Students' framing of laboratory exercises using infrared cameras

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Thermal science is challenging for students due to its largely imperceptible nature. Handheld infrared cameras offer a pedagogical opportunity for students to see otherwise invisible thermal phenomena. In the present study, a class of upper secondary technology students ($N = 30$) partook in four IR-camera laboratory activities, designed around the predict-observe-explain approach of White and Gunstone. The activities involved central thermal concepts that focused on heat conduction and dissipative processes such as friction and collisions. Students' interactions within each activity were videotaped and the analysis focuses on how a purposefully selected group of three students engaged with the exercises. As the basis for an interpretative study, a "thick" narrative description of the students' epistemological and conceptual framing of the exercises and how they took advantage of the disciplinary affordance of IR cameras in the thermal domain is provided. Findings include that the students largely shared their conceptual framing of the four activities, but differed among themselves in their epistemological framing, for instance, in how far they found it relevant to digress from the laboratory instructions when inquiring into thermal phenomena. In conclusion, the study unveils the disciplinary affordances of infrared cameras, in the sense of their use in providing access to knowledge about macroscopic thermal science.

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I. INTRODUCTION

Thermal science remains challenging for students [1–4]. One reason for this challenge is the fact that, in contrast to typical mechanical scenarios, it is difficult to perceive and manipulate many thermal phenomena [5]. Recent development of easy-to-use, handheld infrared cameras offers a pedagogical opportunity to address challenges for teaching and learning thermal science, by making the invisible visible.

Xie, a developer of educational technology solutions, some of which make use of IR cameras, compares IR technology to traditional thermometer measurements [6]:

> *With a thermometer you get only one data point at a time. With an IR camera, you get thousands of temperature data points at once and these data points are instantly used to create an easy-to-understand picture on the camera's screen. All you need to do is to point the camera towards the subject, just like what you do with a conventional digital camera. With a holistic image that shows the dynamic change of a temperature field, you will be able to see subtle, transient phenomena that would otherwise go unnoticed.*

In recent years, we have conducted a research program where we have designed IR-camera-based laboratory exercises implemented at different educational levels spanning from grade 4 science classes up to university thermodynamics teaching [7–10].

The purpose of the present study was to investigate and describe how a group of upper secondary students perform a set of physics laboratory exercises that involve engagement with an infrared camera. We chose a qualitative approach to analyzing the data, because we were primarily interested in how the exercises and the technology used influenced what students paid attention to in terms of what they found to be relevant in the activities and phenomena that they encountered; in other words, how the students *framed* the exercises. Accordingly, the study was conducted in response to the following research question:

How does a group of upper secondary students frame a set of IR-camera based physics laboratory exercises?

In the remainder of this section, we review previous research on students' ideas of heat-related and dissipative phenomena and the use of IR cameras in educational settings. In Sec. II, framing is introduced as an analytical framework for the study. In Sec. III, the methodology is outlined, including describing the context of the study and the data analysis approach. In Sec. IV, the results of the study are presented in the form of a "thick," narrative description of how a group of students conducts the exercises. In Sec. V, we present conclusions from the study by returning to the research question, and finally, we point to some educational implications of the findings in Sec. VI.

A. Students' ideas of the nature of heat and heat conduction

Conceptions of heat among students of different ages, and in particular concepts of heat conduction, have been the focus of considerable educational research for many decades, and are continuously revealed as being problematic.

Engel Clough and Driver [11] interviewed 12–16 year olds on their ideas of heat conduction, with questions such as, Why does a metal spoon dipped in hot water feel warmer compared to a wooden or plastic one? What are the temperatures of a metal and a plastic plate that have been left in a room overnight, and why does the metal plate feel colder? Why do the metal parts of a bicycle handlebar feel colder than the plastic parts on a frosty day? While a majority of the students could account for why the spoon feels warmer in terms of conduction of heat through the metal, this was much more challenging in relation to the cold metal plate and handlebars. Engel Clough and Driver conclude the following: "quite simply students find it difficult to think of conduction of heat when they feel cold" (p. 181). Interestingly, in accounting for why a metal spoon conducts heat so efficiently, five of the students proposed that heat concentrates on the surface but does not penetrate the metal. Overall, we tend to believe (although often misleadingly) that our sense of touch is a dependable thermometer. As a reaction to such challenges, Erickson [3] (p. 59) proposed the following:

If pupils were able to 'see' this phenomenon [that metals feel cold] in terms of a transfer of energy from their body to the object, this sort of situation would likely be less of a problem than it seems to be at present.

In interview studies among 9th graders and nonscience college students, Wiser and Kipman [12] revealed a concept of heat that conflates characteristics of the physical quantities of heat, energy, and temperature but is reminiscent of historical models of heat [13]. Students at both levels express an idea of heat as being both intensive, as it has a certain temperature and felt "hotness," and extensive, since a large hot object has a larger effect on the surroundings than a smaller one, but they "*have no concept of amount of heat in the extensive sense*" [12] (p. 2, italics in the original). In addition, Wiser and Kipman claim that "this undifferentiated concept is resistant to change: the students' concept of heat is well articulated, rich and coherent" (p. 3). In order to help students differentiate between heat and temperature, they developed computer-based laboratory exercises involving molecular models, but it still remained surprisingly difficult for grade 9 and grade 11 students to adopt a scientifically accurate view of heat in terms of energy transfer.

Building on these results, Wiser and Amin [14] argue that in learning about heat as a physical quantity, i.e., energy transfer from an object of higher temperature to an object of lower temperature, "the core stumbling block is ontological: the students' concept of heat is hotness" (p. 332). The scientific view and students' preconceptions cannot be simply reconciled, since "energy is not hot" (p. 338). In order to encourage students to take on the physics view of heat in terms of energy transfer, Wiser and Amin developed a computer simulation of conduction where energy is exchanged between a hotplate and a piece of metal by means of molecular interaction. In one of the modes of depiction, units of energy were represented as "E" letters in motion in the system, where the amount of heat was represented as the number of "E's" in transfer, and the temperature as their crowdedness. One crucial component of the teaching sequence was to promote learning of the scientific meaning of "heat" as learning another sense of the word, in addition to previously known everyday senses of the word, based on perceived hotness.

As part of the development of the knowledge integration framework, Linn and Eylon [15] report on the design of computer-assisted teaching sequences for 8th-grade thermal science. The associated teaching approach focuses on a heat-flow model, in order to explain thermal equilibrium, heat conduction, and insulation. Lewis and Linn [2] administered written tests to approximately 150 8th graders (12–14 year olds) before and after a teaching sequence on thermal science. They also interviewed 37 of the students before the course, 9 adult novices and 8 scientists (physicists and chemists) in order to assess their intuitive understanding of thermal phenomena. Before the course, the majority of the students stated, for example, that a metal plate would have a different temperature compared to a Styrofoam plate after being left in a room for some time, and that wrapping a soda can in aluminum foil is effective for keeping it cold. The posttest revealed a marked improvement in students' understanding after the course, with a focus on heat conductivities of different materials. The novice adults' intuitive understanding was found to be similar to that of the students prior to the course. Only a single novice explained that a set of objects on a tray would have the same temperature after some time, yet would feel different to the touch due to different heat conductivities. Indeed, when provided with mercury and digital thermometers, several adults questioned the measurements, as well as the accuracy and precision of the measuring apparatus.

Within the knowledge integration initiative, Clark and Jorde [16] designed a computer simulation for visualizing thermal phenomena, including temperature, heat flow, and thermal equilibrium, for 8th-grade teaching. In a test group, the computer environment was complemented with information about how objects of different materials would feel at different temperatures. For instance, simulating touching a metal table at 80 °C was presented together with a speech balloon stating, "This feels painfully hot!" Using the simulation, pupils were significantly better in explaining why objects feel the way they do and accounting for thermal equilibrium than a control group that interacted with the same environment, but without such indication. One justification for using a virtual rather than a physical laboratory environment was that pupils tended to focus heavily on small differences in temperature readings, for example, a piece of metal being 0.2 °C warmer than a piece of wood, instead of considering them as being of approximately the same temperature. Clark [17] went on to conduct a longitudinal study where he interviewed 8th-grade students on five occasions during the teaching of a thermodynamics module, and two and four years afterwards, regarding their understanding of thermal phenomena, and reported on four of the students. Building on diSessa's [18] knowledge-in-pieces framework, but in contrast to the view of Wiser and Kipman [12] that students have a robust and coherent concept of heat, Clark [17] found that the students expressed several, yet sometimes mutually contradictory, ideas in relation to heat. Ideas such as "metals feel cold" were context sensitive and experientially grounded, and at times employed in conjunction with the taught content in idiosyncratic ways. For instance, one of the students tried to reconcile the fact that metals feel cold at room temperature by developing an explanation related to the smooth surface of metal objects.

B. Students' ideas of energy transformation in dissipative processes

Students' conceptions of energy and issues around how energy should be taught at different ages have been another central theme in science education research. Duit [19] has proposed four aspects of energy to consider in teaching:

- *Energy transfer*. Energy can move from one object or location to another.
- *Energy conversion* or *transformation*. Energy can exist in different forms and transform from one form into another.
- *Energy conservation*. The first law of thermodynamics, which states that the total amount of energy remains the same, regardless of what transfers and transformations occur.
- *Energy degradation*. There is a tendency for energy to dissipate and lose value or usability in natural processes, which relates energy to the second law of thermodynamics and the increase of entropy.

Duit [19] points out further that the concept of energy conservation is counterintuitive to students, not least from the perspective of everyday life experiences, where it is interpreted as a matter of avoiding waste of energy for environmental reasons, rather than seeing energy as a constant quantity. In contrast to a common focus on energy conservation only, he suggests that energy degradation could be introduced earlier in teaching.

In order to assess the feasibility of introducing the second law of thermodynamics to younger students, Kesidou and Duit [20] performed clinical interviews with grade 10 students (age 15–16 years) on their understanding of central concepts in thermodynamics in relation to irreversible processes. In line with Wiser and Kipman [12], many of the students did not regard heat as an extensive quantity. Only a minority explained the phenomena using a particle model, and those who did struggled to coordinate it with the macroscopic level. For instance, one student conceived heat as being produced due to friction arising from molecules rubbing against each other. Intuitively, the students grasped that many of the processes they were presented with could not proceed in reverse, such as a swinging pendulum coming to rest. However, they rarely explained such phenomena in terms of a transformation of energy into thermal energy, and this included students who recognized that friction evokes a temperature increase.

Relying on Duit's [19] framework in the development of a learning progression of energy, Neumann *et al.* [21] investigated grade 6–10 students' understanding of aspects of energy through multiple-choice questions. They found that typically students first developed the idea that there are different forms or sources of energy. In a second stage, they displayed an understanding of energy transfer and transformation, but also an early understanding of energy degradation. In contrast to the findings of Kesidou and Duit [20], this was expressed as an awareness that some energy is converted into thermal energy in dissipative processes, e.g., by means of friction. Nevertheless, by grade 10, only a minority of the students had developed an understanding of energy conservation.

Within physics education research, Scherr and colleagues [22] have produced professional development activities for in-service science teachers within the Energy Project, including the enactment of physical processes as part of an "energy theater" where each participant represents one energy unit. Daane, Vokos, and Scherr [23] have studied participating teachers' discussions of processes involving energy degradation, in terms of transformation of kinetic energy into thermal energy or energy dispersal. In such processes, energy is typically perceived as losing value or becoming less useful or available, and tending to transform into thermal energy, the least useful form of energy. Daane *et al.* consider such ideas productive resources for developing an in-depth understanding of the second law of thermodynamics. Daane *et al.* [24] have further focused on subtle dissipative processes where energy transformation into thermal energy is not indicated by a perceptible sensation of warmth or measurable temperature increase. In this regard, they provide a striking example (p. 3):

> *Changes in mechanical energy of about 1 joule may be associated with easily perceptible indicators (e.g., lifting a basketball* $1/4$ m*), but if all of that energy were transformed to thermal energy, it would only increase the temperature of a typical room (50 cubic meters) by an imperceptible* 10^{-5} K *(*10^{-5} °F*).*

Other scenarios raised by the same authors are the imperceptible transformations from kinetic energy to thermal energy of a rollercoaster due to air resistance, or a pendulum that eventually comes to a stop. Without perceptible indicators, the participating teachers were prone to reject the idea of transformation from kinetic to thermal energy and failed to consider energy conservation. Some of the teachers coped with such situations by imagining exaggerated scenarios, as a type of extreme-case reasoning [25], where there would be a perceptible temperature increase, such as comparing the rollercoaster to a space shuttle reentering the atmosphere.

C. Laboratory activities in physics education: The case of infrared cameras for learning

Practical laboratory exercises have long been assumed to be an integral part of physics education. However, reviews on the topic have revealed that school laboratory exercises are often carried out without a clear learning objective, and against a background of limited empirical evidence of effects on students' learning [26,27]. Physics education research has shown that traditional teaching, in which students typically follow recipelike labs with limited opportunities for interactive engagement, is associated with low learning gains on the Force Concept Inventory test [28]. Similarly, Hofstein and Lunetta [26] argue that although school laboratory activities have the potential to support science learning, this is inhibited when students are expected to follow cookbook instructions that provide limited opportunities for minds-on reflection. In conclusion, in relation to school laboratory practices, they see a lack of

> *…teaching strategies, assessment tools, and resources that are effective in helping teachers and students to attain important learning goals that*
> - engage students with different abilities, learning styles, motivational patterns, and cultural contexts;
> - engage students in using inquiry empowering tools and strategies; and
> - engage students in justifying assertions on the basis of scientific evidence (p. 48).

In response to such laboratory challenges, infrared imaging or thermography—the technology of interest to the current study—has particular promising educational laboratory prospects for learning and teaching thermal science [29–34]. Infrared imaging is based on the phenomenon that all bodies above a temperature of 0 K emit electromagnetic radiation, the spectrum of which lies predominantly in the infrared range for objects at temperatures below 1000 K. An IR camera detects the IR radiation spectrum from different parts of the surface of solid objects or liquids. In turn, the temperature is calculated from Planck's law of blackbody radiation, modified by assumptions of the emissivity (ε) of the particular surface. The temperature of the different parts of the surface is then rendered visually as an image on a screen, where the temperature range is represented by various color-coding alternatives [30]. Easy-to-use and robust handheld IR cameras, such as the i3, E4, and C2 models from FLIR™, have been developed for professional applications, such as for detecting heat leakages from buildings. In particular, with the introduction of smartphone IR-camera accessories such as FLIR ONE™, IR imaging is becoming an increasingly viable option for application in science and technology education.

Vollmer and colleagues [29–31] have brought forth the potential of IR imaging in science and engineering education, in subjects such as thermodynamics and mechanics. Similarly, Xie and Hazzard [32,33] have used IR cameras to inspire inquiry-based approaches in physics and chemistry education, and Xie [6] has created a suite of IR experiments for educational application. Overall, IR imaging holds the promise of realizing Erickson's [3] vision, since students are able to actually see heat, not only in their mind's eye, but externally visualized.

Pendrill, Karlsteen, and Rödjegård [35] used an IR camera to measure the temperature change of the magnetic braking fins of a rollercoaster as it comes to a stop. The temperature data are used to model the deceleration of the train, which is compared to accelerometer measurements. In this way, through the use of IR cameras, students can model dissipative energy transformations that go beyond the typical transformation from potential to kinetic energy, which Daane *et al.* [24] showed to be challenging in the shared context of rollercoasters.

In terms of application of university students' interaction with IR imaging in practice, Cabello *et al.* [36] have described the use of IR cameras in a laboratory component of a thermal engineering course to help students connect theory and real thermal phenomena. In addition, Naghedolfeizi, Arora, and Glover [37] achieved impressive learning outcomes regarding the nature of laboratory work and measurements when undergraduate students measured heat exchange using IR-camera imaging and computer simulations. Similarly, in their development of open-ended inquiry-based laboratory exercises in undergraduate thermodynamics courses, Melander, Gustavsson, and Weiszflog [10] have offered students the opportunity to use IR cameras in their investigation of the function of different apparatus, such as a heat pump.

Furthermore, Atkins *et al.* [38] have developed and studied a science museum exhibit involving IR cameras. They found detailed task instructions to be inhibiting for visitors, who tended to rather deploy their own imaginative ways to use the cameras without following the provided instructions, influenced largely by their everyday experiences of thermal phenomena. Examples included taking thermal measurements as they rubbed their hands together or observing melting snow brought in from outside.

In secondary education, Cazzaniga, Gilberti, and Ludwig [39] introduced the use of IR cameras for detecting building insulation defects to a group of building surveyor students. A teaching sequence was developed with the aim to connect physics concepts to practical application of novel technology, as well as to current environmental challenges. As an outcome, the students were found to search for a wide range of explanations for heat dissipation and provided highly favorable evaluations of the activities overall. Kröger [40] has designed a series of laboratory experiments to support the learning progression of energy for grades 6–10 presented above [21]. Several of the suggested experiments involved IR cameras, including measuring the increased temperature due to friction as a block slid down a plane and the increase in temperature as a metal ball struck a felt surface following a 1.5 m drop. As mentioned, Daane *et al.* [24] found that course participants revealed challenges in accounting for such imperceptible dissipative energy transformations, and IR cameras might be of particular value in such situations. Similarly, Dexter [41] has developed a series of IR-camera experiments designed to expose the three mechanisms of heat transfer: conduction, convection, and radiation. Twelve pupils in grades 6 and 7 were invited to carry out the experiments where they analyzed the generated IR imagery and time series graphs of the temperature of the observed objects, including an aluminum bar, the end of which was placed in contact with boiling water. In her evaluation of the technology for educational purposes, Dexter highlights the opportunity to see heat in real time and the user-friendliness as clear advantages of applying the technology, although the high financial cost of the equipment was viewed as the main drawback for implementation in schools.

Meiringer [42] interviewed students of different ages in relation to IR-camera images, in order to study their conceptions of the technology and radiation as a phenomenon. He found that the students struggled to understand the functionality of the IR cameras. It was particularly challenging to grasp the temperature scale. In turn, this may have led to students' subsequent expression of IR radiation misconceptions. Nevertheless, Neumann [43] also sees significant opportunities in using IR cameras for students to come to terms with such misconceptions.

As part of our own research, we have conducted a small-scale qualitative study where eight 7th graders carried out predict-observe-explain (POE) [44] experiments involving a sheet-metal knife and a piece of wood, which had been left in the classroom for some time [9]. Using the POE approach, students are first asked to predict the outcome of an event, typically a laboratory exercise or a demonstration. All students are encouraged to express what they think will happen, and differing views are pointed out and discussed. Next, students are asked to observe as the event unfolds. Finally, students are encouraged to explain the outcome of the event and reconcile what they experienced with their predictions. In the aforementioned study, students were first asked to touch and predict the temperature of the objects, and then asked to maintain contact with the objects with their thumbs for 2 min and simultaneously measure the temperature with an IR camera or digital thermometer, or analyze static IR images of the scenario. The students experienced an emotionally charged cognitive conflict [45], as the metal felt colder than the wood in spite of their measurements showing both the objects to be the same as the room temperature. The pupils did not manage to resolve this conflict throughout their engagement with the experiments, which was potentially attributed to the lack of a model of heat flow, which could have been used to explain their perceptions.

Subsequently, we conducted a 3-day design study on thermal science in two 4th-grade classes, involving full class presentations of thermal phenomena, and small-group laboratory exercises with IR cameras [8]. Based on the experience with the 7th graders, the intervention was modified to include the explicit introduction of a heat-flow model [15]. The laboratory exercises involved studying the following scenarios with IR cameras: holding a metal and wooden object; placing one hand in warm water, and the other in cold water, and then placing both simultaneously in tepid water, and experiencing the difference in perceived warmth; and pouring hot water into a ceramic mug and a thin plastic cup. Overall, considering their young age, the pupils adopted the technology and the heat-flow model in an impressive manner. In particular, our study of one group's interaction with the cup exercise revealed a sustained focus on observing the cups first getting warm and then cooling down, expressed as heat coming out of the cups [8]. In observing the scenario, the pupils also took compelling initiative in conducting spontaneous investigations, such as using the IR camera to observe what happened when they blew on the water surface or placed a pencil in the water. These events were interpreted as cases of *instant inquiry*, i.e., pupils acting immediately upon "what-if" questions driven by their genuine curiosity. Interestingly, as a reaction to such initiatives, there was some initial disagreement among the pupils as to whether or not such spontaneously emerging investigations were relevant to the task at hand.

II. FRAMING AS AN ANALYTICAL FRAMEWORK

Framing involves the process of interpreting something specific—be it an action or an utterance—against the background of a more general understanding of what is occurring, or simply put, our interpretation of "What is it that's going on here?" [46] (p. 8). Tannen [47] relates framing to our expectations of what will or might occur in a particular situation, which, in turn, influences what we notice, and our decisions and actions in relation to what we notice. Furthermore, framing occurs at many levels, including determining the overall setting as well as the interpretation of individual events enacted within it. Consequently, individuals with different personal experiences and cultural backgrounds are likely to frame situations they are confronted with in different ways, which may lead to a mismatch in what they notice and how it is interpreted. As an example, young women from the U.S. and Greece were asked to watch a 6-min short movie, which involved (among other events) a man walking in a countryside setting with a goat by his side. The participants were instructed to explain what they observed in the movie. Here, at an overall level, framing involves the situation of telling somebody about a film you have seen. At a lower level, there is the interpretation of what actually happens in the movie. For instance, American subjects commented that there was a goat walking beside a man. In contrast, most Greek subjects did not mention the goat. While the goat pops out as something unexpected to the Americans, it is not noteworthy for the Greeks; to the latter, it is merely part of the frame of an archetypical rural setting: They do not perceive the goat. Another remarkable example of how the framing of a situation affects interpretation is provided in an experiment by Simons and Chabris [48], where subjects are asked to count how many times a group of basketball players pass a ball between them. Given the instruction to focus on this cognitively demanding task, many subjects fail to see a person clad as a gorilla slowly walking directly through the group. This is deemed a case of *inattentional blindness*.

Building largely on Tannen [47], Redish, Hammer, and colleagues [49–52] have adopted the idea of framing as an interpretative perspective in physics education research. Hammer *et al.* [49] regard "framing as the activation of a locally coherent set of resources, where by 'locally coherent' we mean that in the moment at hand the activations are mutually consistent and reinforcing" (p. 99). They take a particular interest in students' *epistemological framing*, in the sense of what kind of knowledge is seen as relevant to draw on in a given situation. An example of a case where the epistemological framing is an obstacle to a student's learning process is provided by Lising and Elby [53]. They describe a student who struggles to connect taught content to out-of-school experiences, when conducting physics exercises on electric fields and geometrical optics. The student's epistemological framing "places a barrier between formal and everyday reasoning" (p. 376), so that potentially powerful resources are left unused. Redish [51] describes epistemological framing as providing a control structure for choosing relevant knowledge in a particular situation. He further introduces the notion of *messages* to describe individuals' sensitivity to external input in their framing. Such messages can be either overt, as in the example of receiving explicit oral or written instructions, or covert, as in a teacher's unstated expectations of how students should behave.

van de Sande and Greeno [54] have analyzed the process of participants' establishment of mutual understanding in whole-class or small-group problem solving, through an extension of the framing perspective put forward by Hammer *et al.* [49]. They argue that such mutual understanding depends on coming to share not only the epistemological framing of the situation, but also taking into account the *positional framing*, e.g., whether the participants are "listeners" or "sources" of information, and their *conceptual framing*. In this respect, conceptual framing "refers to different structures of information, including what is foregrounded (the central focus of attention) and how components of the situation are understood to be related to each other" (p. 40). It should be noted that when something is foregrounded, other things are deemed less interesting and placed in the background, contributing the frame of the main motif. Through a reanalysis of data from Roschelle [55], van de Sande and Greeno show how a pair of students come to adjust their understanding of how acceleration vectors relate to velocity vectors by means of a change of conceptual frame, although the epistemological frame is shared and remains unchanged throughout the exercise. In our view, epistemological framing concerns *what kind of knowledge* is seen to be relevant in a certain situation, while conceptual framing concerns *what knowledge* is relevant. In this respect, another example of conceptual framing is provided by Chi, Feltovich, and Glaser [56], in their study of how experts tend to categorize mechanics problems by which problem-solving approach is suitable, by considering energy conservation, or Newton's second law, respectively. There is no doubt that the experts have the required knowledge for both approaches; it is rather a matter of knowing what approach is relevant for a particular problem.

The study by Atkins *et al.* [38] on an everyday-experience-grounded engagement with an IR-camera exhibit at a science museum (with or without instructions) provides an interesting case of framing. They conclude that when explicit instructions were provided, visitors framed the situation as a traditional school-like lesson, where one adult—often the mother—takes on the role of a teacher; there is no natural role for other adults in the dialogue, or room for initiatives deemed irrelevant as "off task." In contrast, with no instructions

> *…visitors interpret the exhibit as a tool: a sophisticated, aesthetically intriguing thermometer. In solving the question of framing ("what is going on here?") visitors answer: collect and create things to measure with this thermometer. Indeed, interactions at the heat camera were largely concerned with devising interesting patterns of heat to view—including using friction, water, bubbles, breath, and going outside to change the temperature of the body. In this scenario, all visitors have a role and share their ideas and what they are doing and noticing. A premium is placed on creative ways of manipulating temperature, and these are shared enthusiastically with and mimicked by other members of the group (pp. 169, 170).*

Our previous research on students' use of IR cameras in laboratory settings could be reinterpreted from the point of view of framing. In the study of the 7th graders [9], participants' conceptual framing involved seeing the physical scenario as a temperature increase of the knife, rather than a case of heat conduction. In contrast, the situation of the 4th graders' interaction with the IR camera [8] clearly involved epistemological framing. Mirroring the findings by Atkins *et al.* [38], pupils negotiated relevant actions in relation to the exercise and the equipment: How far could they digress from the worksheet instruction, without losing focus on the overall objective of the task?

Finally, Gibson's [57] notion of *affordance* can be a meaningful adjunct to analyzing the influence of the conditions of a particular learning environment on students' framing of a situation. Toward what interpretations and interactions are students invited in the setting? Affordance shares the focus on an individual's sensitivity to external input with Redish's [51] use of messages, but emphasizes the interaction between the individual and the surrounding. In our case, given favorable circumstances, students may take advantage of the *disciplinary affordances* [58,59] of IR cameras, in terms of "the inherent potential of [a] representation to provide access to disciplinary knowledge" [58] (p. 658) in the thermal domain.

III. METHODOLOGY

A. Context of the investigation

The present study was conducted as part of an overall research program focusing on how IR cameras can support physics learning at different educational levels [7–10]. The study could further be characterized as drawing from the genre of design-based research [60]. In this regard, it represents a second iteration of using IR cameras in upper secondary physics. In a preceding study we designed and piloted four laboratory stations at a different upper secondary school. In our redesign we commenced by deciding to play a more passive role in relation to the students and to focus on capturing fine detail of the students' interaction. At the same time, we would emphasize and encourage them to follow the predict-observe-explain format [44] of the exercises.

The student groups, which were composed of three or four students, worked through and then rotated between four laboratory stations involving IR cameras. At each of these stations students were given an activity worksheet based on the POE approach. This involved first asking students to orally *predict* what would happen in a given physical scenario, then *observe* how the scenario actually played out, and finally *explain* what they observed happened, which included expressing and reasoning about any discrepancies that emerged between their prediction and observation.

The class was first given a brief introduction to the functionality of the IR camera technology. They were told that the cameras detect IR radiation emitted from solid and liquid surfaces and render their temperatures as a 2D image. They were also told that certain objects, such as the Sun, gases, or shiny surfaces, might give erroneous temperature readings.

At the first station, where the worksheet was titled "Friction," students were invited to investigate friction, as an example of how IR cameras could be used to visualize dissipative phenomena, which has been suggested by Vollmer and Möllmann [30]. Here, the students were asked to explore the imagery generated by the IR camera while an eraser was rubbed against a table and when one of the students walked or ran on the floor (see Fig. 1).

The second station, titled "Conservation of energy," presented a further dissipative phenomenon inspired by the design of Kröger [40]: dropping a 1 kg metal ball onto asphalt from a height of approximately 3 m. While working at this station, students were encouraged to think about what happens to the kinetic energy at the point of impact (see Fig. 2). As reported by Daane *et al.* [24], science teachers have difficulties in describing transformation into thermal energy without perceptible indicators. Here the IR camera could be used to provide such perceptible indicators to the transformation into thermal energy, which is otherwise difficult to experience in the classroom.

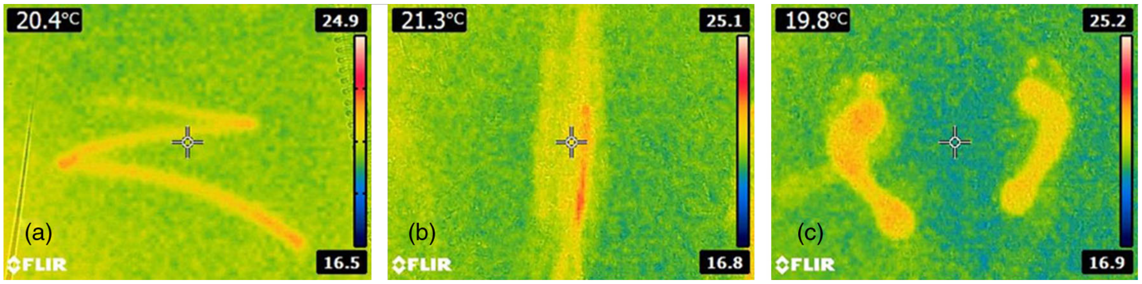

FIG. 1. (a) IR image of the temperature increase due to rubbing an eraser on a notepad, (b) IR image after a student has slid to a stop on the floor with shoes on, and (c) IR image after a person has stood on the floor with socks on.

The third station, with the headings “Objects at room temperature” and “Objects in contact with hands,” respectively, asked students to account for why metal feels cold at room temperature, which has been found to be challenging for many students [2,11]. Here, following our previous design [8,9], students were asked to predict and measure the temperature of a piece of wood, a sheet-metal knife, and a woolen beanie, which had been placed in the room for some time, and then to grasp the ends of the piece of wood and the knife, and maintain contact for about 2 min [9] (see Fig. 3).

At the final (fourth) station, titled “Two different cups” (see Fig. 4), which also followed our previous design in relation to 4th graders [8], students were asked to explore what happens when hot water is poured simultaneously into a ceramic coffee mug and a thin plastic cup.

B. Data collection and data analysis

The laboratory exercises were implemented on site at the school in a class ($N = 30$) of 11th-grade upper secondary students (age 17–18) in a technology program, prior to the thermal science unit of the physics course. The students were divided into groups of three or four, and the data collection process closely followed six of the eight groups of students through video and audio recordings of the groups performing the tasks at hand.

In the data analysis reported here, we focus on an illustrative group of three students (who are identified with pseudonyms), as they completed the four IR-camera station tasks, while being followed by one of the researchers (J. H.). The student dialogue at each of the four stations was transcribed verbatim in Swedish and the analysis was performed based on the Swedish transcript. For the purpose of presenting the results, relevant excerpts have been translated into English. The group was selected through purposive sampling [61], based on their high level of engagement with the exercises and what we interpreted as insightful lines of reasoning in relation to the physics content. In addition, the students’ different approaches to the tasks and the implicit roles in the group dynamic that

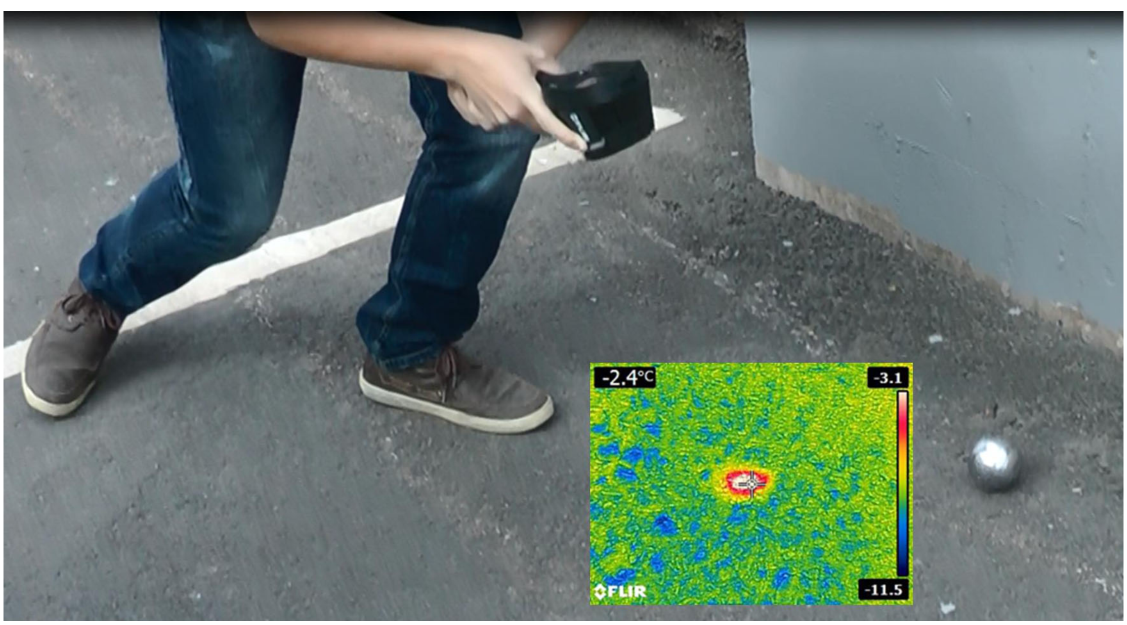

FIG. 2. A student using an IR camera to observe the point of impact immediately following dropping a steel ball onto asphalt, with an inset displaying the corresponding IR camera image of the impact surface.

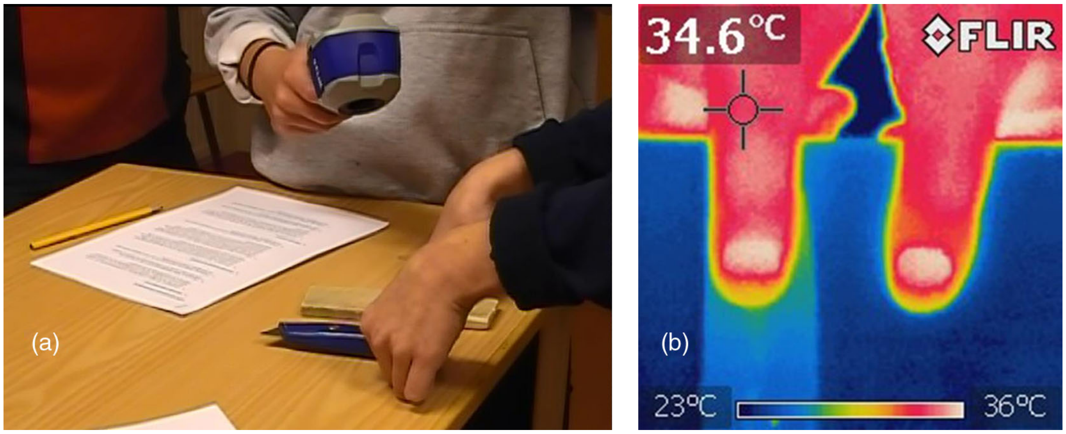

FIG. 3. (a) Photo of a student holding her thumbs to a sheet-metal knife and a piece of wood, while her lab partner observes the thermal contact with an IR camera. (b) IR image of the student's respective thumbs after having been in contact with a sheet-metal knife and a piece of wood for approximately 2 min.

led to negotiations of what was seen as relevant actions provided another aspect of the data set. Here, we focused on identifying "the most salient video chunks that best illustrate and represent one day or month of data collection" [62] (p. 12), as the grounding for developing a rich narrative account of the students' interactions. To generate a detailed and systematic account of the dialogue in the selected excerpts, we created a "thick description" [63]. In this regard, we explicitly focused on fine distinctions in meaning-related conceptual understanding.

The qualitative analysis was conducted in a collaborative fashion, where all of the researchers contributed with layers of interpretation. The data comprising the episodes, and their interpretation, were discussed multiple times. In this manner, emphasis was on pursuing trustworthiness in our collective interpretation of the data, and the inferences drawn from them [64]. In particular, we adopted an approach to qualitative analysis that is similar to that of Scherr and colleagues [24,65] in closely studying videos of the interaction of participants' engagement in small-group exercises. This interaction is presented in the form of rather extensive dialogue excerpts, in order for the reader to be able to follow the participants' utterances and actions, interleaved with our interpretations of what is occurring, in turn forming a chronological narrative account of the unfolding events.

The narrative account was structured from the point of view of the students' framing of the situation, the adopted analytical framework of this study. In line with Tannen [47], we investigated unfolding situations at different levels of interaction and interpretation of the group within the task context. In this respect, we took particular analytical interest in how the participants framed the events at the following levels:

- At the overall level of *epistemological framing* [49,51], what kinds of knowledge and actions did the students find relevant in relation to the exercises? Would a digression within the topic of thermal

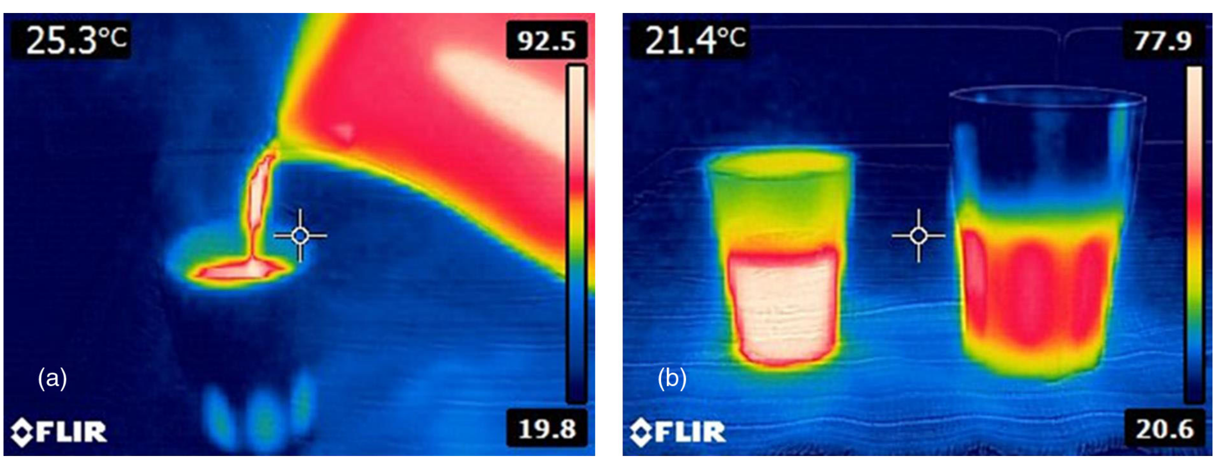

FIG. 4. (a) IR image of hot water being poured into a ceramic cup. (b) IR image of hot water contained in a thin plastic cup and a ceramic mug.

science, but not included explicitly worded on the worksheet, be considered as relevant to pursue or not? In addition, what were the students' criteria for an acceptable explanation of a phenomenon?
- Within each exercise, what were the students' *conceptual framing* [54] of the studied phenomena? In particular, How were the students cued by overt messages [51] in the form of particular statements on the worksheet or from the researchers regarding what to attend to? What disciplinary affordances [58] were associated with the IR camera? What aspects of the studied phenomena did the students place in the foreground or background, respectively? If students do not draw on a seemingly relevant scientific concept in a particular situation, is it a matter of lacking conceptual understanding in general or a failure to see the relevance of the concept in these circumstances?

IV RESULTS AND DISCUSSION

The group of students' interactions within the four laboratory stations are presented in the chronological order in which the group was exposed to them. The choice of chronological presentation places emphasis on describing the participants' changes in framing as they approached new tasks and charts how tensions built up between them as the exercises unfolded.

A. The friction station: "What is it that generates the heat?"

The three students commenced their rotation by first visiting the friction station. In this activity, the students were instructed to predict, observe, and explain what it would look like on the IR-camera display when an eraser is rubbed against a table, and when they walk at constant speed or accelerate on the floor. After reading the instructions, they start discussing the scenarios and make predictions:

Felix: I think the eraser will heat up the table.
Hjalmar: Yes.
Kalle: If you think…
Felix: …and the shoes will heat up the floor.
Kalle: …when you rub the eraser repeatedly, it gets warmer.
Hjalmar: Yes
Kalle: At least after a while. So there you can draw a conclusion, what it will be like. /…/
Hjalmar: If you like lift your feet, you shouldn't… leave so much heat.
Kalle: No, it's gravity, not friction. If they are still on the floor, and then you lift them… Then, when they slide, there will be… there will be, like…
Hjalmar: …run, and you will slide more…
Kalle: Yes. Then more pressure will be applied, like a friction.
Hjalmar: Yes.
Kalle: There will be a friction force against… that will counteract the motion forwards… but maybe not so much that there will be a temperature change.

They make the reasonable prediction that when an eraser is rubbed against the table, the table will be heated up, and thereby get warmer. In turn, they predict that there will be no temperature increase when they walk on the floor with their shoes on, since there is not enough friction (seemingly ignoring static friction). However, if they slide or drag their feet, there might be a temperature increase.

After having made their predictions, Felix picks up the IR camera:

Felix: The table is 18 [degrees C] Who's going to rub the eraser, then? [looks at Hjalmar, who picks up the eraser] /…/
Hjalmar: Can you see this? [rubs the eraser quickly against the table]
Felix: Yes, yes. It… [Hjalmar rubs the eraser slower with even pressure repeatedly, and Felix observes the screen of the IR camera] Yes, it left tracks behind, which disappear quite quickly. /…/ It leaves a track at like 22 degrees…

They observe that the eraser generates tracks on the table that are visible with the IR camera, which represent a temperature increase and are explained as being due to friction.

Next, they turn to studying what is shown on the display when Kalle walks on the floor with his shoes on:

Felix: Just walk a bit at pretty even pace. That way. [Felix points along the hall. Kalle starts to walk and Felix observes the IR camera display] No, as far I could see, there were no marks. /…/ Try to drag your feet a bit. [Kalle drags his feet on the floor].
Hjalmar: [Looks on the IR-camera display] There is some.
Felix: There's a tiny light blue track… almost no difference at all.
Kalle: There doesn't seem to be so much friction, when you walk…

When Kalle walks with his shoes on at a slow pace, nothing noteworthy is observed on the IR camera display. However, when Felix encourages Kalle to drag his feet behind, he observes some tracks, but they are faint blue. Again, they attribute this effect to there not being much friction involved.

J. H. encourages Kalle to accelerate his walking speed across the floor, to see whether that generates a more distinct temperature increase. At the same time, Felix attends to the idea of acceleration, but in the context of rubbing the eraser across the table:

> *Felix: [rubs the eraser swiftly across the table and looks at the IR-camera screen] It gets warmer, the quicker you rub.*
> *Kalle: Yes, that seems logical.*
> *Felix: But, I mean… if you rub it like this [rubs the eraser] and then faster, then… [rubs faster] it gets… the warm stuff [66] stays longer…*
> *Kalle: Friction… /…/ there is more friction, resisting… / …/*
> *Felix: [notices the spot on the table where the eraser was lying] And there's like a warm mark where the eraser was lying [moves the eraser to another spot] /…/ There's like a mark where the eraser was lying before [laughs and picks it up again] There's a mark where it was lying this time too!*

Felix reacts by enacting a scenario with the eraser on the table, which, interestingly, is used as a kind of application model for Kalle's acceleration on the floor. Felix concludes that the faster he rubs, the longer the generated IR image due to increased temperature remains on the table surface. In this way, Felix notices and acts upon the parallel between the two contexts with a focus on friction as a phenomenon. As he experiments with the eraser, Felix also notices that after it has been heated up, the eraser leaves marks on the table when he picks it up even without rubbing. This fascinates him, but he does not explain what causes these heat marks by means of contact, and continues with the exercise. One question that arises is, why does Felix not attend more to these heat marks? In our interpretation, he is likely to be familiar with the idea that heat may be conducted from a warmer to a colder object. Instead, Felix is heavily influenced by the task worksheet underpinning the station, which is titled with the heading "Friction." The worksheet communicates that the group should explicitly focus on temperature changes due to friction. Therefore, although Felix notices that heat is conducted from the eraser to the table when they are merely in contact, this does not prompt him to take further action. Heat conduction is framed out of what he sees as relevant concepts for the task. It should be noted, however, that J. H. does not comment on this digression from the instructions in the worksheet.

After Kalle walks and runs, he slides to a halt, which delivers more clearly contrasting IR images due to temperature increases. Felix repeats Kalle's motion, but with his feet clad in socks:

> *Kalle: [Looks at the IR-camera display, as Felix drags his feet on the floor in his socks and slides to a stop] Yes, it turns a bit light blue. /…/ [Felix repeats the motion by running and then braking again]*
> *Kalle: Yes. Yes, there's friction…*

Here, they vary the experiment, by having Felix run with his socks on. He drags his feet and comes to a stop, and Kalle observes light blue streaks on the IR-camera display, which they explain as a case of friction. Since there is less friction against the floor with socks than shoes, the IR image contrasts are less prominent. However, intriguingly, they do not consider the heat conduction between their feet and the floor surface, which in the case of bare feet ought to generate a visible temperature increase, in addition to that already resulting from friction (see Fig. 1).

The group turns to explaining the scenarios:

> *Kalle: Well, the eraser… bits come off it during the time… it can be that it radiates heat, or something…*
> *Felix: Well, it leaves small heated parts of itself… maybe they give more reading than the friction itself…?*
> *Kalle: That's a possibility.*
> *Hjalmar: There is very high friction against the surface here, as well [refers to the eraser].*
> *Kalle: Yes.*
> *Hjalmar: …but not the feet. /…/ The feet do not have that much friction… you walk… there was more [friction] when you started… when you really got going…*
> *Kalle: …acceleration… a counteracting force…*
> *Hjalmar: And then, when you were about to brake…*

Kalle and Felix entertain the idea that the increased temperature when the eraser is rubbed against the table is due to small bits of the eraser that come off, but they return to their earlier explanation that the phenomenon is due to friction, in terms of a force that counteracts motion. However, Kalle is not satisfied with this line of argument, and seeks a more fundamental underlying explanation, a mechanism of the heat generation:

> *Kalle: But, I mean, what is the connection to heat? The force, and that?*
> *Hjalmar: What do you mean now?*
> *Kalle: That it generates heat… but what is it that generates the heat?*
> *Hjalmar: The friction. What do you mean?*
> *Kalle: Well, but I mean, I thought more like… the heat has to come from somewhere… is it the floor that radiates heat…? Or is the heat created, or…?*
> *Felix: Well, isn't it more… when they're rubbed against each other [gestures motion of objects against each other] it like… stirs up [gestures whirling motion] atom… cell things, that you're made up of. [laughs]*
> *Kalle: Yes, but isn't it so that the heat is created when there is friction.*
> *Felix: Yes, and that is like, I mean… they get into disorder [gestures whirling] and move about and create heat… angry…*
> *Kalle: They move about more… so it's… maybe you could say that the friction moves the atoms, which get into motion…*

Felix: But it also creates heat… /…/
Kalle: From the other [refers to the walking activity], it created… or the motion energy created heat energy, right… that seems logically summed up… /…/ with soles, other than like wool or something… wool does not have the same friction, whereas this [slides with his shoes on] I had to lift my feet when I slid and slowed down.

During this line of reasoning, Kalle wishes to establish the nature of the connection between friction and heat generation. Has the heat, as he says (possibly influenced by the interaction with the IR camera), radiated from the floor, or is it created there and then in some way? Here, Felix offers a microscopic explanation, in that the interaction due to friction causes atoms to move about in a disorderly manner, which in turn creates the heat. However, using this reasoning he seems to regard the generated heat as separate from the motion of the atoms: "But it also creates heat." In response, Kalle introduces the notion of energy in explaining that "motion energy" creates "heat energy" through friction, which in our view contains the core understanding of dissipative phenomena.

After the group provides explanations of the observed phenomena, they proceed outdoors toward the next task station. While outside, Felix takes an interesting initiative and directs the IR camera toward a passing vehicle on the street adjacent to the school building:

Felix: Check out the car /…/
Kalle: [Directs the IR camera to the vehicle's tires] Well, there wasn't so much friction on that one… it has like good grip… there was some when it accelerated… / …/ …after the turn. It got a bit… er, greener then… on this scale.

This episode may be characterized as a case of instant inquiry [8]. Felix and Kalle wonder how the tires would appear in the IR camera, and they spontaneously direct the camera to the intended object and receive instant feedback to their question. They observe a temperature increase when the vehicle accelerates, but not when it travels at constant speed, which Kalle explains as due to the low frictional force and the effective grip between the tires and the asphalt (in which he again ignores the influence of static friction).

The group's conceptual framing of the exercise is heavily influenced by the "Friction" heading of the worksheet, which provides an overt message [51] of what to remain focused on. It is striking how one word can influence what the group notices and what they choose to act upon. In an impressive way, they enact and vary instances of friction between the eraser and their feet, and between the different surfaces, and notice various similarities and differences. They also retain and place their interest in friction in the foreground after they have departed from the station, by exploring the temperature change of a vehicle's tires as it accelerates; this demonstrates the strength of their conceptual framing, also when extended to an everyday context outside of the classroom. On the other hand, with the sustained focus on friction as a phenomenon, other aspects are placed in the background. In particular, Felix briefly notices that the warmed up eraser leaves heat marks on the table, without the active generation of friction. This would have been an interesting opportunity to start thinking about heat conduction due to temperature differences. Similarly, when Felix starts to walk on the floor with his socks on, there ought to have been marks from his feet visible with the IR camera, due to heat conduction, but the group did not search for or notice them. This may be seen as an example of inattentional blindness [48], once again largely due to the students' conceptual framing of the task.

While the students largely share their conceptual framing of the exercise, their relative epistemological framings differ somewhat. Kalle is unsatisfied with stating that friction is associated with temperature increases, but wants to establish their causal relation as an underlying explanation. During this search, in turn, Felix and Kalle engage a microscopic understanding of the phenomena at hand, which involves particulate motion. Using Redish's [51] interpretation of epistemological framing as providing a control function of what resources to engage, we see that the students' ideas of what characterizes a satisfactory explanation also influences what conceptual knowledge they bring into play. In addition, Felix's initiative to model walking on the floor with the eraser and to measure the accelerating car's tires shows his willingness to go beyond the immediate instructions, which, as we will see, causes tension in the group during the subsequent exercises.

B. The collision station: "The kinetic energy has to go somewhere; I guess it turns to heat"

At the next outdoor station, the group starts making predictions about what will happen when a 1 kg steel ball is dropped onto an asphalt surface, from a height of about 3 m.

Kalle: What's our hypothesis?
Felix: It will get warm when it hits the ground.
Kalle: But wait… We've got… We are going to drop it from about 3 meters. [Consults the worksheet] "the ball's kinetic" …force… Well, it will probably dent the ground… and possibly… I mean… when you drop something, there may be sparks… you can make an example… even if it isn't exactly this situation… but some heat may be created…
Hjalmar: Well, then [when there are sparks] it gets really warm. /…/ …at least warmer when it's dropped.
Kalle: I don't think it gets really warm. /…/ A bit warmer.

All members of the group make the prediction that the asphalt will get warmer at the point of impact with the steel ball. Kalle reminisces that there might be sparks when some objects are dropped to the ground, a kind of extreme-case reasoning [25] in this context, but he does not think that this would apply in the present scenario. He concludes that the ground will not become much warmer.

Felix climbs up onto a low brick wall and drops the ball, while Kalle uses the IR camera to measure the temperature at the point of impact of the ball with the asphalt. The group deploys a few "trial drops" to coordinate their actions and observations. Felix drops the ball and Kalle points the camera to the point of impact from a distance of about 2 m. He expresses his observation of a clear temperature increase:

Kalle: Well, it gets… it gets a lot warmer.
Felix: Is it clear… the reading, or…?
Kalle: Yes, from like yellow green… it turns… white at the center… and then red…
JH: You can… the crosshair… you get the temperature out to the left there [points at the screen]
Kalle: Yes… I got about 26 degrees… but, I mean, the color… I think… to hit that small area…

They switch roles, and Kalle climbs up onto the wall, while Felix holds the IR camera. Kalle drops the ball, and Felix directs and positions the camera close to the point of impact:

Kalle: Do you see…? It's very warm there.
Felix: About 32 degrees! [laughs and gives the ball to Kalle]
Kalle: Hjalmar, you could try what it feels like with the fingers… I mean, the heat, and that… [Hjalmar shrugs and does not seem to accept the idea] Well, I mean… More sources, like, more confident… not that this one is wrong [refers to the IR camera] probably isn't wrong… [drops the ball again, and Felix closes in to measure quickly]
Felix: Where is it? [looks on the screen and places his finger on the mark and beside it on the asphalt] Well, it gets a bit warm… then again, you don't feel very much…
Kalle: The kinetic energy is transferred… is stopped… and then transferred… transformed into thermo… energy, or something, I guess…

Felix and Kalle think that it is a good idea to compare the IR-camera readings with what it feels like to the touch at the point of impact, as a kind of triangulation of methods. Hjalmar does not entertain the idea, but Felix carries out the comparison. The pattern remains of Felix, and to a certain degree Kalle, being happy to partially deviate from the worksheet instructions, although arguably always with trajectories relevant to the overall objective of focusing on thermal phenomena. In contrast, Hjalmar prefers to stick within the bounds of the provided instructions. Kalle starts to explain the scenario in terms of transformation of the kinetic energy at the point of impact, in line with the worded title and instructions in the worksheet.

They continue dropping the steel ball:

Kalle: [Drops the ball again and Felix observes with the IR camera] Do you see anything?
Felix: That's kind of interesting! The same second that… it was like, well… gray yellow on the ground…
Kalle: Okay…
Felix: The same second that the ball hit the ground, it turned red everywhere.
Kalle: Everywhere…?
Felix: Yes. And it turned white where the ball hit.
Kalle: So, this means… the thermo energy gets spread out over an area…
Felix: I would say that, yes.
JH: It can depend on its recalibration when new objects enter the picture.
Felix: Yes, I guess… because, I mean… as soon as it hit the ground, it just… it flashed… [gestures outwards movement] and everything turned red.
JH: So it can depend on the ball having another temperature.
Kalle: Yes…

In this episode, Felix has difficulties coping with rapid color changes on the IR camera screen, which J. H. attributes to recalibrations of the temperature scale. In contrast to Meiringer [42], however, who found that students often had difficulties interpreting static IR images, this is one of the few occasions where the participants in the present study struggle to interpret the imagery delivered on the IR-camera screen. One possible explanation of the otherwise relative ease of interpretation at large is that the real-time, dynamic rendering of the IR images helps students understand the images and the corresponding experienced phenomena simultaneously.

After they have dropped the ball a number of times, J. H. asks the group to explain the observed phenomenon:

Hjalmar: It [the ball's energy] has to go somewhere. I guess it turns to heat, when there isn't much…
Kalle: Yes, but if you think about it… There are different types of energy… this was like kinetic… potential… and heat, which are pretty common. /…/ And when there's kinetic and potential… there is maybe heat energy as an alternative…
Felix: Well, heat is… heat is like… in principle… if you look at everything… always an alternative… I guess that's why it turns into heat… there is no… it cannot become electricity, because there is nothing to gather electricity… there is nothing that will turn it into electricity…
Kalle: Technically, electricity doesn't have to… well some, but there could be sparks… it isn't gathered by something…

Felix: No, but I mean… it doesn't turn into electricity…. But, on the other hand, it has to turn into something.
Kalle: Yes.
Felix: And just like you said… [refers to Hjalmar] It turns into heat, because that's easiest for it…
Kalle: Yes. And that energy cannot… like be destroyed… or created… /…/ …only reused and transformed.
Hjalmar: Yes.
Kalle: There was something about that… like the energy law…

When they provide explanations of what happens to the kinetic energy of the ball after the collision with the ground, the group makes use of energy conservation as a constraint: the energy cannot disappear, so it has to go "somewhere." Their first intuitive candidate is that it turns into heat, also referred to by the students as "thermo energy" or "heat energy." They then refute an alternative form of energy, electricity, through a process of elimination. Kalle may have associated sparks from his previous extreme-case reasoning with sparks due to collisions to the context of electricity here. Felix concludes that "it turns into heat, because that's easiest for it."

From the point of view of conceptual framing, we notice that—as opposed to the previous "Friction" station (and, as we will note in both forthcoming stations)—the group does not provide microscopic explanations of this physical scenario. Again, one possible reason is that the overt message of the "Conservation of energy" worksheet heading and the probes in the task may have invited macroscopic lines of reasoning around the inferred energy transformations. With this focus, the students are likely to be satisfied solely in identifying what other forms of energy the kinetic energy from the ball is converted into, and there is no incentive for them to probe further for microscopic mechanisms.

In addition, we notice that the students' differences in epistemological framing begin to manifest as the assumption of different roles and views on what actions to pursue. Should they, as Hjalmar advocates, stick to the constraints of the given task instructions and execute the tasks accordingly as conscientiously as possible? Or should they act upon Felix's initiatives to engage in instant inquiry? These initiatives remain within the thermal domain by virtue of the nature of the disciplinary affordances of the IR camera [58], but are nevertheless digressions from the provided tasks. Is the sense of touch a valid source of information, as a complement to the IR camera measurements? Although not a matter of explicit negotiation at this station, Hjalmar clearly demonstrates that he prefers not to take part in any irrelevant whims.

C. The wood and knife station: "It's an other-way-around machine!"

At the third station, the student group was tasked with predicting the temperature of a sheet-metal knife, a piece of wood, and a woolen beanie, which have remained in the same room for some time. They start by touching, grasping, and holding the objects:

Kalle: [Touches the piece of wood and the beanie] It feels as if the piece of wood is warmer… /…/
Hjalmar: This [takes the beanie] has to be the coldest, or what do you think…?
Kalle: It may be insulating from heat, but this [points to the piece of wood] feels warm… it felt warmer…
Hjalmar: This [the beanie] is like cold. /…/
Kalle: [Picks up the knife] After all, this feels colder. Are you…? Felix, have you touched all objects?
Felix: Yes. /…/
Kalle: [Arranges the objects from perceived "warmest" to "coldest": piece of wood, beanie, knife] Do you agree… from warm to cold…? /…/
Felix: I would rather say that this [the beanie] is the warmest, this [the piece of wood] in the middle, and that [the knife] is the coldest… I mean, honestly… /…/
Kalle: I think this [picks up the knife] is colder… and I think this [picks up the piece of wood] almost feels a bit warmer…
Hjalmar: This [touches the knife] is colder. This… [touches the beanie] don't you think this is pretty cold? This [touches the piece of wood] isn't as cold at all…

When the students predict the temperatures of the objects, and arrange them in the order of perceived temperature, they rely exclusively on touching the objects and judging how warm or cold they feel; a dense "tactile festival" ensues, if you will. They agree that the knife is the coldest, but have different views on the piece of wood and the beanie.

Next, Kalle begins to observe the objects using the IR camera:

Kalle: This one… [looks at the knife] according to this, it is about… /… / about 26 degrees… /…/ It almost went to 27 when you looked close up. [He turns to the beanie] About 23, 24… 24 degrees, on the beanie… [He looks at the piece of wood] and about… just below… 24… a bit colder than [the beanie] I think…
Felix: We had exactly the wrong order! [they all laugh]
Kalle: You can check too, if you want to… but, that's what I can see. /…/
Hjalmar: [Looks at the objects] It seems to be pretty much exactly the wrong order… that we put them in. [laughs] /…/ [Kalle picks up the knife] That one was much warmer than the other ones! /…/

Kalle: Yes, it was red. But it feels cooler, anyway. [laughter ensues]

When they observe the objects with the IR camera, they see that the knife is warmer than the other objects, in spite of it feeling colder when they made their predictions [67]. They are fascinated that their predictions were completely wrong, but remain in good spirits.

Similar to what Lewis and Linn [2] found among adults exposed to the same task, but in that case using traditional thermometers, Felix begins to question the measurements and the accuracy of the equipment:

Felix: But, it is like metal… I don't think that one [points to the knife] is so warm. I think it just reflects the lamp above.
Kalle: Yes, it's… possibly so…
Felix: Because it lies like straight under the lamp, so… that one [points to the knife] is coldest… It isn't possible that it's warmer than the other two!
Kalle: But these two [the beanie and the piece of wood] were… But, no… they were in the wrong order…
Felix: Yes, but the knife… that's a measurement error, because it…
Kalle: Yes, it's like shiny metal.

In questioning the measurements, Felix comes up with an alternative and reasonable explanation that the higher temperature reading on the metal surface of the knife is an effect caused by reflections from the ceiling light above.

J. H. encourages them to investigate the measurement of the temperature of the knife further, and suggests a way to assess the adequacy of the measurements:

JH: But you suspect that one [points to the IR camera] measures wrong… that it is mismeasured, essentially…?
Kalle: Yes.
JH: If you try to put it on the floor [points under the table] so that you protect it from the lamps… /…/ [Hjalmar places the knife under the table and measures with the IR camera] What does the knife get to?
Hjalmar: 26 point… well, about 26… so, it's still the warmest! /…/
Felix: But there are still lamps that… from angles… that can shine… /…/
Kalle: On the other hand, it could be the outside that feels cold… while the inside is warmer.
Felix: But how could the inside be warm…? /…/
Kalle: Well, it's not 26 degrees in here, shall I put it that way… It may be that it insulates against cold…
Felix: [Holds the knife] I can say so much that the blade is warmer than the outside…
Kalle: [places the knife on the table and measures it with the IR camera] Not according to this one.
Felix: No. /…/
Kalle: What is this…?
Felix: It's an other-way-around machine…

They attempt different approaches to explain the surprising measurement of the knife's temperature, but become frustrated with the task, and eventually with each other. In parallel to the findings of Engel Clough and Driver [11], they entertain the idea that the metal has different temperatures on the surface and within it.

Kalle offers a microscopic explanation for the difference between the measurements and the sensation of warm and cold, by recourse to the materials' atomic structure:

Kalle: [He holds the knife] No, it feels a bit cool… I mean…
Felix: Yes…
Kalle: …I mean, more than the wool and the wood… It could be that… every atom is more compact in that [the knife] and that you feel that … as if it is warmer… than the others… which do not radiate as much… the same amount of heat from like all atoms… just a hypothesis… well, do we have an explanation…?

Not having reached a satisfying explanation, they move on to the next worksheet task, which requires holding the respective ends of the piece of wood and the knife for 2 min:

JH: What do you think will happen then… as a prediction…?
Hjalmar: I guess the knife will… change most in heat… because if there was a fire on the knife, it would get pretty warm… but I don't think that the piece of wood… it would burn, but you would still be able to hold it.
Felix: That's because knives conduct heat better than wood. /…/
Hjalmar: …transfer… More heat is transferred in the metal…

They adequately predict that the knife will get warmer than the piece of wood when they hold them, since it conducts heat better. Hjalmar justifies his prediction by making another extreme-case comparison [25], the difference in what would happen to the objects if they were exposed to fire.

Felix picks up the knife and the piece of wood, and holds them at their ends for about 2 min, while Kalle observes the situation with the IR camera:

Kalle: This [the knife] seems to get a bit… more heat increase… the knife, anyway… er, I don't know what to say, really…
Hjalmar: What's the temperature … on the piece of wood… [points on the IR camera screen] on the green there…?
Kalle: About 24…
Hjalmar: And what's Felix's hand?

Kalle: [Looks at Felix's hand] 33. /…/
Kalle: [Looks at the knife, which is about 27 degrees] Well, this goes up. It conducts the heat better. /…/
Hjalmar: The knife has increased more [in temperature], right… than the piece of wood…?
Kalle: Yes, the knife has changed…
Hjalmar: It's about to turn red…
Kalle: It's yellow, red… but it wasn't when we started…

When performing the experiment, they confirm that the knife conducts heat better than the piece of wood.

Next, after Felix has held the objects for 2 min he places them on the table, and Kalle observes them with the IR camera:

Kalle: Well… the piece of wood… right where he held, it's warmed up a lot… about 30 degrees… the other [he looks at the piece of wood] is more… over… all over it… but is just… the temperature just under [reads about 28 degrees on the screen] I don't know… maybe it has cooled down during the time it has been lying here… that it made a difference…
Hjalmar: It has spread more on the knife, at least.
Kalle: Yes. But it's not as warm either…

The students notice that while the knife has a more uniform temperature across its surface, the wood has reached an even higher temperature, but only at the local position where Felix's hand was in direct contact with it.

After they have conducted the experiments, J. H. encourages the group to provide explanations for their observations:

Felix: I would say that the dense structure of the metal's composition… so that it like spreads heat faster than… the sparser composition of the wood…
Kalle: Yes.
Felix: I mean, its atomic structure…
Hjalmar: There are more losses, when it's trying to push the heat onwards, so to speak…

Following Kalle's line of reasoning above, Felix explains the metal's higher conductivity than that of wood by reference to its denser atomic structure. However, when summing up the exercise, the group still cannot quite explain why the metal felt colder than the wood, but was actually slightly warmer according to the IR camera reading from the beginning. Felix still doubts the accuracy of the measurements:

Felix: But the knife contributes a bit… the thing with the lamps… so it is…
Kalle: Yes.
Felix: …that's an error factor… so it is…

In parallel with previous research on students' explanations of why metal feels cold at room temperature [2,9,11], the students in the current study express a cognitive conflict between their sense of touch and the IR-camera measurements. Intriguingly, this tension remains throughout the exercise, in spite of their accurate prediction that, due to its higher heat conductivity, a metal object will undergo a larger temperature increase than a piece of wood when held. What is it that prevents the students from accepting that the knife has roughly the same temperature, or actually an observed slightly higher temperature, than the piece of wood? In terms of framing, from an epistemological point of view, what kind of knowledge is engaged, we suggest that the reluctance to trust the measurement of the IR camera is largely due to the dominance of the sense of touch in experiencing thermal phenomena as evidenced in the initial "tactile festival." The students frame the task as assessing temperature primarily through the tactile perception of hot and cold, and this heavily influences subsequent reasoning during the task. From the point of view of control of what resources to use [51], with this epistemological framing, the students fail to conceive of their hands as warm objects rather than temperature probes, which as a consequence prevents them from relating the sensation of hot and cold to the concept of heat conduction.

D. The cup station: "The ceramic mug will absorb the heat, but the plastic cup will radiate heat straight through"

At the final task station, the group is instructed to pour hot water into a thin plastic cup and a thick ceramic mug. The students start making predictions:

Felix: [Jokingly, with a self-assured voice] Actually, I can already answer this one. Or… I'm not 100% sure, but I think the mug will… I mean, this coffee mug [holds the mug] will show much less heat readings than… the plastic cup.
Kalle: …the temperature… like this [points to the coffee mug] will absorb the heat… but that [the plastic cup] will radiate heat straight through…

In contrast to the preceding challenging task, they are confident that the temperature of the plastic cup will increase more than that of the coffee mug. As in the case of explaining where the heat came from when Felix rubbed an eraser, Kalle uses "radiate" in an idiosyncratic way. Here he seems to refer to rapid conduction through a thin solid. Kalle starts pouring water (at a temperature of about 80 °C) into the cup and the mug, and Felix observes with the IR camera:

Felix: The mug reads about 60 degrees, where there's water… and the plastic cup reads about 80 degrees…
Kalle: It [the plastic cup] kind of radiates directly… maybe that [the coffee mug] absorbs more…

Felix: But inside they're the same… [looks at the water surface of the coffee mug] no, 75! [looks at the water surface of the plastic cup] and here, it's… about 80…
Kalle: It can be that… this one [the coffee mug] has absorbed some heat… and that one [the plastic cup] hasn't radiated it.
Felix: [Touches the coffee mug] It has absorbed heat, so there is less [in the water]… but that one [the plastic cup] has just sent out some [gestures 'outwards'] but not as much… it has kept all heat inside… /…/ The coffee mug… generates heat… it like keeps most of the heat in the ceramic, so to speak… whereas the plastic cup… radiates heat… but then… it takes longer time for it to radiate the heat, than it does for the coffee mug… to take up the heat… and put it… store it. So that one [the plastic cup] hasn't cooled down… the plastic cup hasn't cooled down as much as the coffee mug. /…/
Hjalmar: [looks at the water surface of the coffee mug again] about 68… it has dropped a bit… [looks at the water surface of the plastic cup] a bit warmer…

In explaining why the water in the coffee mug is colder than the water in the plastic cup, the students express that the coffee mug has "absorbed," "taken up," and "stored" some of the heat, whereas the plastic cup has not yet radiated so much heat. In other words, they interpret the heat as a substancelike entity, which is stored in warm objects, reminiscent of the historical "caloric" concept [68].

Suddenly, when exploring various aspects of the experimental setup with the IR camera, Felix notices that soaked paper towels adjacent to the objects of current interest appear much colder than the surroundings:

Felix: Wow! /…/ That was a bit…
Hjalmar: That's not relevant, Felix.
Felix: The cold gets colder than it should be…
JH: What could that depend on…?
Felix: Er… I'll be completely honest: I don't know. [shakes his head] It's just interesting.

Felix notices a phenomenon within the thermal realm, cooling due to evaporation, which might have amounted to an investigation in its own right. As opposed to the previous instances of instant inquiry, Felix was not driven by a "what-if" question but just came to notice this phenomenon. Hjalmar once again deems it irrelevant, but in an attempt to probe further, J. H. attends to the phenomenon and asks Felix for an explanation. After Felix fails to provide one, the group returns their attention to explaining the outcome of the experiment as a whole:

Hjalmar: But it's possible that this one… [touches the coffee mug] thicker material… it's like… if this one is cold, it's bound to transfer its cold to the water quicker than what the air transfers to that one [points to the plastic cup] /…/
Felix: This one [points to the coffee mug] has more like atomic structure… that stores the heat in…
Hjalmar: The only thing that cools the water here [points to the plastic cup] is like the air… whereas it's the actual material in this one [points to the coffee mug] that cools. /…/

As a parallel to previous findings [2], Hjalmar conceives of the phenomenon of the cooling of water as a matter of transfer of cold from the coffee mug to the water. In contrast, also in this exercise, Felix makes an attempt at providing a microscopic explanation.

Some minutes into the experiment, in mirroring a group of 4th graders that worked with the same task [8], the students notice that whereas the water in the plastic cup was warmer than that in the coffee mug when they had just poured the water into the respective containers, the water in the plastic cup cools down quicker. They round off the exercise by explaining the differences between how heat is conducted through the mug and the cup:

Kalle: The heat is insulated better [in the coffee mug].
Felix: Yes, it's like insulated to the area where the water touches the inside… compared to this one [picks up the plastic up] that just sends the heat around everywhere… so if you fill it as much as we have… /…/
Hjalmar: [Looks at the cup and the mug in the IR camera again] This [the coffee mug] doesn't spill [heat] … it doesn't let go of all the heat… as much as that [the plastic cup]
Kalle: What is it now…? [Hjalmar looks on the water surfaces with the IR camera] Well, I mean… it insulates the heat better… in the mug… the ceramic insulates… That one [the plastic cup] seems to be losing temperature quicker now… or…? It goes down a bit there…
Hjalmar: 65 [looks at the water surface of the plastic cup]. Sixty… this one has lost a lot more heat… /…/
Kalle: But that one [the ceramic mug] is starting to catch up now. That one [the plastic cup] was much warmer before. /…/ We could like say this… this one [the coffee mug] keeps the heat longer…

The students sustain their observations to the point where the water in the plastic cup has cooled down to roughly the same temperature as the water in the coffee mug, which they explain as a consequence of the insulating property of the ceramic material. They continue speaking of heat as a substancelike entity that is contained in the coffee mug and does not spread out so quickly through its walls.

Apart from Felix's brief detour toward observing the soaked paper towels, the group shares their epistemological and conceptual framing of this exercise. It is a matter of measuring the temperature change of the outside of the cup and the mug, and the water inside the containers, as the water decreases in temperature. The temperature decrease

TABLE I. Overview of interpretations of each student's overall framing of the laboratory stations.

Student	Epistemological framing	Conceptual framing
Felix	Keen to engage in instant inquiry, while remaining within the realm of thermal phenomena.	Largely shared within the group throughout the exercises, but different from what might have been expected (e.g., ignoring heat conduction at the friction station), and differing between the stations (e.g., adopting an exclusively macroscopic approach to the collision station only).
Hjalmar	Wants to stick to the given instructions at each station.	
Kalle	Not satisfied until he has grasped the underlying (and typically microscopic) mechanism as an explanation.	

is explained in terms of the water losing heat to the surroundings, as if it were a substancelike entity.

V. CONCLUSION

In drawing conclusions from the results of the study, we return to the posed research question: How does a group of upper secondary students frame a set of IR-camera-based physics laboratory exercises? We provide an overview of the individual students' epistemological and conceptual framing in Table I, and show how the exercises correspond to what Hofstein and Lunetta [26] propose as meaningful laboratory tasks.

Overall, from the point of view of their *epistemological framing*, this particular group of students exploited a wide range of approaches to come to understand the phenomena that they observed and experienced, and to justify their ideas. In contrast to the student presented by Lising and Elby [53], they made extensive use of their previous experience from everyday life in making predictions and explaining the phenomena at hand. Previous everyday experiences were also used for extreme-case comparisons of what was *not* expected to happen [24,25], for example, a great temperature increase from sparks as a result of the steel ball striking the ground. The combination of IR cameras and the POE approach was found to allow the students to justify their assertions on the basis of scientific evidence, which serves as one of the requirements of laboratory tasks advocated by Hofstein and Lunetta [26].

As in the cases of introducing IR cameras in science center exhibits [38] and 4th-grade laboratory exercises [8], the upper secondary students in this study frequently engaged in moments of *instant inquiry*. In some cases, such as observing the tires of accelerating cars, this followed the pattern of pondering what something looks like through the IR camera and receiving a prompt answer. In other cases, driven mostly by Felix, it was more a matter of scanning the surroundings at random and all of a sudden noticing something intriguing, such as the wet paper towels at the cup stations, prompting the reaction, "wow, that's strange." Once again, both types of instant inquiry indicate how IR cameras in combination with the POE approach [44] represent distinct "inquiry empowering tools and strategies" [26] (p. 48).

Apart from this generally productive and curious approach to the tasks, the three students did not shy away from revealing evidence of their differing epistemological framing, or even temperaments, among themselves. As detailed in Table I, Felix was the keenest in looking for, or even bringing about, scenarios that deviated from the instructions, while Hjalmar at times felt the need to "reel" him in. In Hjalmar's view, such digressions were simply irrelevant to the tasks. When it came to providing explanations, Felix sometimes tested the waters with speculative ideas, while Hjalmar waited until he was quite sure what had actually happened. Kalle, in turn, probably had the most advanced conceptual understanding beforehand and contributed with a valuable analytical perspective. At times, this difference in epistemological framing evoked frustration, in particular, in relation to the challenging wood and knife station. Overall, however, we are of the view that these tensions and their resolution actually induced the students into contemplating other possible perspectives, and in a sense prompted them to negotiate the meaning of what was happening through genuine dialogue [69]. In contrast to van de Sande and Greeno [54], we see that the students work productively together even with partially diverging epistemological viewpoints. In this respect, the IR-camera-based exercises met the call of Hofstein and Lunetta [26] to engage students with different abilities, learning styles, and motivational patterns. In particular, Felix was probably given more room for his speculative and inquisitive approach in this circumstance than would otherwise be the case in more traditional teaching contexts.

Furthermore, the students were sensitive to the overt messages [51] provided through the phrasing of the instructions. It was particularly clear at the friction station, and also just prior to the collision station, that they focused heavily on friction as a phenomenon, even though many instances of heat conduction might have been noticed and followed up upon. Similarly, at the collision station, the students focused on the instruction of explaining what happens to the kinetic energy of the metal ball at the moment of impact with the ground, which, in combination with the law of energy conservation and the IR-camera input, led to engagement of the principle of elimination in reasoning about the observation that the kinetic energy has to turn into heat.

The influence of J. H. following the group's interaction as they moved through the stations may also be interpreted in terms of overt and covert messages [51]. J. H. expressed interest in Felix's digression initiatives and probed for explanations of what Felix had noted, and thereby did not, like Hjalmar, deem them irrelevant. In general, such probing for deeper explanations was largely shared between J. H. and Kalle.

As shown in Table I, we argue that the students largely shared their *conceptual framing* of the individual exercises, which may have contributed to the fact that the differences in epistemological framing could be kept at bay.

We would also like to point out that at three of the four stations the students actively sought microscopic mechanisms in explaining the phenomena at hand. Felix took initiative toward providing particulate explanations, and Kalle was not satisfied until he had found a plausible causal mechanism for why an object increased in temperature. In contrast to chemistry classrooms, where molecular explanations are a *sine qua non* [70], in physics they are not always provided [71]. In our experience of introducing IR cameras in upper secondary physics contexts during this research program [7], engaging microscopic lines of reasoning has often been a sign of conceptually stronger groups of students, as in the case of the present study. Our observation of the tendency of stronger students to engage microscopic explanations is hardly surprising, since the disciplinary affordances [58] of the IR cameras relate to the macroscopic level of temperature changes.

Finally, in spite of expressing the idea that metal is a better heat conductor than wood, which we would have expected to be necessary, but also sufficient, for understanding why metals feel cold at room temperature, the students were not comfortable with the observed outcome at the wood and knife station even at the end of the exercise. Felix still questioned the IR-camera reading, which corresponds with subjects' assertions found by Lewis and Linn [2]. We think that one crucial and powerful component for this unease is the primacy in students' views of the sense of touch in assessing objects' temperatures. If something *feels* cold, it must *be* cold. Introducing the IR camera in combination with the POE approach did not serve to shift the students' epistemological and conceptual framing in this respect.

VI. EDUCATIONAL IMPLICATIONS

An IR camera inherently invites students to notice relevant aspects of thermal phenomena in an intuitive way, and is thereby associated with disciplinary affordances [58] in the thermal domain. By observing the IR-camera screen, students are provided with real-time perceptions of macroscopic thermal phenomena, which help them interpret, or indeed see, the thermal processes as they occur. In other words, as a thermal looking glass, IR cameras help students concentrate their conceptual framing [54] to the thermal domain. As reported by Daane *et al.* [24], without access to IR cameras, similar otherwise imperceptible dissipative phenomena are also difficult for science teachers to deal with.

Nonetheless, as with all educational tools aimed toward fostering understanding, IR cameras have limitations. For instance, IR cameras give insight into thermal phenomena from a macroscopic point of view. For students to develop an understanding of microscopic explanations of thermal phenomena, such as the molecular mechanisms underlying heat conduction, or to come to appreciate heat as an emergent process [72], explicit introduction of molecular models may offer a more promising avenue. Attractive approaches to the introduction of molecular models include molecular simulation tools [14,73–75], development of bridging analogies [76], and utilizing instructional analogies that relate explicitly to students' personal, embodied experiences [77]. The temperature readings of an IR camera also depend on the emissivity and reflective properties of the measured surface. In this respect, measuring the temperature of polished metal surfaces or glass windows is particularly problematic, but may, as pointed out by Neumann [43], on the other hand, also provide insight into electromagnetic radiation as a phenomenon. In addition, since handheld IR cameras measure the temperature of solid or liquid surfaces, other technologies, such as traditional thermometers, are required to measure the temperature of gases, or within liquids and solids, as opposed to on their surface.

Given students' observed sensitivity to the phrasing of the worksheets and their headings, as teachers, we have to be careful in the instructions we provide our students. In the present research context, we had the opportunity as researchers to follow all the groups as they conducted the station tasks. In an authentic teaching situation, students are often left to their own devices for long periods, attempting to figure out what actions their teachers expect them to undertake [78]. Still, as pointed out by Atkins *et al.* [38], it is a matter of striking a balance between, on the one hand, communicating what is expected, and, on the other hand, not thwarting students' creativity and imagination.

Redish [51] points out that there is an inherent risk in asking students to make predictions, which is an integral component of the POE approach, in that they may be left with an unresolved cognitive conflict between what they have experienced and their original idea. The phenomenon that metals feel cold at room temperature is a notoriously challenging concept to reconcile [2,11]. We had hoped that the students in the present study would have been able to "see" this phenomenon as a matter of heat conduction from their hands [3] when assisted by an IR camera, rather than a case of investigating the temperature with their sense of touch. How can we "negotiate a frame shift with our students" [51] (p. 41) in relation to this phenomenon? One common approach, proposed by Mach [79], and adopted in our preceding pilot study, is to ask students to keep their hands submerged in two buckets of water for some time, one containing warm water and the other ice-cold water, and then ask them to simultaneously submerge both hands into a bucket containing lukewarm water. Since water of the same temperature gives rise to completely different tactile sensations in the two respective hands, the students are presented with a sensory platform to be convinced that their sense of touch is not a dependable thermometer. Another approach can be to explicitly introduce a microscopic model of heat conduction in metals, such as the classical free-electron model [80].

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[66] In Swedish, Felix says "det varma," which literally translates into "the warm" by use of an adjective as a noun. This expression does not have an obvious English equivalent, but is close in meaning to "the warm stuff" or "the heat."

[67] The fact that the knife was warmer than room temperature is probably due to the handling of the knife by students in this and previous groups.

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