaning simultaneously); (5) pen-washing machine (wash germs off pens); (6) instant hair dryer (save time); (7) adjustable table (save space); and (8) digital menu (paperless).

In Phase 2 (problem determination), Group 2 eventually selected detachable umbrella as their main STEM project after in-depth discussion and evaluation. Overall, Group 2 members went through a divergent-to-convergent thinking process when working in the problem space. First, they brainstormed possible design problems and then they singled out one problem after reflecting on the value of each problem, and idea-centered KBE served as their problem space for their design work.

In Phase 3 (solution generation and evaluation), the group focused on the detachable umbrella idea and proceeded to generate as many ideas as possible, including (1) making the metal frame of an umbrella separate from the canopy so that the canopy can be detached; (2) allowing the canopy to be customized with different patterns; (3) using something to fasten the canopy to the umbrella frame; (4) designing umbrellas with different canopy shapes (e.g., square); (5) anti-UV cloth for the canopy; (6) allowing the umbrella be attached to a backpack (instead of handheld) for convenience; (7) using extremely light materials for the frame; and (8) Nano coating for the canopy. All ideas were subjected to careful examination and critical discussion to rule out irrelevant and less useful or innovative ones (e.g., square canopies and the backpack-mounted umbrella). In the last phase, the solution decision phase, the group decided to use buttons, Velcro, or zippers to create a canopy that could be attached and detached from the metal ribs of an umbrella to solve the problem they had chosen, creation of a detachable umbrella. Figure 4 illustrates the key concept behind Group 2’s design solution. As when they were working in the problem space, Group 2 members went through a divergent-to-convergent thinking process when working in the KBE as their solution space.

Fig. 4

Group 2’s chosen solution to the problem of creating a detachable umbrella

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Clearly, the case shown above corresponds to Kelley and Knowles’ (2016) conceptual framework for STEM education, which includes four elements: scientific inquiry, technological literacy, mathematical thinking, and engineering design. Evidently, the students were engaging in a *scientific inquiry* process while using technology to access/evaluate/integrate/communicate information (i.e., *technology literacy*) through *mathematical thinking* (which is defined as a way of looking at things, of breaking them down to their structural essentials, and of identifying the hidden patterns) in order to address an *engineering design* problem.

Discussion and Implications

Previous STEM studies have shown that an effective STEM learning environment is usually characterized by its being able to support interdisciplinary knowledge integration (Honey et al. 2014 English 2016; Stohlmann et al. 2012), engage students in highly design-oriented activities (Gross and Gross 2016; Han et al. 2016; Kelley and Knowles 2016; Siew et al. 2016), foster risk-taking through experiential learning (Barak and Assal 2018; Evans et al. 2014), and value peer collaboration and evaluation (Bruning et al. 2004; Gasiewski et al. 2012). Previous research also indicates that many STEM-oriented classes have difficulties in engaging students with in-depth knowledge-integration tasks (Berland and Steingut 2016). Clearly, more research is urgently needed to explore various strategies to design effective STEM learning environments. To this end, this study engaged students in various idea-centered and design-oriented tasks in a KBE (Lin et al. 2017) by addressing the question of how to help foster integrated STEM learning in an online KBE through three major types of online knowledge-building activities.

To answer the first research question, we examined groups’ overall online performance in the KBE. The results indicated that groups were able to move away from individual learning to collaboration in KF, as reflected in activities such as note linking, note reading, note revision, and note creation.

The second research question is concerned with the three types of online KB activities (*fostering community*, *working with ideas*, and *assuming agency*). With regard to *fostering community,* this study supports the argument from prior research that effective STEM learning environments are inherently collaborative (Sanders 2009), as the findings indicate that group members were able to form a strong community by participating more fully in group activities via discussion about their STEM projects. Nevertheless, the integration of ideas, which requires higher-level online performance, remained more challenging. More scaffolding or guidance needs to be provided to facilitate the integration of ideas. This could include encouraging students to use KF's "rise-above" function as this should prompt them to re-conceptualize their design problem and to consolidate their ideas.

As regard *working with ideas*, we coded notes into idea-relevant and idea-irrelevant categories to investigate how the KBE facilitated idea-centered discourse. This feature of KBEs distinguishes them from other platforms, which typically focus on social interactions (e.g., social chat or information-sharing). The results showed that groups engaged in idea-relevant discussion most of time, hence we can infer that KF provided a suitable online environment for intellectual discourse underpinning productive work with ideas for a STEM project. The findings are consistent with previous research on science or technology-related learning indicating that the design of KBEs makes them suitable for deep inquiries where the emphasis is on ideas (Hakkarainen and Sintonen 2002; Hong and Lin 2018; Lee et al. 2006; Oshima et al. 2006). The present study provides corroboration of the effectiveness of idea-centered platforms as a method of supporting project-based STEM learning and problem-solving.

With regard to *assuming agency*, the results also indicate that groups toned to exercise high-level agency when completing their STEM projects. Higher-level cognitive activities amounted to 28.17% (1.64/(1.64 + 4.18)) of all cognitive activities in the KBE, which is in contrast with most social media platforms, where cognitive activities typically involve information exchange only. In a KBE, by means of collaborating with other members, important ideas are devoted to advancing community knowledge. Higher-level agency enables group members to monitor their idea-centered discourse continuously to help them improve their progress with their STEM projects and is reflected in the decentralized structure of group activities, with group members not only contributing personal ideas, but also building on the ideas of others (Scardamalia and Bereiter 1991).

The third research question is concerned with the STEM product designs produced by the groups. The findings indicate that the students were able to design and improve products in a KBE. Groups were given the goal of improving the design of an existing produce through a process similar to that used by real-world knowledge workers who try to make lives better. As reflected in the pattern of scores on the three CPAM dimensions, groups' product improvement was mainly focused on value, logicality, comprehensibility, and usefulness (i.e., the practical aspects of the products), and they did not pay much attention to other aspects such as their organic qualities and elegance, so there is still room for pedagogical improvement in their project-based STEM learning. Nonetheless, from the process perspective, it is certain that at the outset of the design process they were able to identify ill-defined problems for designing their products and later on to come up with promising ideas and solutions. Researchers should explore ways of providing guidance that would enhance students' design capability to enable them to come up with more original, novel, or elaborated ideas for creative products as part of more effective STEM learning in the future.

Fourth, correlations between online behaviors, KB activities, and creation of STEM products revealed associations between them. These results support the claim that KBE is related to project-based STEM learning activities. Our evidence also shows that groups' KB activities (i.e., fostering community, working with ideas, and assuming agency) in a computer-supported environment moved progressively towards deeper understanding of their STEM projects.

Finally, the results from our case study provide further support for our claim that KBEs support project-based STEM learning. Group 2's KB processes followed the commonly observed pattern for a design process, moving from problem observation and investigation, through problem determination, solution generation, and evaluation to solution decision. This design process also reflects the divergent-to-convergent design processes that drive the development of design thinking.

There are two important implications for further design of STEM learning with KBE. First, the design of conventional learning environments is usually concept-based to help learners systematically acquire, accumulate, and master a set of important concepts for solving problems or puzzles assigned by teachers or suggested in textbooks. The findings in this study, however, suggest that the design of STEM learning environments should be idea-centered, rather than concept-based. When the production, exchange, and development of students' own ideas (i.e., *working with ideas*) are valued in a STEM environment, students' learning is more likely to be intentional rather than passive (thus more likely to *assume agency*) and to share information and resources while working collaboratively with ideas (i.e., *fostering community*). Second, there is a need to further explore and develop relevant tool supports for idea-centered activities for STEM learning. One possibility is to consider turning O'Quin and Besemer's (2006) product evaluation criteria into scaffolds to support effective group discussion, so that when designing STEM products, group discussion would not only focus on the practical dimension as the findings indicated. Another possibility may be to develop learning analytics tools to allow learners to simultaneously reflect and monitor their idea-related activities so that they are more likely to focus on idea-relevant, rather than idea-irrelevant, online discussion activities.

Admittedly, there are limitations to our study. There was no control condition so we cannot compare the effect that working in the KBE has on project-based STEM learning with the effects of other online learning environments or other typical design classes. Nevertheless, we have provided evidence of a positive correlation between KB activities and STEM project outcomes and it would be worth investigating whether this is a causal relationship. We suggest future studies should include a control group. In addition, as work on most design projects in STEM fields is carried out face-to-face, researchers should also consider comparing the advantages and disadvantages of online and face-to-face learning environments and exploring their similarities and differences.

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