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Argumentation-Based Collaborative Inquiry in Science Through Representational Work: Impact on Primary Students' Representational Fluency

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Abstract This study explored the impact of argumentation-promoting collaborative inquiry and representational work in science on primary students' representational fluency. Two hundred sixty-six year 6 students received instruction on natural disasters with a focus on collaborative inquiry. Students in the Comparison condition received only this instruction. Students in the Explanation condition were also instructed with a focus on explanations using representations. Students in the Argumentation condition received similar instruction to the Comparison and Explanation conditions but were also instructed with a focus on argumentation using representations. Conceptual understanding and representational competencies (interpreting, explaining and constructing representations) were measured prior to and immediately following the instruction. A small group collaborative representational task was video recorded at the end of the instruction and coded for modes of knowledge-building discourse; knowledge-sharing and knowledge-construction. Higher measures of conceptual understanding, representational competencies and knowledge-construction discourse were taken together as representational fluency. Students in all conditions showed significant improvement in conceptual understanding, interpreting representations and explaining representations. Students in the Comparison and Argumentation conditions also showed significantly improved scores in constructing representations. When compared to the other conditions, the Explanation group had the highest scores in conceptual understanding and also interpreting and explaining representations. While the Argumentation group had the highest scores for constructing representations, their scores for conceptual understanding as well as interpreting and explaining representations were also high. There was no difference between the groups in knowledge-sharing discourse; however, the Argumentation group displayed the highest incidence of knowledge-construction discourse. The paper discusses how a collaborative inquiry instructional focus on explanation-building using representations fosters representational competencies, while a collaborative inquiry instructional focus on argumentation and explanation using representations promotes representational fluency.

Keywords Argumentation · Earth sciences · Representational agency · Representational fluency

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Introduction

This study explored the proposition that argumentation-promoting collaborative inquiry and representational work in science supports the development of primary students' representational fluency. Learning in science is multi-representational (Lemke 2004) and should lead to the development of representational competencies (DiSessa 2004) where learners are able to effectively interpret, explain and create or construct representations. Multiple representations can be defined as 'the capacity of science discourse to represent the same concepts and processes in different modes, including verbal, graphical, numerical, material and gestural forms' (Waldrip and Prain 2013, p. 15). Learners often tend to learn science with and about multiple representations at the same time, yet they often do not possess domain or representational knowledge (Ainsworth 2011). Therefore, learners need to be supported with appropriate strategies and resources to make meaning from multiple representations and achieve a deep understanding of science. The research presented here builds on the assumption that the key to achieving a deep understanding in science is through engaging in collaborative social interactions with multiple representations (Tytler et al. 2007; Nichols et al. 2013a, b) and developing representational fluency.

As the ideas, conventions, reasoning and practices of science are integrally related to representations, and learning science is a process of evaluation and transformation of different modes, deeper learning of science in the classroom can be achieved by focussing on developing students' representational agency. To have representational agency is to be able to refer, predicate and infer what is being represented and how to represent what is being represented. This skill encompasses representational competencies, involves knowledge of the social, semiotic (meaning-making) and material affordances of representations and the flexibility to reason or explain what is being conveyed by a representation and how it is being conveyed (Kockelman 2007). Construction of scientific knowledge and scientific language practices requires this agency or flexibility to work with representations and is a necessary part of having fluency with representations. Representational fluency in science is the ability to interact with knowledge and translate or transform knowledge from one representation to another at a procedural and conceptual level. It involves using or manipulating representations or generalising information from and across multiple representations to explain, problem solve or reason about scientific phenomena (Nichols et al. 2013). This skill involves both sophisticated scientific language and representational agency to demonstrate sound conceptual understanding in science.

Argumentation and Representations

In the science community, there is a particular importance of visual representations to scientific argument. Representations provide the persuasive tools for scientists to communicate with one another. As Richards (2003) describes, 'scientific arguments routinely use visual representations as appeals to authority' (p. 186). Representations make it possible for scientists to interact with and provide explanations of complex phenomena in a clear way. In short, representations of science are critical to scientists as they use them 'to show one another, argue about and circulate to others in their communities' (p. 185). Indeed, the role of representations in the expression of arguments has been critical in the development of science knowledge and theories (Mathai and Ramadas 2009).

Collins (2011) makes a case that in the classroom 'representations provide a substrate for scientific discourse and argumentation' (p. 111). In support of this claim, Hand and Choi (2010) have found close associations between students' use of representations and building a cohesive argument. Their study revealed that college level chemistry students capable of embedding multiple representations in a text explaining evidence from a chemistry investigation scored higher in the overall quality of their arguments. The researchers found an apparent association between the explanatory skills to construct a reasonable argument and the skill to embed multiple representations in the text.

As a process, argumentation deals with 'the coordination of evidence and theory to support or refute an explanatory conclusion, model, or prediction' (Osborne et al. 2004, p. 994). Science needs to be taught not only as a process of discovery, but students also need to understand argumentative discourse as it is used by the discipline to construct knowledge (Clark and Sampson 2007). Argumentative discourse is a critical part of the social practices in scientific inquiry that involves refuting, defending and persuading about knowledge claims (Duschl and Osborne 2002). Clark and Sampson (2007) maintain that teaching science through an inquiry approach but neglecting to include opportunities for social interactions where students can engage in argumentation and explanation does not represent the authentic nature of science or promote a deep understanding of science. We would argue that the true nature of the discipline cannot be reflected in the classroom unless science is taught through an inquiry approach with collaborative social interactions facilitated by representational tasks that promote argumentation and explanation.

The proposition here is that to learn science effectively, students need to understand different representations of science concepts as well as understand their coordinated use in explanation- and argumentation-building (Hubber et al. 2010). Students not only need to understand the format and properties of particular representations, but they also need to be able to explain science concepts and engage in reasoning or persuasive discourse using representations as well as generalising meaning across different representations. In other words, students need to acquire fluency with multiple representations (Ainsworth 2006; Rau et al. 2013).

The first author of this paper (Nichols et al. 2013a, b) has shown that the cognitive processes used in knowledge-construction as well as to support communication of knowledge through explanation or elaboration, while interacting with multiple representations, can, taken together, provide a measure of representational fluency. More specifically, these previous studies were able to show that demonstrations of students' representational competencies, higher level conceptual understanding and knowledge-construction discourse while working with representations on a task provided a valid measure of their representational fluency. Therefore, this study employs measures of students' high level of knowledge-construction discourse, representational competencies to explain natural disasters phenomena and conceptual understanding together as an indicator of representational fluency.

Argumentation and Explanation in Science

Argumentation and explanation in science work synergistically together, but they are distinct in their goals and linguistic structures. The goal of argumentation is to convince or persuade and to provide justifications for a claim to scientific knowledge, while the goal of explanation is to make unknown phenomena in science known or understandable (Osborne and Patterson 2011). Osborne and Patterson suggest that research studies not only need to make this distinction between argumentation and explanation clear but that instruction in science needs to make these goals and characteristics comprehensible to students. They believe that an instructional focus on argumentation would not be effective if it is 'masked in the cloak of explanation'

(p. 637) and, in order to better develop conceptual understanding in science, the purpose and function of argument need to be distinguished from explanation. But in order to make the distinctions clear to students, teachers need to be prepared with this in mind.

Purpose of the Study

This study sought to explore the relationship between argumentation-driven science inquiry and representational fluency in the primary classroom. A comparison group received training on the implementation of an inquiry unit on natural disasters replete with visual representations and representational tasks. One of the experimental groups, the explanation group, also received training in ways to foster explanatory skills in students using pre-constructed and constructed representations. An additional experimental group received not only the same training as the comparison and explanation groups but also participated in professional learning about fostering student argumentation skills using representations. Given the proposition put forward by Osborne and Patterson (2011) that research studies not only need to make the distinction between argumentation and explanation clear but that instruction in science needs to make these goals and characteristics comprehensible to students, in the argumentation condition, explicit training around the distinction between explanation and argumentation was provided to the teachers.

Methodology

Participants and Design

Participants included 18 grade 6 teachers and 266 students (male=131, female=135, mean age=11.4 years, SD=5.0 months) from eight similar sociodemographic metropolitan schools in Brisbane, Australia. Teachers comprised 6 males and 12 females with teaching experience ranging from 2 to 18 years. Schools (two to three) with small groups of teachers (four to six) were randomly assigned to three conditions (Comparison, Explanation, Argumentation) and tended to consist of a balance of beginning and more experienced teachers. Both private (Independent) and government (State) schools were included in each condition. Table 1 provides an overview of the participant schools and teachers in each condition.

Materials and Procedures

Teachers in the three conditions received a total of 2 days of professional learning. Teachers in all conditions actively participated in the inquiry-based science unit on the topic of natural

Table 1 Description of participant schools and teachers in each condition

Group	Number of participant schools	Number of participant teachers/school	Number of Independent schools	Number of State schools
Comparison	2	3	1	1
Explanation	3	2	2	1
Argumentation	3	2	2	1

disasters as described in the Australian Science Curriculum (Australian Curriculum, Assessment and Reporting Authority 2014) that they had agreed to teach the procedures that they needed to follow to embed cooperative learning strategies into the unit. In addition, teachers in the Explanation group were also trained in representational reasoning and using representations to foster student explanations of science concepts through extended cooperative learning tasks. In addition to the training received by the Explanation group, the Argumentation group also received training in fostering argumentation skills where the distinction between explanation and argumentation was made clear.

The unit of work designed for this study adheres to the thinking that in order to facilitate robust scientific discourse, curriculum needs to be designed with a focus on multiple representations of the same concept, and learning needs to be set in or linked with the real-world domain. The unit of work on natural disasters had a focus on plate tectonics and associated geological events such as earthquakes, tsunamis and liquefaction. The real-world context was created by including information on the 2010 New Zealand and 2011 Japan earthquakes which at the time of implementation of the unit were very recent phenomena. Use of a real-world context makes science units more contemporary and relevant to students and helps them to link science to everyday phenomena around them.

The unit was designed by the researchers of this study using the 5E's instructional model for inquiry curriculum design (Bybee 2006). The type of inquiry approach may also be considered as a guided level 2 inquiry (Blanchard et al. 2010) where students are scaffolded to generate questions that guide the inquiry. The students' questions are then explored through theoretical and experimental approaches with whole class and small group social interactions. Table 2 describes the series of activities and content included in the unit for all three groups. Researchers chose various types of representations (visual/graphical diagrams and pictures, physical models, verbal/written explanations, online interactives) for each topic in the unit and the pedagogical strategies and tasks around the representations or representational tasks. Small group cooperative tasks and graphic organisers (e.g. glossary, word wall) were employed to support student knowledge building and the use of representations to explain the concepts.

The researchers modelled for teachers in the Explanation and Argumentation groups how to choose or create the best representation for the knowledge or idea being presented and how to sequence multiple (different) representations of the same idea. The teachers were trained to reflect on how particular concepts (plate tectonics, earthquake seismic waves, earth structure) are most aptly represented for the particular student cohort and resources available to them. They were engaged in discussion with the researchers regarding different representations of these concepts and asked how best to temporally and pedagogically sequence the different representations. They were also engaged in critical analysis and dialogue regarding the best combinations of modes (i.e. text, visual, gesture, spoken language) and media, tools or resources (i.e. computer-assisted animations, simulations, DVDs) that work best to get information about the concepts across. The training sought to demonstrate how to give students explicit instruction about the forms and functions of various components within and across different representations and how to encourage students to engage with them during representational tasks designed to foster knowledge building.

Teachers in the Explanation and Argumentation groups received training in using representations to support student explanation of key concepts including movement of plates at the boundaries and underlying processes that lead to liquefaction, tsunami and volcanoes. Cooperative learning strategies, graphic representations (i.e. TWLH charts [what we think we know; what we want to learn; what we learned; how we

Table 2 Inquiry unit activities, representational resources, pedagogical strategies and tasks

Phase	Activity	Modalities/resources	Cooperative learning strategies
Engage	The boulder house mystery	Visual pictures Verbal explanation	Students use picture to propose what caused the hole in the house.
Engage	Factual recounts and picture gallery	Written explanations Visual pictures Visual/graphical diagram	Spot the science: students write down scientific terms and draw images, e.g. sand volcanoes, tsunami, liquefaction, magnitude.
Engage	Construct an earthquake-proof building	Physical model Verbal explanation Written explanation Verbal argumentation	Small cooperative group learning task where students are given materials and asked to construct an earthquake-proof building. Students explain their choice of construction.
Explore	Earth's structure and composition	Written explanations Visual online interactive Physical model	Student pairs on computer explore learning object. • Explain using text and drawings. • Construct a model of the earth and justify choice of materials.
Explain	Volcano	Physical model Verbal explanation Verbal argumentation	Students construct a model of a volcano and justify choice of materials.
Explore + explain	Tectonic boundaries Divergent	Visual online interactive Written explanation	Student pairs on computer explore learning object. • Explain using data on interactive as well as text and drawings on worksheet.
Elaborate	Divergent boundaries	Visual pictures Physical model	Students construct a model of a divergent boundary. • Explain what happens. • Justify choice of materials.
Explore + explain	Tectonic boundaries convergent	Visual online interactive Written explanation	Student pairs on computer explore learning object. • Explain using data on interactive as well as text and drawings on worksheet.
Elaborate	Convergent boundaries	Visual pictures Physical model Verbal explanation Verbal argumentation	Students construct a model of a convergent boundary. • Explain what happens. • Justify choice of materials. • Different pairs/small groups do different type of convergent boundary—share with whole class.
Elaborate	Earthquakes at convergent boundaries	Visual pictures Written explanation	Using their model, students discuss how an earthquake forms at that boundary type.

Table 2 (continued)

Phase	Activity	Modalities/resources	Cooperative learning strategies
Explore + explain	Tectonic boundaries Transform	Visual online interactive Physical model Verbal explanation	Student pairs on computer explore learning object. • Explain using data on interactive as well as text and drawings on worksheet.
Elaborate	Transform boundaries	Visual pictures Physical model Verbal explanation Written definitions Verbal argumentation	Students construct a model of transform boundary. • Explain what happens. • Justify choice of materials. • Different pairs/small groups do different type of transform boundary.
Elaborate	Convection cells and tectonic theory	Visual picture Verbal explanation	Using diagram, students work in pairs to discuss how plates move due to convection cells in the mantle.
Explore + explain	Where do earthquakes happen?	Visual picture Written explanation Verbal explanation	Student pairs on computers—one navigates USGS site while other reads the worksheet questions and instructions.
Explore + explain	How are earthquakes measured?	Visual interactive Written explanation Verbal explanation	Student pairs on computers. • Answer questions drawing from data sourced from various web sites.
Elaborate	Earthquake events in Australia to surrounding countries	Written explanations Visual pictures Visual/graphical diagram Verbal explanation	Student pairs read table and create graph. • Think-pair-share about what the graph data is telling us about incidence of earthquakes in Australia vs surrounding countries
Elaborate	So you want to be a seismologist activity	Written explanations Visual pictures Visual/graphical diagram Verbal explanation Verbal argumentation	Small groups of students elaborate on the relationship between the ground (table) shaking and the 'nature' of the seismic waves. Students analyse data from their traces using measurement of seismic wave.
Explore + explain	Geological events associated with earthquakes: liquefaction	Experiment Written explanation Visual moving picture Visual pictures	Pairs or small group experiment, predict, reason, observe and explain. Small group and whole class discussion about how liquefaction occurs.
Explore + explain	Geological events associated with earthquakes: tsunami	Visual moving pictures Verbal explanation Written explanation	Animations/video. Small group and whole class discussion about how tsunami happens.

know]) and kinaesthetic representations (i.e. plasticine models, dioramas, constructions) were discussed with teachers to help promote student explanatory skills (see Table 2). The type of explanations that the training aimed for teachers to develop in their students was what Braaten and Windschitl (2011) refer to as 'causal explanations' of biological phenomena. They found that provision of knowledge about causal scientific explanations to science teachers and encouraging them to grapple with these explanations during training supported teachers to recognise those science ideas that are worthy of a deeper level of inquiry for their students.

Teachers in the Argumentation group also received training in building student argumentation skills. The workshop focussed on unit content and emphasis of scientific argumentation through the use of evidence to justify a position (Simon et al. 2006). We applied a claim/evidence/reasoning framework as a model to support explanation. In other words, we focussed on the structure of a scientific argument where claims are defended with evidence to support students' explanations (Berland and Reiser 2009). Teachers were taught how to elicit the features of a good argument including reasons, facts and evidence to support claims and explanation construction. A statement of knowledge or claim is made and supported by multiple sources of evidence that can include facts and reasons; the evidence is used to substantiate the claim and persuasive language supports substantiation. Finally, a full explanation is provided that includes these argument-based domains. The training of the teachers to support argumentation in the classroom was underpinned by the view that teachers need to be trained to 'assimilate new goals that will foreground and support the discourse of argumentation in their teaching' (Simon et al. 2006, p. 238).

Evidence was collected on students' discourse patterns, students' representational competencies and conceptual understanding. The overall goal was to explore the effects of training teachers to use scientific argumentation-based inquiry through collaborative representational tasks on the development of students' knowledge construction, representational competencies and learning taken together to be representational fluency.

To assess students' conceptual understanding and representational competencies including interpreting, explaining and creating representations, they were asked to complete a test prior to the start of and at the completion of the unit on natural disasters. The test is provided in the Appendix and was utilised by the teachers as assessment for the unit. The test was developed and validated in a previous study (Gillies et al. 2014). Each question on the test was provided a score based on the level of complexity of the answer required. For conceptual understanding, the test score divided by the total possible score (42) for the entire test was used for comparison between the three conditions.

Within the same test, different items examined unique representational competencies. These included interpreting representations (items 3–7) where students were asked to simply label diagrams or match words to pictures; explaining representations (items 4–7) where students were required to explain the science knowledge that a given representation was conveying; and creating representations (items 1, 2 and 5) where students were asked to construct a representation to explain concepts associated with the unit. Each of these representational competency variables was scored using a combination of specific test items. The test score for each representational competency (interpreting [16], explaining [18] and creating representations [16]) divided by the total possible score across all items for that competency was used for comparison between the three conditions.

Student small cooperative group discussions were video recorded as they worked through a small group collaborative representational task to analyse a seismogram they created.

The Representational Task

Your job is to make sense of the seismogram which charts an earthquake that happened in Explodia recently. You will need to talk to your colleagues about what the trace means and, between you, decide on two ways of representing what happened.

Later you and your colleagues will explain what happened to some visitors who do not understand how to read the results, the sequence of jagged lines that appear on your seismogram. First of all though to do this effectively, you will need to consider some important, relevant questions. These will help you as a team to think about your results and show you understand what the trace means.

- What is the relationship between the simulated ground (table) shaking and the nature of the seismic waves on your trace? Remember you simulated weak and strong ground shaking when you shook the table.
- Look carefully at your trace; can you divide it into sections to show the progress of the earthquake? Are there sections of the trace that look similar? How so?
- How could you represent (e.g. draw, label, describe, measure) any differences in the waves in each section?
- Use these different representations as evidence to support your argument about how the nature of seismic waves relate to different strengths of ground shaking.

Hint: You can use the Modified Mercalli Scale to help you think about this.

Analysis of the discourse as they carried out the activity was done using a validated framework developed by Van Aalst (2009) for coding modes of knowledge-building discourse. The framework is based on Bereiter and Scardmalia's (1993) knowledge creation model which assumes that knowledge is the product of a constructive process. According to van Aalst, creation of knowledge requires talk, writing and representational analyses to set goals, investigate problems, foster new ideas and evaluate the extent of advancing knowledge in the learning community. In the current study, two of the modes of knowledge-building discourse that were coded, knowledge-sharing and knowledge-construction, were each derived from different theoretical premises.

Knowledge-sharing as a social practice refers to the transmission of knowledge between individuals and is derived from the transmission theory of communication in learning environments (see Pea 1994). It does not require considerable effort and usually results in prompt learning through the instant exchange of information. However, knowledge-sharing is an accomplishment when it occurs in collaborative interactions because information is not normally or readily exchanged between individuals. The information shared is not constructed or modified by the collaborative interactions, and the sharing tends not to be reflective. Knowledge-sharing discourse includes recalling and sharing existing knowledge, identifying key elements of a given activity and introductory level discussions that do not extend into explanations, evaluations or interpretation. Table 3 provides some examples of knowledge-sharing discourse within each condition in the context of the small group collaborative interactions.

Knowledge-construction in a social context is a process by which students solve problems and construct their understanding around a learning situation. It requires effort and reflection and is situated as it is mediated by social interaction and by representations (Van Aalst 2009). Knowledge-construction features 'qualitative changes

Table 3 Examples of coded knowledge-sharing discourse categories

Discourse type	Treatment group	Example
Recalling existing knowledge	Argumentation	S3: What's this thing called? S2: P waves. S1: Yeah, P waves. Yeah, it's P waves and then over here is the secondary waves because this… S3: I meant this paper… S1: Seismometer. Yeah, it's actually made up of seismograms like a measurer. It's like a Richter scale—it measures from 1 to 10 how strong it is.
	Explanation	S3: Let's look at the modified Mercalli scale. S1: I like the Richter scale better. S3: OK, what damage might have occurred where the low waves are recorded… where the high waves are recorded (reading a worksheet). What? It says look at the Modified Mercalli Scale. S2: So it might have minor damage.
	Comparison	S2: S waves move side to side. P waves can go through oceans and continents. S3: It can go through anything. S2: Only S waves can go through continents. It can't go through water.
Introductions or identifying the worksheet or task	Argumentation	S1: So what do we reckon the small one is equal to? S2: Do we? So we don't have any machine that tells us, do we? We just have to guess. S3: We just have to guess. The small one looks like normal activity to me. S4: Ah, I think it would be like a bit normal than normal. I think it would be like one that we can't feel.
	Explanation	S2: Do we get started two discussion points? Would it be that? No first we got to come up with some important questions. First write your answers and the thoughts on the sheet below? S3: We write important questions. S2: We write important questions and discuss them. S3: Three, three important questions. Check.
	Comparison	S2: Should we write what we did? Like writing or diagram or something at the top, so they would know… Okay. Do you want to draw the house? S1: Yeah, draw. S2: Here, try this. Okay, you draw the first - no, you draw the first house, like what's happened. S3: A big, big house? S2: A big house.

in the complexity of students' thinking about and conceptualization of context-specific subject matter' (Moore 2002, p. 27) and so is considered to be associated with deep understanding. In these more substantive cognitively based social interactions, students communicate higher levels of understanding rather than merely reorganising knowledge. Knowledge-construction entails building on students' prior ideas, concepts and explanations. It involves metacognition and produces deeper knowledge in complex domains of cognition than knowledge-sharing. Knowledge-construction involves a range of cognitive processes, including the use of explanation-seeking questions and problems, evaluating and interpreting new information, conjectures and explanations

Table 4 Examples of coded knowledge-construction discourse categories

Discourse type	Treatment group	Example
Explanation seeking questions	Argumentation	S1: We can see what? S2: You haven't seen buildings collapse yet but you can see… S3: You can see little rough… S2: Yeah, you can see things like—moving like—pretend like this is a rock and it will move like this. The vibration of—the noises making—they move any objects.
	Explanation	S2: Why are there sections with similar heights? S4: It only releases some of its pressure and there's more pressure to be released. S3: When pressure… S4: It releases the same amount of pressure within an hour and then it has less pressure to be released and when it is out of pressure it stops.
	Comparison	S2: How do you know it's gone for two minutes though? S1: So that's each 10 s. S2: Are you sure? S1: So 10, 20, 30, 40 and then it's gone to 120 here. S2: That's true.
Interpreting and evaluating new information	Argumentation	S1: Why is it …? S2: There's the P wave at the start. S3: This is the … this is the secondary wave. S2: The P and the… S1: This is not a S wave. This is the P wave. S2: This is the P wave. S3: This is the P wave and then we have a S wave.
	Explanation	S3: The earthquake gets bigger and smaller? S2: The big ones might be the S waves and small might be the P waves. P waves are primary waves, the main earthquake and S waves are aftershocks. S1: If you look at this it goes smaller and bigger then smaller and bigger.
	Comparison	S1: So do you want to read that out? S2: Yes. The harder we shook the bigger the trace became. The more gentle we shook the smaller the trace became. S1: That's good. Now, can we put anything else that would match that? S3: Read it out again.
Sharing, critiquing, testing ideas at different levels	Argumentation	S1: Which one are you up to—feel? S2: Here where the things are shaking. S1: Yeah, you can hear objects are being moved. S2: Like? S1: Like this thing being dropped. We can hear objects being dropped or… S3: Like this? S1: Yeah, like that. Like this. S3: A person falling from a building
	Explanation	S1: I don't think it would be instrumental. It would be about feeble or slight. I think it would be feeble. S3: Or slight. S1: The middle should be about there. S2: I think the middle should be rather strong or moderate. It's not very strong, it's not very destructive.
	Comparison	S1: where do you think the line should go? Do you think the line should go here? Or where do you want the line to go? S2: There because that one is way bigger than this one here. S1: Do you two want the line to go here or here?

Table 4 (continued)

Discourse type	Treatment group	Example
		S3: I don't care. S1: No, put your hand up if you want it to go here, just say one, random. Okay put your hand up if you want it to go here.
Summarization, synthesis, creation of new concepts	Argumentation	S1: Isn't that number four? S2: One, two, three, four. They're more intense. S1: Really strong, more intense. S3: Just more intense, just they're more intense.
	Explanation	S1: Let's see how long this one is (measures the height of the wave). S2: So, how much is that? S1: That's about 15 basically. Say 15 and above that is very destructive. S2: 16 and 18 are destructive OK? S1: What? Let's say 15 cm and above are very destructive. S2: It is rare.
	Comparison	S2: so if that's gone for a minute and then another 60 s is 120, so that's over two minutes. S1: It's gone for minutes. S2: Oh, yeah, so you can see it starts off really small and then it gets a bit bigger and then it goes small again and then it goes, like, huge. Then it dies down again.

that refer to concepts or causal mechanisms, summarisation, synthesis and creation of new ideas. Table 4 shows coding of the small group activity across the three conditions for knowledge-construction discourse, with some examples.

Data Analysis

Within-Group Analysis In order to test whether the students in the Explanation and Argumentation groups improved more across the unit (from pre-test to post-test) than the Comparison group on conceptual understanding and representational competencies, a one-way within-group Multivariate Analysis of Variance (MANOVA) was performed. Conceptual understanding, interpreting representations, explaining representations and constructing/creating representations were used as dependent variables. Preliminary assumption testing was conducted to check for normality, linearity, univariate and multivariate outliers, homogeneity of variance–covariance matrices and multicolinearity, with no serious violations noted. Post hoc analyses were carried out separately using a Bonferroni test. To avoid a type 1 error, a Bonferonni adjustment to the alpha level that was used to judge statistical significance was carried out. The alpha level 0.05 was divided by the number of comparisons (4; for each dependent variable) to arrive at a new alpha level of 0.0125.

Between-Groups Analysis In order to explore whether or not there existed a significant difference in the post-test scores for conceptual understanding and representational competencies for students in the three conditions while controlling for their pre-test scores, a one-way between-groups Analysis of Covariance (ANCOVA) was conducted. The independent variable was the type of intervention (Argumentation, Explanation or Comparison), and the dependent variables consisted of the scores on the post-test.

Participants' scores on the pre-tests were used as the covariate in these analyses. Post hoc analyses for pairwise comparisons of the dependent variables between conditions were carried out separately using a Bonferroni test.

Students' knowledge-building modes of discourse were coded according to frequency across each of at least two recorded student group sessions within each classroom and represent 100 % of students' group discussion during each session. Two coders, one blind to the purposes of the study, coded a common 4h of audio recordings, and inter-rater reliability ranged from 87 to 95 % for the two categories coded. A total of approximately 21h of students' knowledge-building discourse (i.e. 41 groups for 30 min each) was collected. The frequency of knowledge-building modes of discourse (i.e. knowledge-sharing and knowledge construction) was compared between the three conditions using a Kruskal-Wallis test. A post hoc analysis was carried out to compare individual differences between groups using a Mann–Whitney *U* test.

Findings

Within-Group Comparisons: Argumentation, Explanation and Comparison Groups

A one-way within-group MANOVA was conducted to assess the impact of the different instructional strategies on students' test scores before and after the unit. There was a statistically significant difference within the Argumentation group between the pre-test and post-test scores on the combined dependent variables ($F(4, 169)=25.745$, $p<0.001$; Wilk's lambda=0.621; partial eta squared=0. 379). Table 5 shows the post-test scores for *conceptual understanding*, *interpreting representations*,

Table 5 Mean and standard deviation (in parentheses) of student pre- and post-test scores for conceptual understanding, interpreting representations, explaining representations and creating representations

Treatment Group	Variable	Pre-test	Post-test	$F(1, 172)$	p	Effect size (partial eta squared)
(N=87)						
Argumentation	CU	12.45 (3.988)	20.55 (7.123)	85.623	< 0.001	0.332
	IR	5.37 (1.892)	8.08 (2.611)	61.538	< 0.001	0.264
	ER	3.59 (2.159)	6.91 (4.283)	41.735	< 0.001	0.195
	CR	5.52 (5.795)	10.56 (3.205)	50.517	< 0.001	0.227
(N=91)						
Explanation	CU	15.22 (5.370)	25.85 (8.862)	95.701	< 0.001	0.347
	IR	6.10 (2.011)	10.08 (3.067)	107.183	< 0.001	0.373
	ER	4.97 (3.022)	9.08 (4.679)	49.608	< 0.001	0.216
	CR	8.48 (5.218)	9.22 (4.376)	1.064	0.304	0.006
(N=52)						
Comparison	CU	12.97 (4.127)	18.63 (8.847)	17.510	< 0.001	0.147
	IR	5.07 (1.834)	6.94 (3.691)	10.71	0.001	0.095
	ER	4.07 (2.473)	6.13 (4.446)	8.586	0.004	0.078
	CR	7.46 (5.546)	9.67 (3.579)	5.836	0.017	0.054

CU conceptual understanding, *IR* interpreting representations, *ER* explaining representations, *CR* creating representations *explaining representations* and *creating representations* were significantly higher than the pre-test scores. The large effect sizes indicate that the instruction received by the Argumentation group significantly impacted students' conceptual understanding and representational competencies.

Similarly, there was a statistically significant difference within the Explanation group between the pre- and post-test scores on the combined dependent variables (F(4, 177)=36.258, p<0.001; Wilk's lambda=0.550; partial eta squared=0. 450). The results shown in Table 5 reveal that the post-test scores for *conceptual understanding*, *interpreting representations* and *explaining representations* were significantly higher than the pre-test scores with large effect sizes indicating that these measures were positively impacted by instruction received by this group. However, the instruction received by the explanation group did not significantly improve scores for *creating representations*.

Finally, there was a statistically significant difference within the Comparison group between the pre- and post-test on the combined dependent variables (F(4, 99)=5.322, p<0.001; Wilk's lambda=0.823; partial eta squared=0.177). Table 5 shows positive effects of instruction received by this group on *conceptual understanding*, *interpreting representations*, *explaining representations* and *creating representations*. While there was a large effect size on the improvement of *conceptual understanding*, medium effect sizes were observed for improvement of all representational competency measures (Table 5).

Between-Groups Comparisons: Post-Test Scores and Knowledge-Building Modes of Discourse

After adjusting for the pre-test scores, the ANCOVA revealed that there was a statistically significant difference across the three intervention groups on post-test scores for *conceptual understanding* (F(2, 226)=9.118, p<0.001, partial eta squared=0.075), *interpreting representations* (F(2, 226)=14.927, p<0.001, partial eta squared=0.117), *explaining representations* (F(2, 226)=5.355, p<0.005, partial eta squared=0.045) and *creating representations* (F(2, 226)=7.091, p<0.001, partial eta squared=0.059).

Table 5 shows that the post-test score for *conceptual understanding* in the Explanation group was significantly higher than the same scores of the Argumentation group (p<0.020) and the Comparison group (p<0.001). Although the Argumentation group was not significantly different to the Comparison group (p=0.235), there was a tendency for their post-test score for *conceptual understanding* to be higher.

The post-test score for *interpreting representations* in the Explanation group shown in Table 5 was significantly higher than the same scores of the Argumentation group (p<0.001) and the Comparison group (p<0.001). The Argumentation group's post-test score on this measure was higher than but was not significantly different to the Comparison group (p= 0.154).

Similarly, the post-test score for *explaining representations* in the Explanation group was significantly higher than that of the Comparison group (p<0.004) (see Table 5). The Argumentation group was not significantly different to the Explanation group (p=0.168) or the Comparison group (p=0.381). However, the Argumentation group tended to have a higher test score for *explaining representations* than the Comparison group.

Finally, the post-test score for *creating representations* in the Explanation group was significantly lower than the Argumentation group (p<0.001). The Comparison group was not significantly different to the Argumentation group (p=0.099) or the Explanation group (p= 0.790). Overall, the Argumentation group tended towards the highest overall post-test score for *creating representations* (see Table 5).

Taken together, within-group comparisons showed that instruction received by each group significantly impacted *conceptual understanding* and the representational competencies of *interpreting* and *explaining representations*. However, the Argumentation and Comparison groups also showed significant improvements in their test scores for *creating representations*. The between groups comparisons of post-test scores found the Explanation group had significantly higher scores for *conceptual understanding*, *interpreting representations* and *explaining representations* than the Comparison group. The Argumentation and Comparison groups were not significantly different on these measures, but the Argumentation group tended to have higher test scores than the Comparison group. While the Argumentation group's post-test score for *creating representations* was not significantly different to the Comparison group, it was significantly greater than the Explanation group. Overall, the Argumentation group displayed the highest score on *creating representations*.

A Kruskal-Wallis test conducted to examine the impact of instruction, in each group, on knowledge-sharing discourse during a small group inquiry activity revealed that there was no statistically significant difference across the three conditions (Argumentation, Median=6, Inter-quartile range = 4.5,N=13 groups: Explanation, Median=4.5, Inter-quartile range = 5.5, N= 14 groups: Comparison, Median=3, Inter-quartile range = 0, N=14 groups), χ^2 (2, n=41)= 2.763, p=0.251). These findings suggest that the 3 to 4 person student groups in all three conditions were similarly effective at knowledge-sharing including discourse that supports recalling and sharing existing knowledge, identifying key elements of a given activity, and introductory level discussions that do not extend into explanations, evaluations or interpretation. While there was no significant difference between the three conditions in knowledge-sharing, the Argumentation group tended to rank higher on this mode of knowledge-building discourse than the other conditions.

The same test was conducted to explore the effect of instruction received by each condition on knowledge-construction discourse during a small group inquiry-based representational task. There was a statistically significant difference in knowledge-construction discourse across the three conditions (Argumentation, Median=7, Inter-quartile range = 4,N=13 groups: Explanation, Median=7.5, Inter-quartile range = 7.5,N=14 groups: Comparison, Median=4, Inter-quartile range = 5.5,N=14 groups), χ^2 (2, n=41)=7.187, p<0.028). A Mann–Whitney U test revealed that there was no statistically significant difference between the Explanation and Argumentation groups (U=85.500, z=−0.268, p=0.788, r=0.52) or between the Explanation and Comparison groups (U=58.000, z=−1.848, p=.065, r=0.35). However the Argumentation group showed a significantly higher incidence of knowledge-construction discourse than the Comparison group (U=35.500, z=−2.709, p<0.006, r=0.52). Overall, this result indicates that instruction received by the Argumentation group was more effective at promoting knowledge-construction meaning small student groups were better at explaining, interpreting and evaluating new information, critiquing ideas and synthesising new concepts as they worked with representations in a collaborative inquiry task.

Discussion

The findings of the study provide some interesting insights into learning science through collaborative inquiry and representational tasks that promote explanation and argumentation where a clear distinction was made between explanation and argumentation. An instructional focus on explanation using representations results in the highest scores for conceptual understanding, interpreting representations and explaining representations. An instructional focus on explanation and argumentation using representations resulted in the highest scores for creating representations and incidence of knowledge-construction discourse (requiring higher order cognitive skills) during a representational task. Within the Comparison and Argumentation conditions, there was a significant increase in scores from pre-test to post-test for all representational competencies (interpreting, explaining and creating representations) and conceptual understanding. The Explanation group also showed significant improvement in pre- to post-test scores for conceptual understanding but only in interpreting and explaining representations.

Interpreting and understanding a representation is challenging and is less likely to occur spontaneously, beyond identifying the surface-based features (Kozma and Russell 2005). Hinze et al. (2013) have shown that even when the features of a representation are clear, domain knowledge plays a necessary supportive role for understanding the relevance of these features to the domain of interest. In this study, students' improved scores in interpreting and explaining representations occurred concurrently with improvements in their conceptual understanding of science concepts associated with natural disaster phenomena. The Explanation group had the highest scores for conceptual understanding alongside the highest scores for interpreting and explaining representations.

Specifically with regard to the development of representational competencies, Kozma and Russell (2005) proposed a set of developmental stages. Novices move from more surface level understandings of representations, termed 'syntactic use', to deeper considerations of underlying meanings and constructs, termed 'semantic use' as they develop representational competencies of interpreting, understanding and explaining representations of science phenomena. The cognitive skills necessary for 'syntactic use' include information-gathering and visual processing of the forms/features of the display in a representation. To move towards the skills for 'semantic use', individuals would need to employ problem solving, analytical reasoning and finally integration of new information into existing cognitive structures in order to relate information from representations to the science content they convey. The findings of this study are consistent with these theoretical constructs in that the students in the Argumentation group showed not only an improvement in interpreting and explaining representations but also creating representations to explain the science concepts. Moreover, students in this group had the highest scores for knowledge-construction and displayed significantly higher incidences of explanation-seeking questions, evaluating and interpreting new information, conjectures and explanations that refer to concepts or causal mechanisms, summarisation, synthesis and creation of new ideas. This suggests that the students in the Argumentation group were most successful in moving from syntactic to semantic use of representations.

The finding in this study that overall, argumentation-driven inquiry significantly improved conceptual understanding and knowledge-construction when compared to the Comparison group is consistent with previous findings. A study of fifth grade students learning about light and sound (Mercer et al. 2004) found that students in the study's Argumentation group had higher knowledge scores than the Control group. They found that the discussions in the Argumentation group were more likely to be on-task and showed greater overall task participation. Another study of fifth grade students learning about pollution (Mason and Santi 1994) found that student's use of argumentation gave them an awareness of knowledge-construction procedures.

Osborne and Patterson (2011) maintain that engaging students in the goal of producing explanations *initiates* them into construction of knowledge, but engaging students in argumentation enables students to more successfully engage in knowledge-construction discourse by promoting higher order thinking and reasoning; hallmarks for higher level scientific discourse. The reason for this distinction Osborne and Patterson explain is that argumentation demands skills of analysis, synthesis and evaluation. Students in the experimental Argumentation condition were significantly better at knowledge-construction compared to the Explanation and Comparison groups and so were able to participate in higher level conceptual discourse around content through collaborative inquiry and representational tasks. The results of this study are consistent with previous findings showing instruction that promotes argumentation in a social context facilitates reasoning strategies and higher order thinking, skills that are embedded in argumentation (Jimenez-Aleixandre and Erduran 2007). This study goes beyond previous work by showing that argument-promoting inquiry instruction that focuses on building and facilitating student's representational competencies through collaborative inquiry and representational tasks promotes students' conceptual understanding, representational competencies and knowledge-construction of science concepts, which together reveal representational fluency skills.

Implications

But what is this construct representational fluency? And how do representational competencies, representational agency and representational fluency relate to each other? The theoretical ideas behind representational fluency have been better explored in mathematics education where individuals require the skill to flexibly translate meaning from one form of mathematical representation to another. This skill requires generalising and particularising information across multiple forms of mathematical representations to explain, reason, synthesise and construct mathematical knowledge (Nistal et al. 2009). Representational agency in science is the ability to understand the social, semiotic and material affordances of science representations and requires that individuals are able to interpret, explain and create representations or that they possess these representational competencies. But in order to fluently translate or transform meaning across multiple representations of science to construct knowledge or to have representational fluency, students need representational agency. This study builds on previous work (Nichols et al. 2013a, b) that was able to show that measures of knowledge construction during small collaborative inquiry tasks where students are asked to translate meaning across multiple representations and explain science phenomena, taken together with measures of representational competencies (interpreting, explaining and creating representations), and conceptual understanding provides insights into students' representational fluency. In this study, the Argumentation group, with significantly improved and higher scores in conceptual understanding and representational competencies, as well as significantly higher knowledge-construction during a collaborative inquiry representational task compared to the Comparison group, displayed evidence of greater representational fluency.

Taken together, these findings indicate that while an instructional focus on representations through a representation-rich unit of work on natural disasters is sufficient to positively impact students' conceptual understanding and representational competencies, an argumentation-promoting collaborative inquiry using representations promotes students' representational fluency.

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Appendix

Pre/post-test for conceptual understanding and representational competencies (interpreting, explaining, creating representations)

1. Use the labels in the box below to label the diagram to show the four main layers in the Earth.

Mantle	**Crust**	**Inner core**	**Outer core**

Main layers in the Earth

A cutaway diagram showing the main layers of the earth with arrows pointing to each layer to be labelled.

2. Circle either A, B, C or D for each of the following.

i. A place where an earthquake starts is called the __________.

A. Focus

B. Tsunami

C. Fault Line

D. Epicenter

ii. The name of the sea wave that can cause great damage as the result of an earthquake is called a __________________.

A. Tidal wave

B. White water

C. Tsunami

D. Breaker

iii. Severe earthquakes are more likely to occur in which of the following places. There may be more than one correct answer.

A. New Zealand

B. Australia

C. Japan

D. All of the above

iv. Sometimes after an earthquake, there is a lot of damage to structures because water is forced to the surface changing the composition of the soil. What is this process called?

A. Quick sand

B. Water damage

C. Liquefaction

D. Landslide

v. The instrument seismologists use for recording the magnitude (size) of an earthquake is called a _______________.

A. Seismograph

B. Earthquake recorder

C. Seismogram

D. Egg beater

vi. Scientists can tell where earthquakes happened by detecting two types of waves. What are these called?

A. F and P waves

B. Y and Z waves

C. P and S waves

D. J and K waves

3. Match the descriptions labelled A, B, C or D in the text box below to their corresponding representation. Print the letter A B C or D in the table next to 'answer' for each description.

A. The Earth must be made of solid and liquid layers because secondary waves do not pass all the way through but primary waves do.

B. Oceanic-oceanic and continental-continental divergent boundaries

C. Energy is released from an earthquake as vibrations that travel through the Earth and cause movement in the Earth's crust.

D. Tectonic plates crash into one another.

A cutaway diagram of the earth showing waves radiating out from the epicenter of an earthquake.	**Answer**
A diagram showing the earth in cross-section with signals for P waves and S waves radiating across the layers. The image comes from a Learning Federation digital learning object that students have interacted with during the unit.	**Answer**
An image showing a divergent boundary that runs through Iceland between the North American and Earasian plates with arrows to designate the direction of the movement of the plates.	**Answer**

4. The tectonic plates are moved around **by the underlying hot mantle convection** cells. Explain what this means and what is happening at A and B.

A cutaway diagram of the earth showing the individual layers. Within the mantle layer are arrows showing convection cells or currents. An arrow at A points to the where two plates are diverging and an arrow at B points to where plates are converging.

5. How do earthquakes happen?

A plate boundary map with arrows to show a convergent boundary between the Australian plate and the Pacific plate, a divergent boundary between the Pacific plate and the Antarctic plate and a transform boundary between the Pacific plate and the Carribbean plate.

Look carefully at the map of the world and the positions of the tectonic plates. Notice the **circled arrows** at points **A, B** and **C** and how these arrows move in different directions. **Write down the terms** to show what is happening where you see each pair of arrows

A _______________________

B _______________________

C _______________________

Describe how an earthquake might occur at **A.**

6. What has happened here?

An image showing a house that has sunk into the ground due to liquefaction.

The house above was badly damaged after an earthquake. Explain what has happened using the representation below to help you.

An image showing changing nature of the ground from solid bedrock to poorly consolidated sediment to water-saturated sand and mud with houses sitting atop each ground type.

7. Look carefully at the diagrams below. They show different tectonic plate boundaries, and indicate four places where tectonic activity occurs (**A, B, C** and **D**). Then read the headlines below the diagrams.

4 images showing plate activity at convergent (plates subduct, plates collide), divergent (plates separate) and transform (plates slide past one another) boundaries.

The headlines below appeared in local newspapers the day after the tectonic activity occurred:

3 images showing the following headlines:

"*explosive volcanic eruptions kills 9000*",

"*mighty mountains grow taller by 20 cm over last century*",

"*geologists race to the site of youngest rock*"

Use your knowledge of tectonic activity occurring at plate boundaries to complete the table by doing the following:

- match each headline to the most likely area of tectonic activity (**A, B C**) and then write an explanation for what is occurring;
- create a headline for the likely activity occurring at area **D**
- write an explanation supporting your headline in **D**.

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