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Supporting Students' Collective Ideas Improvement Through Learning Analytics-Augmented Meta-Discourse

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Abstract: This study investigates how secondary school students engaged in collective inquiry enriched with analytics-supported meta-discourse in a knowledge-building environment. Twenty grade 11 students in a Singapore science classroom participated; the domain of the study was photosynthesis. Students engaged in knowledge-building inquiry mediated by Knowledge Forum (KF) and enriched with learning analytics-augmented meta-discourse over six weeks. Specifically, they employed the embedded KF analytics tools, word cloud to reflect on and continuously improve their collective ideas. Findings indicated that students improved their understanding of key concepts in photosynthesis and engaged in deepening discourse moves over time. Analysis of classroom dynamics, KF reflection and artefacts revealed that with the support of KF analytics-pedagogy, students engaged in meta-discourse, rising above, deepening, and identifying emerging research areas for collective knowledge advances. Implications for how to use analytics-supported to support meta-discourse for knowledge building are discussed.

Introduction

Scientists engage with progressive inquiry, in which they formulate questions and construct coherent explanations. Questions keep emerging as they coordinate new information and existing explanations (Hakkarainen, 2002). However, in many science classrooms, questions do not emerge from students' inquiry but rather pre-determined by teachers, researchers, or instructional designers (Chinn & Malhorta, 2002). Although researchers have designed pedagogical approaches that leverage students' ideas (e.g., ambitious instructions (Stroupe, 2018)), students are not able to determine their inquiry path (Scardamalia, 2002). Therefore, how students engage in knowledge building to chart their scientific inquiry pathways and how collective inquiry can be supported by analytics and learner-generated data are important questions for investigation.

In a knowledge-building learning environment, students engage with an iterative and progressive inquiry process in which they ask research questions, formulate tentative explanations, collect information that supports or refutes initial explanations, and ask new and emerging questions (Scardamalia & Bereiter, 2014; Zhang et al., 2007). The ultimate goal is to improve community ideas. No prescribed scripts are assigned in this process; students determine their inquiry trajectory. Such a process leverages students' epistemic agency (Scardamalia, 2002). Engaging students with productive discourse is important in knowledge building. Unlike using procedural prompts in scaffolding discourse, researchers scaffold students towards developing knowledge-creation discourse in which the community considers discourse as an object of inquiry upon which they reflect (van Aalst, 2009). The whole community continuously monitors and reviews its collective understanding, figures out its remaining questions, and co-constructs inquiry structures to identify inquiry topics, participatory structures, and inquiry activities (i.e. reflective structuration; Zhang et al., 2018). Further inquiry trajectory will emerge from reflective conversations and practices occurring in the community. This process has been examined as meta-discourse for students to reflect on ongoing knowledge building work and chart future progress (Zhang et al., 2015; Tong et al., 2020; Resendes et al., 2015).

While progressive knowledge-building discourse is important for creative knowledge work, collective agency among students in developing such work is highly complex. Recently, researchers have examined how knowledge building can be scaffolded by designing learning analytics that present students' meta-level discourse information in KF. Parallel to the interest in CSCL collaborative analytics (Wise et al., 2021), knowledge building analytics have been developed to support these collective reflective processes as students engage in meta-discourse and meta-cognitive conversation about their knowledge-building inquiry. For example, Resendes et al. (2015) designed an analytics-based pedagogy by using a word cloud. The tool demonstrates students' word cloud, experts' word cloud, and the overlap between the two. Chen et al. (2015) designed the Promising Ideas Tools, which aggregate students-identified interesting topics into themes and demonstrate connections between different themes using connections to encourage students to identify future inquiry paths. Zhang et al. (2018) designed Idea

Thread Mapper, which visualises the development of ideas in individual idea threads, the interrelation between multiple ideas threads, the intensity of contributions in each thread, and cross-thread connections.

The importance of placing learner-generated Knowledge Forum data in students' hands for epistemic agency and transformative assessment is an important theme in knowledge building (Scardamalia & Bereiter, 2014). In our ongoing research, we designed a Knowledge Connection Analyser to support students' collaboration, information synthesis, and inquiry into integrating emerging ideas (e.g., how do our ideas develop). Students reflected upon the data from their KF inquiry and identified ways to improve their community knowledge. (Yang et al., 2016). As KBDex (Oshima et al., 2012) has often been used for the analysis of KF discourse, we adapted a network of keywords from KBDex and developed an Idea Friend Map to encourage students to connect ideas across different groups by demonstrating neighbouring groups' ideas in the vicinity of their ideas (Feng et al., 2019). This encouraged students to make ideas connected in the community for collective advance. A common theme drawn from these studies was how collaborative learning analytics could be designed to externalise and visualise community knowledge and demonstrate the community knowledge gap in a more salient way. The visualisation of analytics created a shared inquiry object around which students conducted meta-discourse to plan their future inquiry steps and improve collective community knowledge.

This study builds on current research examining how students can use learning analytics to engage in meta-discourse to promote their knowledge-building inquiry in a high school biology classroom. We designed a knowledge-building learning environment in which students engaged in collective inquiry into the problem of photosynthesis, enriched with KF learning analytics of how they had written on KF, and students engaged in meta-discourse (meta-cognitive conversations) to reflect on what they have accomplished and to plan for future inquiry. Through this process, new questions and research themes kept emerging, sustaining the collective scientific inquiry for advances in community knowledge. This study examined the following research questions: (1) Did students improve their understanding of photosynthesis before and after knowledge-building activities? (2) How did students engage in knowledge-building activities that supported collective ideas improvement? (3) How did students engage with analytics-supported reflective assessment and meta-discourse to improve their collective knowledge-building inquiry?

Method

Pedagogical Context

This study was conducted in a Singapore secondary school science class in which photosynthesis was the major topic. Twenty-two eighth-grade students participated in the six-week study, continuously engaging in collective inquiry and improving community knowledge through meta-discourse enriched by analytical tools: word clouds and an author-network tool embedded in Knowledge Forum (see figure 2). This study collected students' domain understanding, KF notes, classroom discourse, students' reflective notes, and classroom artefacts.

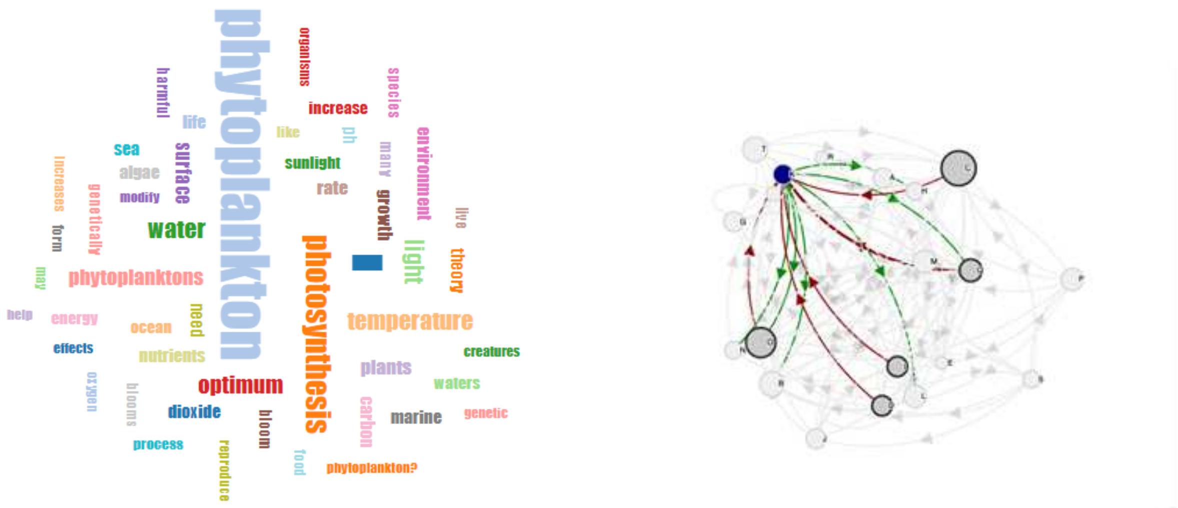

Figure 1. Word Cloud (left) and Idea-Building Tool (right)

Pedagogical Design Analytics Tools

The pedagogical design integrated learning analytics (see Table 1). Phase I: Students freely participated via Padlet and transferred their initial questions to KF based on the criteria of good questions co-constructed by students and the teacher (week 1-2; see the left picture in figure 2). Phase II: Students generated rise-above ideas through learning analytics-augmented meta-discourse and constructed concept maps (week 3-5; see the right picture in figure 2). Phase III: Students extended ideas by engaging in meta-discourse supported by a set of learning analytics, including word clouds and ideas-building tools (week 6; see figure 1). Phase IV: Students engaged with reflective assessment (week 6), writing portfolio notes individually using scaffolds (e.g., "big ideas we want to understand; we used to think; from our discussions; how we understand; we want to know further; we want to read more").

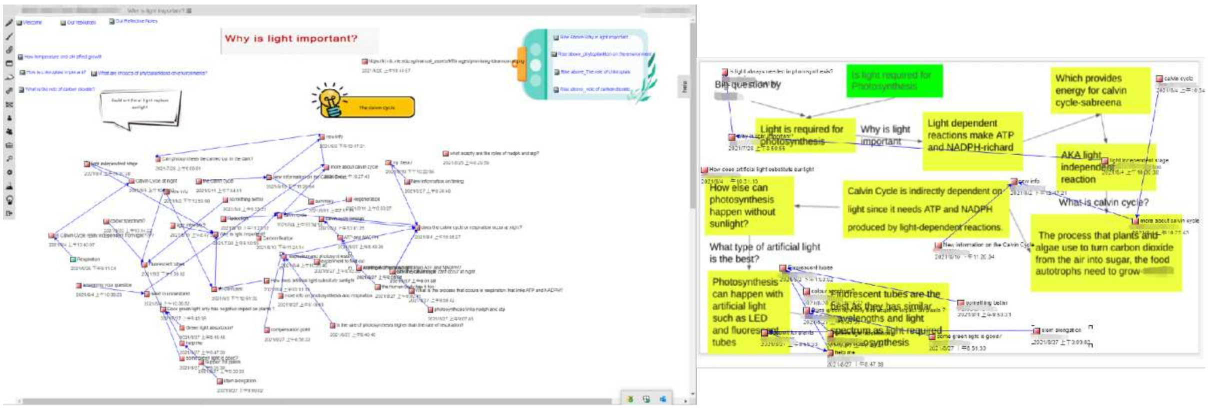

Figure 2. Students KF view (left) and students created concept map (right)

Table 1: Major pedagogical design features and analytical tools involved

Key Design Feature	Activities	Technological Tools
Phase I; initial problem formulation (week 1-2)	Students freely participated via Padlet and transferred their initial questions to KF based on the criteria of good questions, which were co-constructed by students and the teacher	Padlet, KF
Phase II: Deepening inquiry with analytical tools and meta-discourse (week 3-5)	Students created rise above view with assistance of word cloud; students deepened ideas through creating, annotating and sharing concept maps in class.	Word cloud; KF
Phase III: Learning analytics-supported meta-discourse and idea extensions (week 6)	Students run trials on word cloud and ideas-building tool, wrote reflective notes, reviewed inquiry process, and planned for inquiry path.	Word cloud, ideas-building tool, KF
Phase IV: portfolio assessment	Students engaged with portfolio assessment with customized scaffolds.	KF

Data Analysis and Results

RQ1. Did students improve their understanding of Photosynthesis?

Students were tested before and after the intervention. We asked the same open-ended question in the pre- and post-tests ("Write down as much as you know about photosynthesis") to ensure consistency. Students' answers were coded based on a scheme adapted from the literature examining middle school students' systems thinking (e.g. Hmelo-Silver et al., 2007; Tao & Zhang, 2021). Three levels were identified to characterise students' trajectory of understanding: 1) describing the components involved in the process of photosynthesis, 2) explaining the processes but not mentioning the mechanisms of photosynthesis, and 3) offering explanations that integrated processes and mechanisms. The results of a paired T-test suggested students improved their understanding of photosynthesis following the session ($t = 5.144$, $p < .001$).

RQ2. How did students participate in knowledge building activities that support their ideas improvement?

Students wrote 252 notes over six weeks amongst them including 32 reflection notes. Students' knowledge building notes were parsed into different inquiry threads (Zhang et al., 2007) and the following themes emerged: 1) surface features of phytoplankton; 2) impact of phytoplankton on the sea; 3) ATP and NADPH; 4) Calvin cycle; 5) mechanism of chloroplast; 6) the dynamics of phytoplankton, photosynthesis, and environment; 7) optimum environment for phytoplankton; 8) light; 9) RuBisCo; 10) temperature and phytoplankton; and 11) CO2. We adopted a coding scheme (Resendes 2016) to analyse notes in each inquiry thread and understand how students engaged with knowledge-building activities, such as constructing explanations, incorporating new information, and sustaining the inquiry (Table 2). A primary coder coded all the data, and an independent rater coded 20% of the data; the inter-rater reliability was 89.62%.

The coding results indicated that students engaged in different knowledge-building discourse moves, including questioning, constructing, and meta-discourse (Table 3). Results showed that students actively pursued ideas in certain inquiry questions (e.g. #3 ATP and NADPH, #4 Calvin cycle, #8 light, #9 RuBisCo). Students constructed explanations by asking explanation-seeking questions, continuously asking new questions to sustain the inquiry, improving an existing explanation, and supporting an explanation with new evidence or justifications (Table 3). In addition, in these threads, students engaged in community-oriented discourse. For example, they referred to their peers' ideas, made connections to their understanding, rose above different ideas, and synthesised threads of understandings, suggesting students engaged with high-order thinking activities in these inquiry threads. However, in less extensively discussed inquiry threads, few high-order thinking activities were observed. For example, in inquiry thread #7 (optimum environment for phytoplankton), students asked facts-related questions, but few explanation-seeking questions or questions sustaining the inquiry.

Table 2: Coding scheme of how students constructed explanations

Codes	Sub-codes	Descriptions
Questioning	Fact-seeking	Questions that ask for facts or information
	Explanation-seeking	Questions that ask for explanations or open-ended questions
	Sustained inquiry	Further questions based on prior notes to deepen the discussions
Constructing explanations	Simple claims	Students demonstrated agreement or disagreement or proposing a statement with further elaborations
	Proposing an explanation	Proposing an explanation to a phenomenon for the first time
	Supporting an explanation	Using evidence to support an existing explanation or providing justifications
	Improving an explanation	Improving an existing explanation by elaborations, new evidence or information
	Enriching an explanation	Enriching an explanation by new information
	Challenging	Challenging an existing explanation by showing disagreement or new questions
Meta-discourse	Connection	Referencing to peers notes or quoting parts of their peers' notes as references
	Rise-above	Summarizing what has been discussed, asking new questions, monitoring the inquiry process, paraphrasing an explanation or evaluating their own or others' notes
	Synthesize	Summarizing collective ideas from prior discussions

Table 3: Students' ways of constructing explanations across threads

	Low level discourse			High level discourse							
Thread	Fact	Simple	Propose	Explain	Sustain	Enrich	Support	Improve	Connect	Rise	Synthesize
#1	5	1	11	7	1	9	0	4	0	0	0
#2	0	1	5	5	2	5	3	4	3	2	2
#3	0	0	9	0	4	3	3	12	11	13	13
#4	1	0	6	3	2	4	4	13	10	11	10
#5	0	0	4	5	0	1	1	2	0	0	0
#6	0	0	1	2	0	2	1	3	0	0	0
#7	2	0	4	2	1	0	0	0	0	0	0

#8	0	0	7	4	1	4	6	13	10	15	12
#9	0	0	9	7	0	3	1	4	2	4	2
#10	1	1	4	4	0	5	3	4	0	0	0
#11	0	0	2	0	0	0	0	0	4	5	4
Total	9	3	62	39	11	36	22	59	41	50	44
Mean	0.82	0.27	5.64	3.55	1.00	3.27	2	5.36	3.73	5.5	4

Change over time and trajectory of Knowledge Building discourse moves

To understand if students demonstrated different KB discourse patterns across four stages, we did a set of one-way repeated measures ANOVA with four stages as within-subject factors. As no students asked facts-seeking questions, made simple claims in later phases and no students engaged with community-oriented discourse, such as connection, rise-above and synthesizing in earlier phases, we will only analyse discourse moves with which students engaged across all four phases. The results were shown in table 4. Except "enriching an explanation" all other types of discourse moves differed across different phases. Follow-up post-hoc analyses show different patterns across four phases. In later phases, students' low-level discourse moves decrease. For example, students proposed fewer explanations than earlier phases. However, students demonstrated more high-level discourse moves in later phases. Students asked more explanation seeking questions, supported more explanations with evidence and justifications, and improved the explanation with new data. This pattern of discourse showed students engaged with high-level discourse moves with learning analytics-augmented meta-discourse.

Table 4 Results of repeated measures ANOVA showing difference in phases in terms of students' discourse

Discourse	Phases (P)	M	SD	df	F	*Post-hoc analyses*
Proposing an explanation	P1	1.17	1.23	3	5.054*	P1>P3*
	P2	0.70	0.97			P2>P3*
	P3	0.17	0.38			
	P4	0.65	0.93			
Explanation seeking questions	P1	0.57	0.79	3	3.408*	P4>P3*
	P2	0.78	1.09			
	P3	0.78	0.52			
	P4	0.35	0.65			
Enriching an explanation	P1	0.57	0.99	3	1.303	
	P2	0.43	0.72			
	P3	0.17	0.39			
	P4	0.43	0.59			
Supporting an explanation	P1	0.09	0.29	1.945	3.122*	P2>P1*
	P2	0.39	0.58			P4>P1*
	P3	0.13	0.34			
	P4	0.57	0.99			
Improving an explanation	P1	0.35	0.83	3	6.316*	P2>P1* P2>P3* P3>P4*
	P2	0.87	1.10			
	P3	0	0			
	P4	0.70	0.88			

*p<.05.

RQ3. How did students engage with analytics-supported meta-discourse to improve their collective ideas?

Analysis was conducted to examine how students employed KF analytics for their rise-above meta-discourse and charting collective inquiry in knowledge building. Multiple data sources were used to construct a narrative to illustrate to what extent learning analytics supported students to improve collective ideas and the learning analytics' supportive roles. We report two key areas: 1) analytics-supported reflective inquiry and meta-discourse using the word cloud tool; and 2) students running KF analytics and reflecting on the process to support their collective inquiry.

Areas I: Analytics-supported reflection and meta-discourse using word-cloud tool

Students engaged in analytics-supported reflection on their KF writing using the KF word cloud and the teacher's scaffolding questions. After the first two sessions, in which they freely participated on KF and articulated initial ideas and questions, students reviewed the visualisation of KF writing exported from the word cloud. The teacher introduced the word cloud to the students. Students worked in pairs to identify large research areas with prompting questions (e.g., "What do you notice from this word cloud? Any observations related to our inquiry? Are there any words you find interesting and want to find out more? Are there any small words you think should catch more attention? Which words do you think may go together to form a research area?"). Students reviewed what they had discussed, identifying areas they needed to understand and how such emerging areas facilitated formulating a research area. We identified three types of meta-discourse strategies students used while working on analytics for advancing knowledge: a) Summarising what they had discussed, b) Identifying areas they did not understand, and c) Formulating a research area.

First, Students *summarised* what they had discussed by connecting big words; for example, students mentioned: "Along with 'phytoplankton', 'photosynthesis' is the second largest, suggesting that the idea of the functions of the phytoplankton are more commonly discussed. Hence, the main purpose of the phytoplankton mainly revolves around photosynthesis." In this example, **students compared words sizes visualized on word-cloud. They identified the largest word as phytoplankton and the second largest as photosynthesis, which allowed them to consider how these two "big" words were connected in KF discourse**. In addition, students also made connections among multiple words and explored the dynamics among them. For example, students mentioned that: "The bigger words like phytoplankton, optimum, photosynthesis are related to increasing rate of photosynthesis to increase the amount of energy released (energy is a small word)." In this example, students identified different word sizes (i.e., phytoplankton. photosynthesis are big words, whereas optimum and energy are small), connected them, and constructed a preliminary understanding of the dynamics between photosynthesis and energy. Second, Students identified areas that *they did not understand* by deliberating connections of small words, conjecturing how the connections might inform future discussions. For example, one student mentioned that "'Genetic' and 'Algae blooms' are some interesting topics that are not commonly talked about. *We would like to find out more about these words as we are still unsure of the relations.*" In this example, **the student located multiple small words from the word cloud and linked the pattern shown with their KF discussions; thus, new questions kept emerging.** Third, students *formulated a research area* by connecting different types of words (big and small). For example, one student wrote ""Sunlight," "rate," "growth," "carbon dioxide," and "temperature" can go together for examining the research of rate of photosynthesis as lights and temperature are needed for photosynthesis." In this example, the student connected words of varying size from across the word cloud visualization, rose above the divergence of these words, and formulated a research area.

Area II: Students running KF analytics and reflecting on the process for supporting their collective inquiry

While the first area involves the teacher running the word-cloud tool and using the visualization to prompt students' inquiry, this area involves students using the analytics tools themselves and reflecting on this process and writing their reflection on KF. Students ran the tool themselves, reviewed the processes and wrote on KF which was facilitated by a set of prompting questions designed as scaffolds on KF. These questions include: (1) click on the assessment icons and choose word cloud or activity network. (2) run the tool and identify three key words and discuss why these ideas are important and (3) how these diagrams help you with your ongoing Knowledge Forum inquiry. Specifically, Students engaged with three types of meta-discourse moves: a) leveraging ideas to a conceptual plane, b) expanding ideas by connecting peers' discussions, and c) identifying future inquiry topics.

First, students leveraged ideas to a high conceptual plane by selecting words from word cloud, connecting the words to make rise-above conceptual statements, and linking them to even higher-level concepts. For example, one student noted that: "3 words that interest us are Calvin cycle, carbon and glucose. We learnt more about how the light dependant and independent stages of photosynthesis affect each other and understood more about how the Calvin cycle works, the stages of the Calvin cycle and its relationship to the light dependant stage of photosynthesis, as well as how carbon dioxide is the raw material required in photosynthesis to make glucose." **In this example, students selected three words related to the Calvin cycle and how carbon could be transformed to glucose. Students not only articulated how these words could be connected to formulate a conceptual statement, they also connected their discussions on KF and classroom discourse, identified how these connections could be linked to a broader conceptual understanding of photosynthesis, namely, light independent and dependent processes.** These KF reflection suggest how students used word cloud analytics to support their rise above ideas for advancing their understanding of photosynthesis.

Second, students expanded ideas by connecting their own words with their peers. For example, one student wrote on KF, "by locating our three words, the diagram on the word class has made us realise how small the words are for such a large impact on the ecosystem." Another student also mentioned, "it helps us notice what ideas we should build on. By mapping our words with our peers, we missed out too many keywords that our classmates have filled up but gone unnoticed, this led us to being able to build on key topics easier." In these two examples, **both students noted that through comparing their own ideas with their peers and negotiating which ideas they want to incorporate into their discussion, students connect ideas with their peers.** This process enacts students' epistemic agency to improve collective and individual understanding.

Third, students identified future inquiry topics by analysing various sizes of different words. Students noted that there were some words (concepts) that were less thoroughly discussed. They also realised that these words might need more attention from the community. For example, one student noted that "it allows us to expand on our ideas easily. The words which are used frequently is already being talked about a lot so there is a lot of information about it. However, the words repeated less frequently, are the words which we can prioritise and research and build on more about so that we can find out a lot more about them." Then this group decided to focus on respiration in their future discussion as "few people mentioned it." **From this example, new ideas began to emerge, and students began to identify less commonly used words and discuss which words deserved more attention from the community.**

After using the KF6 analytics word-cloud tool to reflect on their Knowledge Forum work and writing KF reflection notes, students continued their KF collective inquiry, pursuing newly identified problems and research areas that needed further investigation. The meta-discourse that helped them identify what they had accomplished and connect diverse ideas to higher-conceptual planes also helped them identify new areas for more focused collective inquiry. Students wrote, in their post-tests, how the analytics-supported approach support their understanding. One student reflected that: "It is satisfying sometimes when my classmates and I find new information and can link it with each other's answers to form one big big big big idea/answer." This student also considered how the "word cloud helped them connect ideas from different people" so they could better rise above diverse ideas and formulate new research ideas for community inquiry. Students regarded the word cloud as an important tool because it helped the community narrow down cognitive gaps. The student mentioned, "It allows me to get a sense of whether I am going in the right direction. Because I can see which keywords are being neglected, I can continue to build on them and work towards the gap in our concepts and theories."

Discussion

This study examined how students engaged in collective inquiry of photosynthesis, supported by Knowledge Forum and its embedded analytics tools for knowledge advance. Students pre- and post-test domain responses demonstrated they understood more about the mechanisms and processes and could connect concepts across different levels. The notion of idea development in knowledge building embraces more than conceptual growth and domain understanding. Idea authentic scientific inquiry involves new ideas and questions emerging continually from students' knowledge-building inquiry processes. The trajectory of how ideas develop is not pre-determined, but emerging. In this study, students showed how to engage in deepening inquiry by using more sophisticated discourse moves. The quantitative analysis demonstrated students' uses of less sophisticated discourse moves decreased as the intervention progressed, but sophisticated ones increased. As students inquired, they began to use more evidence to support their peers' explanations and integrated more information to their ongoing discussions. Students asked more explanation-seeking questions in later phases which suggests they were deepening their inquiry with more questions emerging after they engaged with manipulating word cloud by themselves. This result is triangulated by inquiry thread analysis, which demonstrated new ideas continually emerged as students engaged in analytics- augmented knowledge-building discourse. These results suggest students continuously engaged with knowledge building discourse which featured by continuous ideas improvements.

In this study, the idea emergence process was supported by analytics-augmented meta-discourse. In the earlier design phase, students were shown visualisations exported from the word cloud. By connecting words of different sizes and deliberating on their relationships, students summarised what they had discussed, identified what they did not understand, and formulated a research area. The technological affordances of the word cloud facilitated community-level meta-cognitive conversation by demonstrating ideas in an explicit and comprehensible way. This allowed students to identify conceptual gaps and improve collective ideas. The dynamics of different sized words allowed students to synthesise thoroughly what had been discussed and identify which important ideas had been neglected, creating opportunities for the community to negotiate why certain ideas were important. This allowed new ideas and questions to keep emerging. In later design phases, students ran trials using learning analytics, analysed results, and wrote KF reflections. They compared words contributed by their and others' notes, referred to KF notes, and considered how to connect their ideas with others'. Throughout this process, they charted the inquiry journey themselves, enacting their collective epistemic agency to improve ideas. Furthermore, the students' word cloud creating process encouraged them to trace ideas back to KF and link the word cloud with their KF notes. The word cloud and reflection thus acted as a "bridging artifact," allowing students to investigate how diverse ideas from KF had been synthesised and rise above to a high conceptual plane in the word cloud.

This study examines an iterative process of ideas improvement in knowledge building and how this process could be supported by learning analytics and meta-discourse strategies. This study also explores the possibility of granting students' more epistemic agency by allowing them to manipulate learning analytics tools, supported with scaffolds and reflections on KF. This study emphasizing student agency and collective inquiry may enrich existing CSCL studies- many focusing on researchers/ teachers using or demonstrating visualisations, such as dashboards, to monitor students' progress. Through using the analytics tools reflectively and collectively, students may develop their understandings of how diverse ideas can be integrated for rise above, thus moving to a high conceptual level for community advance. The study has implications for knowledge-building analytics research for further improving the designs via using collective reflective assessment in advancing knowledge building. In future studies, we will further investigate the effectiveness and mechanisms of other learning analytical tools, such as author network to support students' collective ideas improvement.

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