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Author(s)	Bo Pei, Wanli Xing, Gaoxia Zhu, Kristine Antonyan and Charles Xie

Integrating Infrared Technologies in Science Learning: An Evidence-based Reasoning Perspective

Bo Pei[1]
Postdoc Associate
Phone:3528712203
Email: bpei@nd.edu

Wanli Xing[2]*
Assistant Professor
Phone:5735294442
E-mail: wanli.xing@coe.ufl.edu

Gaoxia Zhu[3]
Assistant Professor
Phone: 65928215
Email: gaoxia.zhu@nie.edu.sg

Kristine Antonyan[2]
PhD Candidate
Phone: 8475320556
Email: kantonyan@ufl.edu

Charles Xie[4]
Chief Scientist
E-mail: charles@intofuture.org

[1]Lucy Family Institute for Data and Society, University of Notre Dame, Notre Dame, IN 46556, U.S.A.
[2]School of Teaching & Learning, College of Education, University of Florida, Gainesville, FL 32611, U.S.A.
[3]Learning Sciences and Assessment (LSA), National Institute of Education, Nanyang Technological University, Nanyang Walk, 637616, Singapore
[4]Institute for Future Intelligence, 26 Rockland St., Natick, MA 01760, U.S.A.

*Correspondence details

Dr. Bo Pei is a postdoc associate jointly supported by Lucy Family Institute for Data and Society and ND Learning in the University of Notre Dame. His research interests are STEM education, educational data visualization and machine learning.

Dr. Wanli Xing is an Assistant Professor of Educational Technology at the University of Florida. His research interests are artificial intelligence, learning analytics, STEM education and online learning.

Dr. Gaoxia Zhu is an assistant professor in the Learning Sciences and Assessment Academic Group at National Institute of Education, Nanyang Technological University. She has Educational Technology and Learning Sciences backgrounds. Her research interests include Knowledge Building, computer-supported collaborative learning (CSCL), student self-driven learning, socio-emotional interactions, and learning analytics.

Kristine Antonyan is a PhD candidate in School of Teaching & Learning, College of Education at University of Florida. Her research interests include data visualization comprehension and strategies, learning analytics and smart tutoring systems, online learning, instructional design with AR, VR, MR and other emerging technology.

Dr. Charles Xie is the founder and chief scientist at the Institute for Future Intelligence. His research includes computational science, learning science, machine learning, artificial intelligence, computer-aided design, mixed reality, Internet of Things, molecular simulation, solar energy engineering, and infrared imaging.

Integrating Infrared Technologies in Science Learning: An Evidence-based Reasoning Perspective

Bo Pei[1], Wanli Xing[1], Gaoxia Zhu[2], Kristine Antonyan[1], Charles Xie[3]

[1]*School of Teaching & Learning, College of Education, University of Florida. 1221 SW 5th Ave, Gainesville, FL 32601, U.S.A.*

[2]*Learning Sciences and Assessment (LSA), National Institute of Education, Nanyang Technological University, Nanyang Walk, 637616, Singapore*

[3]*Institute for Future Intelligence, Natick, MA 01760, USA*

Abstract

Infrared (IR) technologies have been universally acknowledged as a valuable pedagogical tool for exploring novel and abstract scientific subjects in science education. This study explores the roles of IR images played in middle school students' Evidence-based Reasoning (EBR) process in support of the understanding of the heat radiation process. Specifically, we implement image processing algorithms explicitly for the visual artifacts mentioned in students' descriptions of the radiation phenomenon to obtain the numeric representations of their corresponding features. Meanwhile, the quality of those descriptions is further coded with the guidance of the EBR framework for indicating students' understanding levels of the phenomenon. Finally, the associations between the numerical image features and the quality of descriptions are analyzed to examine the effectiveness of the IR visual artifacts in helping students understand the heat radiation process. The analytical results found that the image features are further positively correlated with the quality of the descriptions generated by students for the heat radiation. The results further suggest the IR images have the potential of driving students to think proactively and explore detailed procedural changes in learning the heat radiation process. Finally, our study calls for the integration of interdisciplinary instructional approaches in science education to reduce students' cognitive load and guide learning attention, for example, incorporating visualization and relevant processing approaches to present and analyze the otherwise invisible abstract process to help students make sense related knowledge more easily.

Keywords: Science Education, Evidence-based Reasoning (EBR), Infrared (IR) Imaging, Interdisciplinary Instructional Approaches, Image Processing

[1] Corresponding Author: wanli.xing@coe.ufl.edu

1 Introduction

A wide variety of emerging technologies have been employed by recent science education practices for supporting students to better understand abstract and sometimes complicated scientific phenomena/concepts. Multiple studies, such as Haglund et al. (2015a, 2016) and Kácovský (2018), have been conducted to explore the roles of infrared (IR) imaging technologies in supporting learning the heat-related concepts and processes. In these studies, IR cameras were used to visualize the abstract heat process to help students observe the related processes that are otherwise unobservable. Ebadi et al., (2020) stated that visualizing the invisible processes can support students to learn in an interactive and proactive way, at the same time these visualized artifacts would further motivate and help students in the activities for interpreting and making sense of abstract phenomena. More specifically, these visual artifacts are further considered as evidence in the evidence-based reasoning (EBR) framework (Brown et al., 2010) for science learning. This framework is a combination of Toulmin's (2003) argument framework and assessing systems of reasoning quality, and has been recognized as of great significance in preparing students for workplaces and higher education by the Next Generation Science Standards (NGSS) (Fiaidhi, 2014).

The EBR framework can be used as a guidance for supporting and evaluating students' scientific argumentation processes. Students' scientific argumentation about natural phenomena involves a bidirectional process from phenomena (evidence) to theory: applying theory to explain the occurring phenomena (evidence) and using the evidence to substantiate the current theory. As such, during this process, the quality and appropriateness of the evidence students used to make sense of the phenomenon can indicate their understanding levels of the relevant knowledge. The affordance of IR imaging in science education provides students with additional dimensions to see the on-going scientific phenomenon (i.e., the traces of heat radiation). These visualizations, on the one hand, could engage students in scientific knowledge inquiry activities by liberating them from the passively conceptualization process of what described in textbooks to visually observation and exploration activities. On the other hand, the interactions with the evidence in combination with students' existing knowledge could further deepen students' understanding of the new knowledge. Researchers (Osborne et al., 2004; Berland & Hammer, 2012) have recognized the positive effects of evidence on learning by assessing to what extent students' argumentations are supported by the evidence. Despite that the effectiveness of visualizations in supporting science education has been recognized by these studies from a qualitative perspective, little quantitative approaches research has been conducted, especially with the recent advance in computer vision that provides additional dimensions for analyzing visual artifacts.

To fulfill this need, our study makes initial attempts on incorporating image processing approaches to automatically extract and quantify the image features used in students' argumentations about heat radiation. At the same time, the quality of each student's argumentations is evaluated and coded under the EBR framework to indicate students' understanding levels of the heat radiation process. Specifically, this study was conducted in the following aspects: (1) Investigating what IR image features are commonly used by students for describing the heat radiation phenomenon to shed light on student cognitive learning processes; (2) Implementing image processing algorithms for extracting and quantifying those features to examine how the features influence the quality of the reasoning for informing instructors what features should be highlighted for students to facilitate the meaning-making processes; (3) Examining how the image features correlate to students' reasoning quality under the guidance of EBR to shed light on the practice of automatic assessment in science education. With the analytic approaches conducted in this study, it is hoped that our study could extend the EBR framework as well as provide implications to develop software to automatically evaluate students' experimental processes in combination with the emerging technologies in science education.

2 Literature review

2.1 How to analyze scientific knowledge from argument texts?

EBR has received increasing attention due to the potential to engage students in an iterative process of security and revision on their arguments about a certain phenomenon based on the available evidence (Brown et al., 2010; Furtak et al., 2010). Giri and Paily (2020) developed a novel argumentation analytic framework, combining Toulmin's argument pattern (TAP) with a Think-Read-Group-Share-Reflect (TRGSR) strategy, to analyze how critical thinking impacts secondary students' biology learning achievements. The analytical results on students' discussion vignettes suggested a significant correlation between students' higher-order thinking skills (e.g., synthesis, evaluation, creation) and their understanding levels of the topic. In another study, Probosari et al. (2017) analyzed the process of learning biology in different stages, such as claim-making stage, data explaining stage, and explanation justifying stage. The study suggested that activities such as classroom discussions as well as comparisons in terms of argumentative writing assignments and oral presentations have significant contributions to maintaining students' higher-level learning motivations and argumentation skills. Furtak et al. (2010) investigated approaches for assessing students' scientific argumentation abilities through examining how students connect scientific theories with evidence to support their claims. The study categorized students' scientific argumentations into three levels focusing on the theory-evidence relationships: no distinction between theory and evidence in the claims, certain distinctions between theory and evidence, and a clear distinction between them. The results of this study indicated that the quality of students' scientific claims was positively correlated with the distinction levels between theory and evidence in the corresponding claims. Taken together, this body of research suggests the potential of estimating students' understanding levels of a scientific phenomenon from their argumentations through examining the evidence they used to support their reasoning processes.

2.2 How visual representations support science learning?

In recent years, the increasing adoptions of IR cameras in science classrooms provide additional dimensions for students to explore abstract heat-related phenomena in greater depth (Haglund et al., 2015a). These IR cameras can automatically map the differences in temperature to regions on IR images with different color schemas. These visual representations can show the abstract process in great detail which could greatly reduce students' cognitive load, especially while engaging in some complicated Fields (Bohrmann-Linde & Kleefeld, 2019). At the same time, students' reasoning process can also be publicized to their peers by these visualizations, which can engender complementary opinions from their peers to improve their own knowledge about the phenomenon. Moreover, the real-time visualization showing the changes in the flow of thermal energy can also direct students' attention toward subtle changes that might go unnoticed otherwise (Xie & Hazzard, 2011). In the research of Haglund et al. (2015a), authors applied IR imaging techniques to visualize the differences in effects of heat and temperature to clarify the misunderstandings about the two phenomena. Similarly, in another study, Vollmer and Möllmann (2017) adopted IR techniques to illustrate Newton's law of cooling through examining the differences in cooling processes of objects of various sizes. Moreover, the artifacts on the IR images can also provide a ground for instructors to evaluate the quality of students' reasoning processes in combination with students' scientific claims. For example, by examining the claims made by students toward a specific phenomenon in the aspects of whether the provided claims are fully supported, whether the supporting evidence includes all critical artifacts and so on, instructors could have a general understanding of which parts students have weak a knowledge and further provide customized interventions.

These studies extensively investigated the role of IR imaging techniques in supporting students to cognitively understand about scientific phenomena (Evagorou et al., 2015; Haglund et al., 2015b; Melander et al., 2016), however, they did not examine how the images correlate with the process in which students make sense of these phenomena from a quantitative perspective. The lack of research in this aspect largely limits the potential applications of IR technologies in a much broader area like implementing automatic assessing applications and frameworks on students' scientific argumentation and lab exploration process. To this end, our study explicitly investigates how visual artifacts on IR images were used by students to make sense of the heat radiation process in a lab experiment. Specifically, we attempt to answer the question of "*How the visual features of IR images used by students are correlated with the quality of their scientific argumentations, and whether can we elicit students' understanding level of an abstract process from the scientific argumentation process?*". The answers will offer something new that is currently not well-addressed in the science education domain, especially in terms of evaluating reasoning processes using visual artifacts in addition to written text.

3 Methodology

3.1 Participants and experimental procedure

The experiment was conducted during the spring semester of 2018-2019 in four different middle schools across the Massachusetts area in the U.S. involving 278 students in total. These students were placed into pairs of similar age to explore the heat radiation phenomenon using IR cameras in a designed laboratory activity. To actively engage them to explore the heat radiation, the Predict-Observe-Explain (POE) instructional strategy (Liew, 1998) was adopted in the experiment. In each step of POE shown in Figure 2, students were asked to report their findings, claims, and supporting evidence in detail. As this was a volunteer activity, most students did not fully report their experimental processes, although they completed the whole experiment. Consents of allowing to analyze the learning reports for research purpose were obtained and all sensitive information for identifying a specific student was removed before screening the data. After screening the reports, 29 (8 of them did not provide IR images as evidence for their claims) of them were selected for the relatively completed report data that fulfills the analytical requirements in this research.

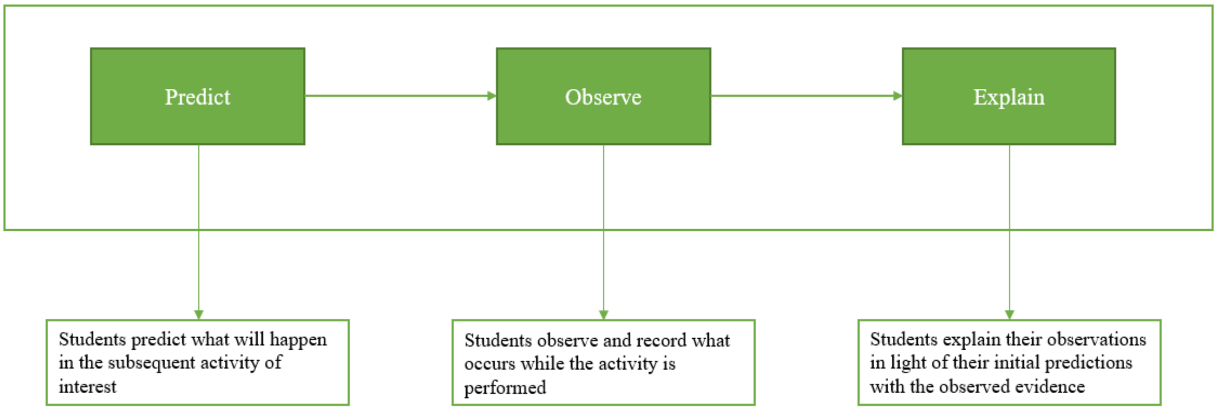


Figure 1 The POE instructional strategy

According to the steps in Figure 1, students were first required to answer the predictive questions in the predict(ion) step. These questions generally ask students to predict what will be happening in the subsequent steps (e.g., what will be happening on the paper if facing the jar at 1 inch (2.54 cm) away) of the experiment based on their existing knowledge. Then, in the observe/(ation) step, students were asked to conduct the experiment according to the provided instructions/manuals and at the same time observe the whole process with IR cameras. In the process, students performed and compared the observations under two conditions as shown in Figure 2. Observation #1 -- Paper faces to the jar with hot/ice water: in this stage, the paper was first placed 1inch away for 60 seconds, during which process students used IR cameras to capture the status of the paper every 10 seconds. Then, the paper was moved to 2 inches away from the jar for another 60 seconds, and students repeated the same activities as before. Observation #2 -- Paper faces sideways to the jar with hot/ice water: similar to the operations in observation #1, students were required to record the paper status while placed at 1 inch and 2 inches away from the jar, respectively. Finally, in the explain (explanation) stage, students were asked to answer open-ended questions for assessing their understanding level of the heat radiation phenomenon after going through the whole experiment.

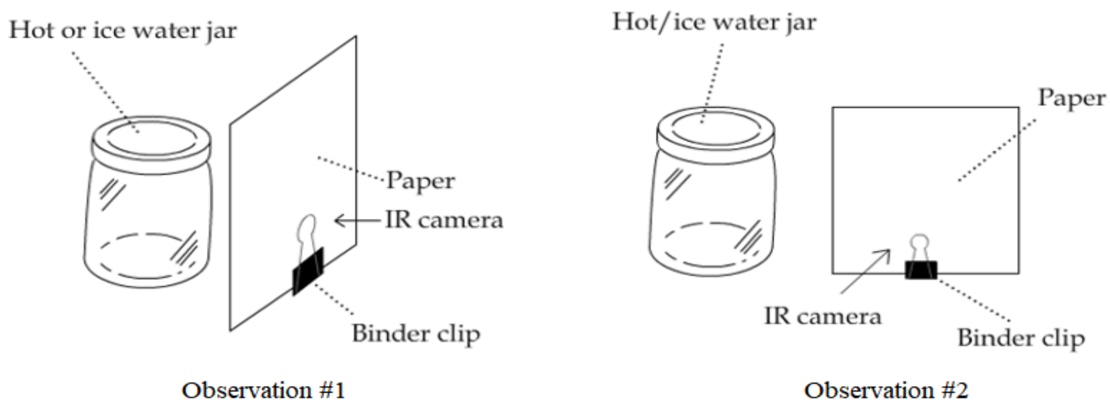


Figure 2 The two experimental stages in examining heat radiation

3.2 Framework for evaluating students' understanding levels of the heat radiation

Students' understanding levels of the heat radiation phenomenon will be evaluated in three stages in correspondence to the POE strategy based on the framework depicted in Figure 3. In the prediction and explanation stages, the same set of evaluation metrics is used to assess students' descriptions of the process for quantifying the magnitude of knowledge gains about the heat radiation through conducting the experiment. In the observation stage, we adopt the EBR framework to evaluate the quality of students' reasoning process based on the involvement of visual artifacts (evidence) in the descriptions. Finally, we evaluate how the features in IR images correlate with students' knowledge gains about heat radiation through impacting the quality of students' scientific reasoning.

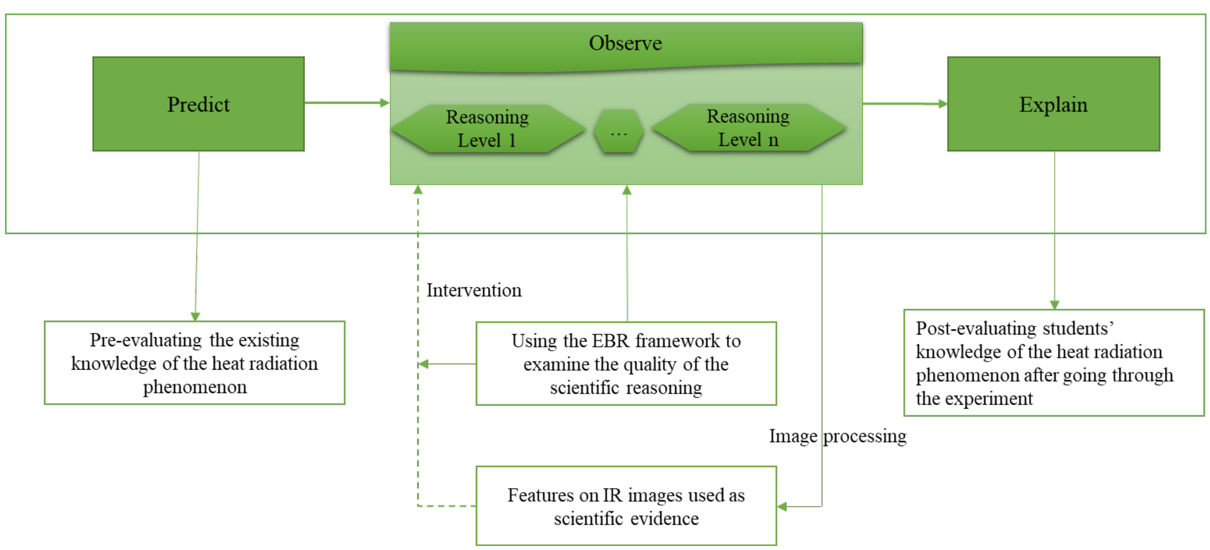


Figure 3 Incorporating the EBR framework into the observation stage of POE

According to this framework, the levels of students' existing knowledge and understanding of the heat radiation phenomenon will be evaluated at the prediction and explanation stages, respectively. In these two stages, students' knowledge and understanding of the heat phenomenon were mainly represented by their descriptions about observed phenomena provided in the open-ended questions. There were over 300 descriptions in total generated by students in the two stages, and three domain experts were involved to code the understanding levels based on the rating schema presented in table 1. Specifically, the answers were coded into 3 levels: wrong or off-topic (1 point), partially correct (2 points), and fully correct (3 points). And the final scores were given to students to indicate their understanding levels of the heat radiation at each stage after all the experts reached full agreements on the uncertain answers.

Table 1. A rating scheme to analyze students' predictions and explanations

Score	Items	Criteria	Examples
1	Prediction Q1-3 Example question: What will happen to the temperature pattern of a piece of paper when it faces a jar of hot or ice water? Explain why.	The explanation is wrong or off-topic.	When further away, the transfer of heat will be less because the heat will take longer to travel. It will be a uniform color and temperature.
	Explanation Q1-3 (the claim is given) Example question: In the image you took for Table 7 (a) shows, the paper warmed up when it faced a jar of hot water. Is this phenomenon radiation, conduction, or convection? Explain.	The explanation is the rephrasing of question stem, off-topic, or containing the big error(s)	This phenomenon is not conduction because there is no direct contact involved. It is not radiation because there are no electromagnetic waves. Therefore, it is convection because the air is transferring the heat molecules from one object to the other.
2	Prediction Q1-3 Example question: What will happen to the temperature pattern of the paper when it is further away from the hot or ice water jar? Explain why.	The explanation is not correct and may include some misunderstanding	The temperature pattern will change colors and show either a higher temperature or lower temperature depending on if the paper is close to the hot water jar or the ice water jar. This is because of the heat transfer process of radiation. The pattern will be less defined because the heat has to move farther through the air to get to the paper.

	Explanation Q1-3 (the claim is given) Example question: When the paper was further away from the hot water jar, you observed a phenomenon shown in Table 7 (b). Explain why it happened?	The explanation is partially correct or having minor error(s).	The jar was farther away, so there was more air to get through.
3	Prediction Q1-3 Example question: What will happen to the temperature pattern of the paper when it does not face the jar (Figure 5)? Explain why.	The explanation is correct.	The temperature of the piece of paper will absorb less heat than if it were facing the jar. It won’t get as hot or cold as in figure 4, because there is less surface area facing the source. it will heat up less since less surface area will be available to receive radiation.
	Explanation Q1-3 (the claim is given) Example question: When the paper did not face the jar (Figure 5), you observed phenomena shown in Table 7 (c) and (d), Explain why the phenomena happened.	The explanation is correct.	When the pattern of a piece of paper does not face the jar of hot water the paper will still get hot but not as hot because there is less surface area.

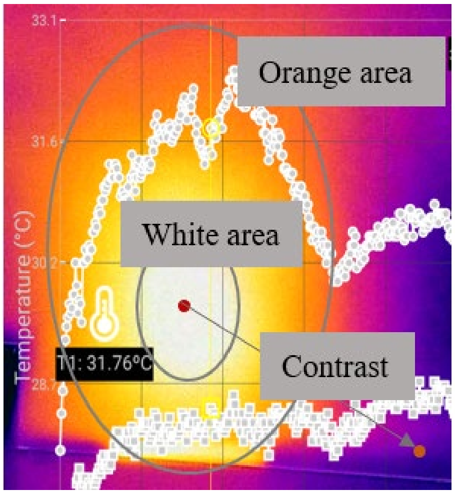
In the observation stage, two different analytics will be involved to analyze associations between the reasoning quality and the features of visual artifacts. These associations will be further used to provide informed guidance about which features should be paid attention to fully comprehend the phenomenon (shown as the dashed line in Figure 3). In this section, we only focus on evaluating students’ reasoning quality based on the EBR framework. According to Brown et al. (2010), the EBR framework can be an assessment tool for analyzing students’ reasonings in writings and classroom talks as it describes “the use of evidence in scientific reasoning” (p. 134). The evidence presented in students’ scientific reasoning serves to connect the common rules about the phenomenon and claims made by students under specific conditions. Drawing on this notion, our work adapted the evaluation framework proposed by Furtak et al. (2010) and the quality of students’ reasoning were coded as: phenomenological reasoning, relational reasoning, and ruled-based reasoning. The detailed coding schema and the relevant definitions are described in Table 2.

Table 2. Quality of Reasoning in the Description for Heat Radiation in Observation Stage

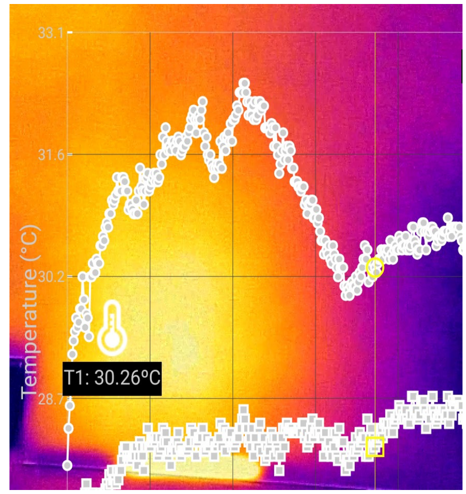
Quality of Reasoning	Definition	Description	Examples
Phenomenological Reasoning	No evidence or data used to support the claims	The claims are simply about the descriptions of the phenomenon without any supporting evidence provided	The glow gets dimmer.
Relational Reasoning	There are evidence or data used to support the descriptions of the phenomenon	The claims about the phenomenon are made based on the observed evidence or data and indicate a certain relationship	The heat transferred to the paper is weaker when the paper is placed at 2 inches away since the heat has more distance to travel.
Rule-based Reasoning	There are rules or principles involved in the descriptions indicating a certain level of inductive or deductive reasoning	In addition to involving the related evidence or data presented under certain circumstances, the description also includes the always hold principles (e.g., the law of radiation) indicating the abilities of inductive or deductive reasoning	When the paper is placed alongside the jar, the heat will be radiated to a less extent in the picture, because less surface area causes less heat transfer.

3.3 Quantifying the visual artifacts on IR images with image processing approaches

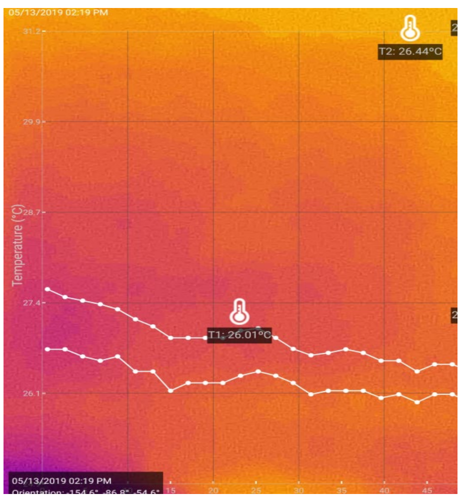
With IR imaging technologies, invisible differences in temperature on the surface of the paper are presented as the different color regions in the images as shown in Figure 4. These figures indicate the influences of the heat radiation on the temperature of the paper surface with the distributions of color under different paper-jar positions. To compare the images under different conditions, in this paper, we mainly examine the differences in features such as the orange area, white area, and image contrast. The reason we used these image features, on the one hand, is these features are most mentioned in students' descriptions; On the other hand, these features are most obvious in images and the differences in them can easily capture students' attention. More specifically, the orange area in the image is the larger area that is influenced by the heat radiation with the reddish color indicating that the region's temperature is higher than that of the room. The white area is the smaller area with the white color indicating that the area is mostly influenced by heat radiation. Image contrast is the difference in grayscale color between a point from the area that was influenced most by the heat radiation and that from the area that was influenced the least.



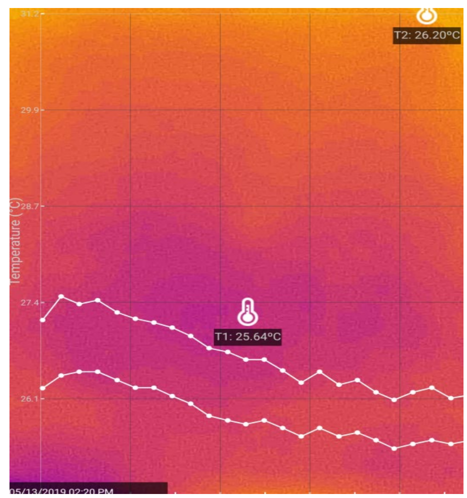
(a) the temperature distribution of the paper placed at 1inch away facing to the jar



(b) the temperature distribution of the paper placed at 2 inches away facing to the jar



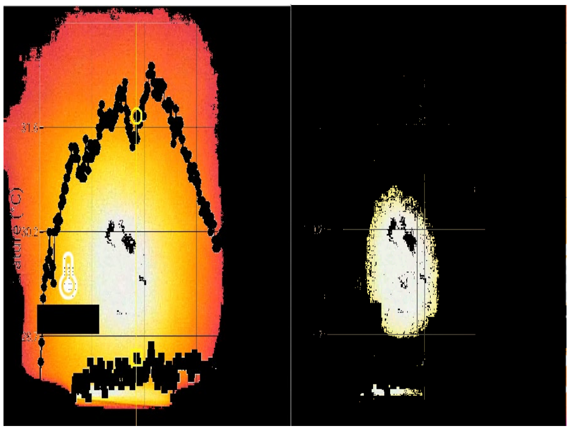
(c) the temperature distribution of the paper placed at 1inch away facing sideways to the jar



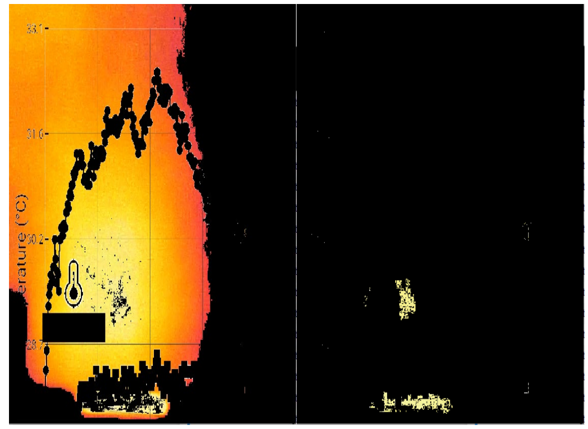
(d) the temperature distribution of the paper placed at 2 inches away facing sideways to the jar

Figure 4 The infrared images present the distribution of the temperature on the paper when the paper is facing/sideways to the jar at varies distances

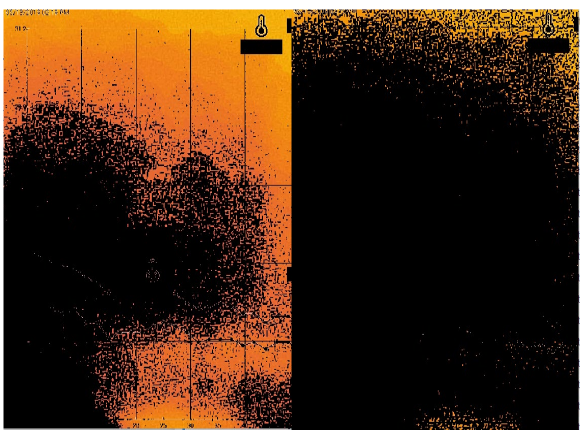
With these features being identified, image processing approaches (authors, 2019) were applied to the feature extraction and quantification process, such as extracting the region of interests (ROIs), calculating the area of the ROIs, and calculating the image contrast. Specifically, we implemented a colored-based region segmentation approach using OpenCV (Abdelrahman et al., 2017) to automatically extract color regions in the image based on the differences in colors. The areas of the ROIs were indicated by the number of pixels in the corresponding region. To calculate the contrast of the image, we implemented an approach to the automatically brightest and darkest point in the corresponding grayscale image and calculate the differences in the grayscale of these two points. Figure 5 shows the extracted ROIs corresponding to the images in Figure 4 using the implemented image processing approaches. It should be noted that the white areas in the images generated when the paper is placed alongside the jar are quite small, which limits the following-up analysis for drawing informative conclusions. To solve this problem, we set a lower segmentation threshold for incorporating the brightest pixels in the images in the real segmentation process. For example, the yellow pixels in the following images are categorized into white areas for avoiding no white areas being detected under some conditions.



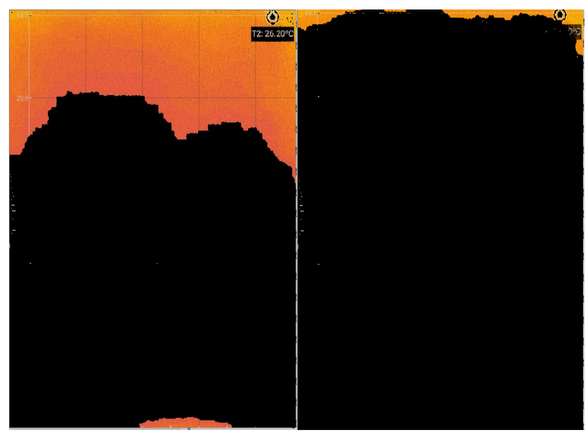
Orange region White region
(a) Images facing the jar with a distance of 1 inch away



Orange region White region
(b) Images facing the jar with a distance of 2 inches away



Orange region White region
(c) Images alongside the jar with a distance of 1 inch away



Orange region White region
(d) Images alongside the jar with a distance of 2 inches away

Figure 5 The extracted ROIs of images under different conditions

3.4 Analyzing the associations between visual features, argumentation quality, and knowledge gains

Data were analyzed statistically for exploring how visual representations relate to students' argumentation quality and then influence their knowledge gains of the heat radiation phenomenon. Specifically, the understanding scores in the prediction and explanation stages were first compared respectively between students who provided visual artifacts to support their reasoning and those who did not. Then, for students who used visual representations to support their reasoning processes, we examined the distributions of scores in the prediction and explanation stages to examine whether there was an improvement in understanding level through the experiment. Finally, we also analyzed the distributions of students' argumentation quality across different stages as well as how the extracted image features influence the quality.

4 Results

There were 8 pairs of students who did not provide IR images in their descriptions of heat radiation. In this section, we analyzed whether the visual representations are associated with students' learning achievements. Figure 6 presents mean scores of heat radiation knowledge between students who used IR images to support the reasoning process and those that did not in both the prediction and explanation stages. From the figure, it can be found that the students in the group that provided images to support their reasoning processes had much prior knowledge compared with students who did not. According to Wade and Kidd (2019), this is in part due to that a certain level of prior knowledge could stimulate students' curiosities about the phenomena and guide them to explore further about subtle changes in the process. As a result, these students would be more likely to share their exploration process with detailed descriptions supported by evidence or have more confidence to articulate their claims using various visual artifacts as evidence.

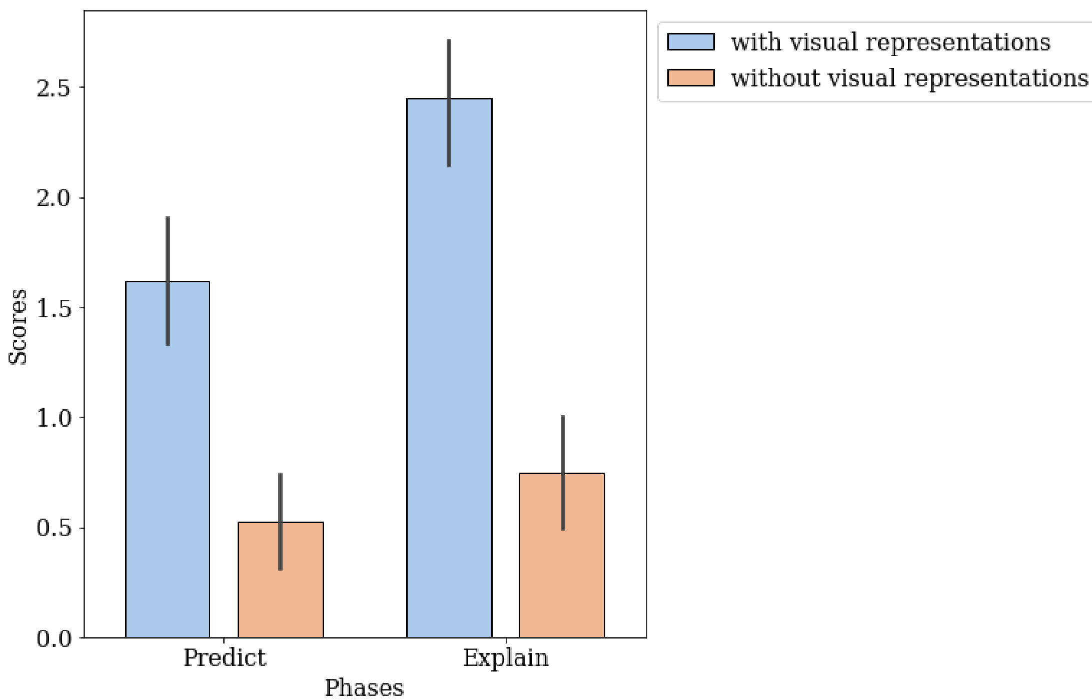


Figure 6 The mean scores indicating understanding levels of student groups with/(-out) visual representations provided in prediction and explanation stages

Moreover, there is also an increase in the mean scores in the explanation stage compared with that of the prediction stage in both of the two groups. To investigate whether the visual features influence the degree of students' knowledge gains, we employed the *t*-test to evaluate the differences in the scores between the two stages in two groups, respectively. The results indicate that there is a significant difference in magnitude of knowledge increasing (t (27) =2.460, p<0.050) between the explanation and prediction stage across the group (*M*=0.833, *SD*=0.930) using IR images and the group (*M*=0.277, *SD*=0.340) did not. This means that visual representations play a significant role in helping students make sense of the heat radiation phenomenon.

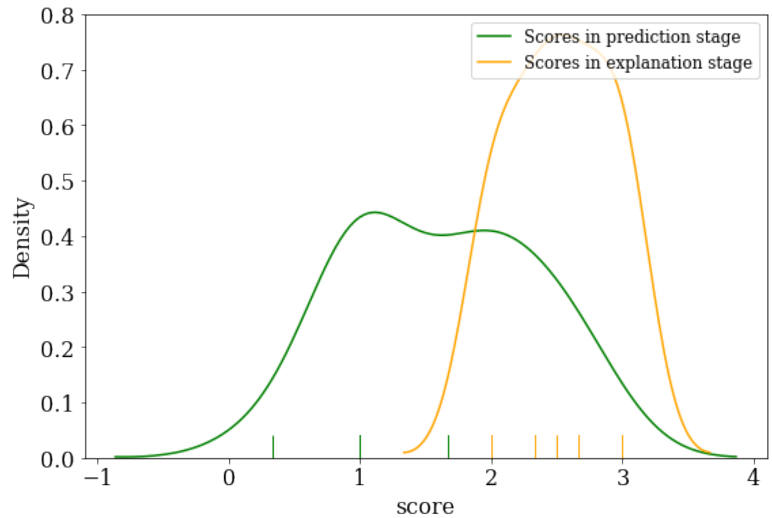


Figure 7 The distributions of students' knowledge of the heat radiation in prediction and explanation stages

Focusing on the group in which visual artifacts were used to support the reasoning processes, Figure 7 presents the distributions of the evaluation scores in the prediction and explanation stages, respectively. It is obvious that in the prediction stage, students had a relatively lower understanding level of the heat radiation phenomenon (*M*=1.619, *SD*= 0.677) compared with the scores in the explanation stage (*M*=2.524, *SD*=0.375). Moreover, the shrunk standard deviation (0.375 vs 0.677) in the explanation stage compared with that of the prediction stage also explains the effectiveness of visual representations in improving students' understanding of heat radiation.

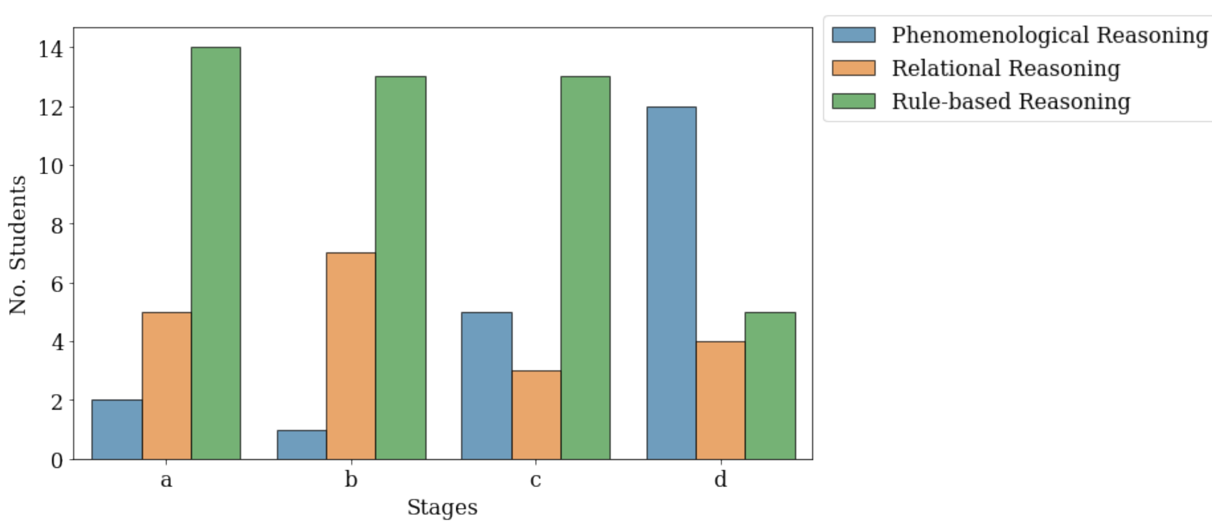


Figure 8 The distributions of student argumentation quality across different stages

In Figure 8, we present the distributions of student reasoning quality at different stages of the experiment: (a) paper placed facing to the jar at 1 inch away; (b) paper placed facing to the jar at 2 inches away; (c) paper placed facing sideways to the jar at 1 inch away; and (d) paper placed facing sideways to the jar at 2 inches away. From the figure, it can be found that Rule-based Reasoning predominates in the first three stages in comparison with Phenomenological Reasoning, and Relational Reasoning, while Phenomenological Reasoning stands out in the last stage. This is in part due to the changes in the visual features, in the first three stages, which are easier to be observed and captured because of the positions of the paper to the jar. Students, presented with the visual process showing details of every aspect in the dynamic processes of heat radiation, are more likely to refer to the learned rules or theories to explain what has been observed. In contrast, in the last stage in which without much visual process presented, it is difficult for students to connect what has been observed to a higher theoretical level, especially with the potential absence of the key information to the sense-making process.

Apart from this, we also conducted a Pearson Correlation analysis to examine whether there is a correlation between students' reasoning quality and the magnitude of knowledge gains for those students who used IR images to support their reasoning processes. The analytical results indicated that students' reasoning quality has a strong correlation with the magnitude of their knowledge gain in heat radiation (r (19) =0.767, p<0.010).

Table 3. The influences of the image feature difference across stages on reasoning quality

Stages	Df	Sum Sq	Mean Sq	F Value	Pr(>F)
Within facing and alongside the jar					
Feature differences when paper placed facing to the Jar					
Differences between the orange area	1	2.132	2.132	5.780	0.027*
Residuals	19	7.010	0.369		
Differences between white area	1	2.236	2.236	6.151	0.023*
Residuals	19	6.907	0.364		
Differences between contrast	1	1.206	1.206	2.886	0.106
Residuals	19	7.937	0.418		
Feature differences when paper placed facing sideways to the jar					
Differences between the orange area	1	0.029	0.029	0.060	0.808
Residuals	19	9.114	0.480		
Differences between white area	1	0.119	0.119	0.251	0.622
Residuals	19	9.024	0.475		
Differences between contrast	1	1.570	1.570	3.938	0.062
Residuals	19	7.573	0.399		
Across facing and alongside the jar					
Features differences when paper placed 1 inch away from the jar					
Differences between the orange area	1	0.777	0.777	1.764	0.200
Residuals	19	8.366	0.440		

Differences between white area	1	0.153	0.154	0.324	0.576
Residuals	19	8.989	0.473		
Differences between contrast	1	0.614	0.614	1.367	0.257
Residuals	19	8.529	0.449		
Features differences when paper placed 2 inches away from the jar					
Differences between the orange area	1	2.117	2.117	5.723	0.027*
Residuals	19	7.026	0.370		
Differences between white area	1	3.227	3.227	10.36	0.005**
Residuals	19	5.916	0.311		
Differences between contrast	1	1.851	1.852	4.825	0.041*
Residuals	19	7.291	0.384		

The image features such as the area of the orange region, the area of the white region, and the image contrasts were extracted and quantified using the implemented image segmentation algorithms. Considering that students' descriptions about the heat radiation phenomenon were made based on the comparisons of the IR images from different stages, in this section, we employed ANOVA analysis to investigate how the differences in image features across different stages correlate with students' reasoning quality (see Table 3). From the table, it can be found that when the paper is facing to the jar, the area differences between at 1 inch away and 2 inches away from the jar in terms of the orange regions (F (1,19) =5.780, p<0.050) and white regions (F (1,19) =6.151, p<0.050) both had a significant influence on students' reasoning quality. However, the differences in the image contrast did not show a significant influence on students' reasoning quality. Interestingly, none of these features presented a significant influence on reasoning quality when the paper is placed facing sideways to the jar. Examining the differences of image features under the condition that the paper is placed at a certain distance from the jar, it can be found that the feature differences at 1 inch away from the jar did not have a significant influence on reasoning quality. While the paper is placed at 2 inches away from the jar, significant influences on students' reasoning quality were found in terms of the differences in orange areas (F (1,19) =5.723, p<0.050), white areas (F (1,19) =10.360, p<0.050), and image contrasts (F (1,19) =4.825, p<0.050).

5 Discussion

Our study investigated the process that students explore the heat radiation phenomenon using IR cameras, with a particular focus on how students use the generated IR images to support their reasoning processes and gain knowledge about the phenomenon. We explicitly examined how students made sense of the heat radiation through investigating the image features students used to support their argumentations about the phenomenon. We found that the involvement degree of image features (i.e., the distributions of colors) in argumentations has significant correlations to students' knowledge gains. These findings suggest potential benefits of leveraging visual artifacts to support science education, especially in terms of teaching abstract concepts while designing curriculums and instructional strategies. Taken together, visual representations can be an approach to support students in seeking clarification, developing understanding, and building connections between phenomena and rules as well as increasing students' competence in science.

In line with Bohrmann-Linde and Kleefeld, (2019), our findings confirmed that the visual representations of the abstract phenomenon have the potential to reduce students' cognitive loads and further to encourage them to produce more detailed and concrete descriptions about the process. The color distributions on the IR images make it easier for students to understand the invisible heat radiation procedure by allowing them to perceive the differences in the status of the paper impacted by heat. Students were also found likely to notice subtle effects of the heat radiation with the support of visual artifacts, which could drive students to generate new understandings about the phenomenon. For example, one student concluded that the temperature changes of the paper were caused by two different mechanisms: heat radiation and heat conduction. The student argued that at the very beginning the temperature on the paper was caused by the heat radiation. Then, as time goes on, the certain areas on the paper with a relatively higher temperature would conduct to the areas with a lower temperature that was less influenced by radiation. Such a view of considering the effect of heat conduction across different regions within the same paper is what most people might ignore even for the experimental designers, which might need further exploration.

Another aspect that was identified in this study is that the use of visual images is correlated with the students' reasoning quality about the phenomenon. The students who had lower quality of reasoning about the heat radiation were found to have relatively simple and superficial descriptions of the process. They treated the IR images just as static pictures and described them in a rather intuitive way without any focus. However, the students with higher reasoning quality were found more likely to describe these images from a dynamic perspective with greater details about subtle changes. Visualizations for these students have the potential to push them to explore beyond the common understandings and try additional explanations for the phenomenon. As a result of the interactions between the existing knowledge and visualizations, students would have a more comprehensive understanding of the phenomenon. This also corroborated what Gooding (2006) has argued -- the generation of new knowledge is a process involving the interactions between verbalization and visualization.

A particularly interesting finding of our study is that students favored visual information over numeric temperature values for making sense of the heat radiation phenomenon. For example, most students used the color information on the images to support their claims even though the temperature information was also provided on the images with a virtual thermometer. This is in part due to that compared with numeric values, visual information can more easily capture students' attention and contains more intuitive information that can be directly used as supportive evidence for claims. One side effect of only using visual information is that students might misinterpret the temperature information of regions with similar color information. For example, some students misinterpreted the temperature of some regions as higher than others even although with numerical temperature presenting otherwise. In light of these findings, we suggest that practices in incorporating technologies from the area of computer vision in science education, especially for designing automatic argumentation quality assessing framework, should be conducted to fully realize the potential emerging technologies in education.

6 Implications

Based on the findings from the present study, the following implications can be drawn to better support science education using emerging technologies in future instructional practices. Firstly, platforms incorporating advanced technologies for supporting students' learning process are needed. As presented in this research, IR technologies have huge potential in support of the learning of abstract heat-related concepts in science education due to the capabilities of presenting the traces of heat that are otherwise invisible. Even though multiple studies have been conducted to highlight the importance of IR technologies in facilitating the meaning-making processes, no such study that attempts to incorporate automatic approaches to quantify the visual evidence and investigate the roles of them in scientific argumentation from a quantitative perspective. Incorporating these technologies in a whole platform can contribute to facilitating students' learning process through automatically identifying and highlighting the critical processes and artifacts to meaning-making practices. Moreover, with such a platform, students would be focusing more on the real knowledge acquisition processes instead of spending time in exploring how wo use IR camera, which can also reduce students' cognitive load. Additionally, the recent advance in computer vision makes it feasible to implement such a learning support system focusing on the assessment of scientific argumentation in science learning. Secondly, the evidence-based reasoning abilities should be emphasized in the current curricular design for science learning. The EBR is a must-have ability for all students to make argumentations with evidence-supported and distinguish evidence from claims. As illustrated in this study, students who have a large increment in knowledge gains and more detailed descriptions about the heat radiation process are those who use IR images as evidence in their descriptions. Especially with the wide applications of advanced technologies (e.g. IR cameras) in educational settings, students have more opportunities to access the intermediate artifacts about an abstract process that is otherwise invisible.

7 Conclusion and future directions

This paper explores an approach to quantitatively investigate the role of IR imaging technologies in supporting students to make sense of the scientific phenomena during experimental laboratory activities. Particularly, this study contributes significantly to science education by extending the knowledge in the following aspects: (1) Conducting the first research about incorporating algorithms to automatically quantify image features and analyze how the features correlate with students' knowledge gains through the scientific argumentation process to provide insights on which features should be identified and highlighted to facilitate the learning process; (2) Adopting the EBR framework to assess students' understanding levels through examining how visual evidence is used in the processes of making sense of scientific phenomena. Apart from that, our study also confirms the role of IR technologies in facilitating students' meaning-making processes in science education. Although the number of participants involved in this study might be a potential limitation, the proposed analytical framework in this paper shows the potential to be easily generalized to other areas. To further extend the contributions of our study, the future research could focus on the following potential veins: (1) Developing platforms specifically for facilitating the process of learning abstract phenomena with modules that can automatically recognize, highlight, and quantify the visual evidence that is critical to the meaning-making process; (2) Exploring the transferrable instructional strategies that can foster students' EBR capabilities. With these aspects fully explored, it is hoped that science education could be more converged with a focus on obtaining scientific knowledge through engaging in argumentations from the evidence proposed by the NGSS.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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