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"But metal really is just colder!" Pupils' use of thermoimaging in conceptualising heat transfer

Konrad J. Schönborn[1], Jesper Haglund[2], Charles Xie[3]

[1]Department of Science and Technology (ITN), Division of Media and Information Technology, Linköping University, 601 74 Norrköping, Sweden; [2]Department of Social and Welfare Studies, TekNaD, Linköping University, 601 74 Norrköping, Sweden; [3]The Advanced Educational Modeling Laboratory, The Concord Consortium, Concord, Massachusetts 01742, United States

[1]Corresponding author:

Phone: +46-11-363609

Fax: +46-11-363270

Email: konrad.schonborn@liu.se

Abstract

Infrared (IR) thermal imaging is a powerful and increasingly affordable technology, which holds the pedagogical potential of 'making the invisible visible'. Perennial misconceptions about thermodynamics include ambiguous interpretation of temperature and heat, treating the sense of touch as an infallible thermometer, and asserting that different materials have inherently different temperatures. Literature suggests one remedy would be to 'see' thermal phenomena in terms of energy transfer from pupils' bodies to an object. This study explored how augmenting tactile experiences with thermal imaging might influence pupils' conceptual understanding of heat and temperature. Prior to formal teaching, eight 7th-grade pupils (12-13 years old) worked in pairs across three discovery task conditions (*real-time IR imaging*, *static IR images*, or *thermometers*) to predict, observe and explain (POE) the temperatures of a knife, a wooden object, and a woollen beanie during various interactions, such as observing thumb-to-object contacts. A cognitive conflict between perceived object 'coldness' and 'measured temperature' was induced in all three conditions, although reasoning about the anomaly in the real-time IR groups emerged as a more pronounced affective experience. Explicit notions of heat flow, and extensive quantities such as 'heat' or 'energy', were found to be lacking. Although the results provide encouraging preliminary evidence that the inquiry-based approach could certainly induce a cognitive conflict, it remained a challenge for pupils to actively adjust their existing conceptions upon exposure to the imaging technology alone. Future research will build on this explorative study to inform guided approaches for exploiting augmented multisensory experiences in teaching thermal phenomena.

Keywords: *Thermal imaging, Heat, Temperature, Multisensory experience, Discovery learning, Cognitive conflict*

Introduction

In recent work, Xie (e.g. Xie 2011; Xie and Hazzard 2011) has purported that thermoimaging technology involving infrared (IR) cameras could enhance the understanding of invisible phenomena such as heat transfer. Xie's prediction has educational implications for pupils' construction and reasoning about heat transfer and related thermal concepts. From a cognitive standpoint, we hypothesise that when augmented with pupils' real-time tactile interaction with objects of different temperatures, referential connections offered by the unique multisensory haptic-visual experience could allow for a powerful perceptual platform to build richer and more meaningful conceptions of thermal phenomena. In so doing, the multimodal perception of complementing everyday tactile experiences with thermal imaging could provide a cognitive pathway for making conventionally taught aperceptual ideas of thermal concepts actively 'visible'. Furthermore, apart from the vivid and external visualization of temperature differences, thermoimaging also has the advantage of providing real time data, which could possibly enable an accelerated inquiry process, without the need for the otherwise traditionally taught intermediary steps of first recording data and then plotting results. Instead, as part of a predict-observe-explain (POE) inquiry-based approach to learning thermal concepts, the multisensory perception offered by thermoimaging during laboratory activities has exciting pedagogical and cognitive prospects for the learning and teaching of heat-related concepts.

The present study seeks to investigate the effect of combining the sense of touch with real-time thermoimaging in an inquiry-based heat transfer exercise with eight (n = 8) 12- to 13-year-old 7th-graders, prior to exposure to any formal teaching on thermal phenomena. Particularly, how would pupils account for the fact that metal feels colder than wood at room temperature?

Theoretical background

Inquiry-based and discovery learning

Discovery and inquiry learning approaches have been put forward in order to increase motivation and learning in science education, and have been influential in curricular development (Klahr et al. 2011) in the USA (Olson and Loucks-Horsely 2000) and in Europe (Rocard et al. 2007).

Terms such as "inquiry-based learning" and "discovery learning" are often used in multiple ways to refer to different learning aspects, with no one single definition encompassing these notions. Inquiry-based learning is often referred to as an educational approach with an emphasis on posing good, genuine questions, amassing evidence and interpreting it against a background of theories (Kuhn et al. 2000). It may range from promoting "hands-on" learning experiences through to stimulating pupils to pose and answer "good" questions in the classroom, as well as incorporating ideas of "active learning", "open-ended processes", and "scientific inquiry skills". Edelson et al. (1999) have studied how the use of scientific visualization technology can be used to support inquiry-based learning approaches. Their work suggests that visualization technology can provide a "valuable context for learners to acquire, clarify, and apply an understanding of science concepts", and thus offer opportunities to support new forms of inquiry.

Discovery learning in science education is often spoken about with respect to the learner as the main actor alongside his/her process of knowledge construction and acquisition (de Jong and van Joolingen 1998). It is viewed by scholars as closely associated with "constructivist learning", "curiosity", "generalisation of experiences", and often concerned with learners independently harnessing the scientific reasoning associated with processes of scientific discovery, usually through hands-on manipulation and interaction with materials. For de Jong and van Joolingen, discovery learning processes include hypothesis generation, experiment design, interpretation of data, and regulation of learning. Work by de Jong and van Joolingen has shown that discovery learning with computer simulations can promote pupils' construction of scientific knowledge, because novel learning environments can be exploited, where learners are stimulated to draw on their own self-directed initiative in the discovery process.

Cognitive conflict and learning science

Posner, Strike, Hewson and Gertzog (1982) suggest that creating a cognitive conflict is essential to inducing conceptual change, defined as "fundamental changes" in a learner's conceptual ecology, which in turn is characterised as his/her set of conceptions related to a particular area of knowledge. *Anomalies* serve as the essential preparation of a radical change to a learner's conceptual structure, i.e. an "accommodation" (Piaget 1929). For these researchers, an anomaly takes the form of a situation where the learner cannot "assimilate something that is presumed assimilable", and simply cannot make sense of the experienced situation. Consequently, Posner et al. (1982) suggest that, "the more students consider the anomaly to be serious, the more *dissatisfied* they will be with current concepts, and the more likely they may be ready ultimately to accommodate new ones". Accordingly, a learner's process of dissatisfaction with an existing alternative conception is pivotal in making an adjustment to an existing conceptual ecology. In further support of this notion, Kang, Scharmann and Noh (2004) argue that there are two types of cognitive conflict in learning, namely, "the conflict between a student's conception and the experience, and the conflict between two different cognitive structures related to the same phenomenon". However, decades of science education research have perilously demonstrated that it is in fact very difficult to get pupils to "weaken" their existing alternative conceptions through anomalies (e.g. Chinn and Brewer 1993).

Multimodal processing of information: Tactile and visual perception

Multimodal processing and learning

Multimodal learning theory suggests that learning can be enhanced by building connections between different sensory modalities (Moreno and Mayer 2007). In particular, research in educational psychology has shown that combining auditory and visual information, compared with receiving visual information alone, leads to superior transfer of learning (known as the *modality effect*) (Mayer 2005). Recent research by Schönborn, Bivall and Tibell (2011) has referred to a *visuohaptic modality effect*, which suggests that knowledge integration might also be promoted by simultaneously coordinating *visual* and *tactile* perception. It could be hypothesised that actively combining and processing visuospatial and tactile sensorimotor interactions in the macroscopic world might assist the construction of scientific knowledge about unobservable heat-related phenomena at the microscopic scale. In this way, a visuohaptic modality effect could be exploited as an agent for inducing conceptual change with respect to notoriously robust alternative conceptions of heat.

According to Ernst and Banks (2002), when exploring an object with one's hand, both the sense of vision and touch contribute to an interpretation of the object, with vision usually dominating the visuohaptic "percept" that arises. However, often, the construction of the percept is heavily influenced by our tactile sense. For instance, some studies concerned with investigating different types of "intermodal conflict" (e.g. Hershberger and Misceo 1996) have shown different influences of the major dominance of touch and vision when the visual and haptic senses are in conflict (e.g. Power 1980). Studies have suggested that in some cases, the visual and tactual senses weigh the perceived intermodal information almost equivalently (e.g. Lederman and Abbott 1981).

In a way, the visual information that is generated on the screen of a thermal camera can be thought of as a computer-generated supplement to a human's already existing perception of the real world. Here, the user's interaction in the real world is augmented with real-time visualized thermal imagery, where both processes coexist in a combined real and computer-visualized space.

Psychophysics of temperature perception

Humans often believe that perception of temperature through touch is an accurate thermometer. It is not. In fact, heat and cold receptors in our skin do not react to temperature, *per se*, but to *changes* in skin temperature and "…although thermal cues are used to recognise objects by touch, it is the thermal conductance and heat capacity of different materials that is used to identify that the object is made from metal, glass or wood and not the absolute temperature which may be the same for each object palpated" (Jones and Berris 2002). Jones and Berris (2002) have also shown that in comparison with our extremely acute visual and olfactory (the sense of smell) perceptual channels, our perceptions related to thermal stimuli are limited.

With respect to the present study context, given that without visually experiencing predominantly 'invisible' phenomena such as 'heat flow', learners will of course rely heavily on thermal sensations to grasp a phenomenon, which might inadvertently induce misconceptions such as believing some materials to be intrinsically colder than others. Since the process of human construction of knowledge is closely linked to sensorimotor interactions in the world (Wilson 2002), we also often rely on our somatosensory experiences to learn science (e.g. metals really do feel colder than plastic at room temperature). In such cases, it follows that it is plausible to assume that learners construct a scientific understanding of thermal phenomena by depending heavily on what they can feel but cannot see. Hence, the construction of abstract ideas such as 'heat' will be born largely out of learners' somatosensory everyday experiences of invisible phenomena. Albeit so, even if you suddenly would be able to see such phenomena, you are used to exploiting your sense of touch to understand them and would have to learn to interpret any new visual input in this context; a requirement that would demand new visual literacy skills (e.g. Schönborn and Anderson 2006).

Conceptions, misconceptions, and the teaching of thermodynamics

Given the background of misconceptions in the field of thermal phenomena that have been identified in science education research (e.g. Sözbilir 2003) and Yeo and Zadnik's (2001) *Thermal Concept Evaluation*, we think that the following alternative conceptions of heat and temperature are the ones that are most relevant to the current study, and therefore constitute our *target misconceptions* for several reasons. Firstly, they can be assumed to be held by many 12- to 13-year-olds, the age at which physics starts to be formally taught as a subject in Sweden. Secondly, we believe that they have the potential to be addressed by use of IR cameras, and do not require a microscopic account of thermal phenomena. Thirdly, they can be assumed to be connected and likely to change relative to one another. The target misconceptions of interest are as follows:

- The sense of touch, feeling with your hand, is an accurate thermometer (Clark and Jorde 2004; Yeo and Zadnik 2001).
- There is no difference between heat and temperature (Erickson 1985).
- Some substances are naturally colder than others, e.g. metals are cold (Brook et al. 1984; Erickson 1985).

In addition to these target misconceptions, other associated relevant conceptions of thermal phenomena reported in the literature include:

- Heat is hot, but temperature can be cold or hot (Erickson 1985).
- Metals often have extreme temperatures, i.e. very cold or very hot, also when surrounded by objects of less extreme temperatures (Clark 2006; Lewis and Linn 1994).
- Objects in thermal contact do not necessarily move toward the same temperature, i.e. lack of awareness of thermal equilibrium (Clark and Jorde 2004; Yeo and Zadnik 2001; Lewis and Linn 1994).
- Heat is a material substance, like steam (Erickson 1979; Lautrey and Mazens 2004).
- Heat and cold are opposite fluid substances (Brook et al. 1984).

Piaget and Garcia (1977) have identified that the ability to provide causal explanations of heat transmission is delayed by one developmental stage, compared to explanations of transmission in mechanical phenomena that involves the coordination of hands-on manipulation and vision, perhaps reminiscent of the visuohaptic modality effect described above.

The view of heat as a kind of substance that can be contained in and move between physical objects is reflected in everyday language and has been found to be adopted by children as young as 7 years of age (Lautrey and Mazens 2004). This conception may hinder grasping thermodynamics theory, typically introduced in secondary teaching, in which heat is defined as a process of energy transfer, but not something that can be contained in objects.

Erickson (1985) reports that pupils do not view the situation of touching objects of different materials at room temperature in terms of heat transfer, but attribute *ad hoc* inherent properties to the materials, such as metals feeling cold due to their ability to "attract" cold, or just as a matter of fact. Similarly, in an investigation of the conceptions of heat and temperature among eighth-graders, non-specialist adults and natural scientists, Lewis and Linn (1994) found that as a response to the finding that materials can be of the same temperature yet feel different to the touch, several adults even questioned the accuracy of the mercury or digital thermometers. As a reaction to such findings, Erickson (1985) proposed:

> 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 (p. 59).

Arnold and Millar (1996) have presented a teaching sequence that focuses on a 'story' about the interrelationship between the concepts of 'temperature', 'heat' and 'thermal equilibrium'. They argue that the issue of separating the intensive character of temperature from the extensive character of heat and energy is one of the main challenges of secondary-school teaching of thermal physics. Due to the difficulty for pupils to view heat in terms of energy transfer, Arnold and Millar adopted the approach of using the term 'heat' as something that is stored in and flows between warm objects, i.e. in line with the caloric theory of heat which was otherwise abandoned in science with the introduction of the energy concept. The intended story is introduced by showing an analogy between heating water with a candle and controlling the water level in a glass container with input and output valves, where the temperature of the heated water corresponds to the water level in the container. The candle corresponds to the input valve and the heat being transferred can be regulated by adjusting the distance to the water. Heat dispersed to the surroundings is mapped to the water flow through the output valve. After heating, the temperature of the water reaches a stable level (steady-state), which is explained by equal amounts of heat being added to and dispersing from the water.

Clark and Jorde (2004) 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 reading, "This feels painfully hot!" Using this 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 the tactile reference. One justification for using a virtual rather than 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 approximately the same temperature.

In other work, Zucker et al. (2008) have reported a series of inquiry-based instruction studies in grades 3-8 on the use of probeware with real-time computer graphing. They found that the use of measurements with temperature probes led to particularly high learning gains in comparison to no-probeware set-ups, even more so than for other types of probes, such as motion or pressure sensors.

Furthermore, Wiser and Amin (2001) found that it was challenging for a group of eighth-graders to overcome their preconceptions and grasp a microscopic account of heat, involving the concept of heat as energy transfer due to molecular interaction, in spite of being subjected to a carefully designed teaching sequence. Overall, due to the difficulty in grasping a microscopic particle account of matter, Wiser and Smith (2008) suggest that it should rather be introduced at a later stage in a learning progression on matter.

Use of thermocameras as a tool for enhanced learning

The potential use of IR cameras in physics teaching for visualizing thermodynamics phenomena, and ideas related to friction and insulation have been previously recognised by Vollmer, Möllmann and colleagues (Vollmer et al. 2001; Möllmann and Vollmer 2007). In these contexts, IR cameras have been used primarily in demonstrations, but as the equipment becomes increasingly affordable, application to student laboratory settings becomes more realistic (Möllmann and Vollmer 2007). For example, Cabello et al. (2006) have described their use of IR cameras in a laboratory component of a thermal engineering course to help students establish a connection between theory and thermal phenomena in reality. In addition, Naghedolfeizi et al. (2011) achieved good learning outcomes regarding the nature of laboratory work and measurements wherein undergraduate students measured heat transfer dimensions using IR camera imaging and computer simulations.

With respect to the above, Xie (2011, 2012; Xie and Hazzard 2011) has recently argued that IR cameras present an exciting and potentially powerful learning opportunity in science education to visualize the often 'invisible' and unobservable energy transfer processes that are common in science experiments. An IR camera presents the prospect for learners to *see* thermal energy transfer, and also infer other types of energy conversions from interpreting thermal energy displays. Doing so may allow learners to directly 'discover' and investigate many of the otherwise invisible physical, chemical, and biological processes related to the 'absorption' or 'discharge' of thermal energy. In this way, classroom inquiry processes could be potentially accelerated by means of this novel technology, since the rich and stimulating thermal information that can be communicated in real time with an IR camera is either inaccessible or would take students many hours to deduce using conventional apparatus, such as thermometers.

Overall, exploiting IR cameras could go a long way in making Erickson's (1985) dream a reality, where pupils are no longer only restricted to 'seeing' heat flowing in their mind's eye, but can actually see it with their own eyes. The challenge for educational research becomes the pursuit for empirical evidence that supports the notion that applying such modern technology in science education is of conceptual benefit, and perhaps superior to otherwise traditional approaches for learning core scientific concepts. On this note, we nevertheless remain aware of the word of caution offered by work showing that the mere introduction of novel technology in classrooms does not *automatically* lead to positive learning outcomes. In this regard, research must aspire to move 'beyond the wow factor' (Chandler 2009) when introducing novel technology in teaching. This transition from superficial learning assumptions associated with new 'cool' technology toward useful application in the classroom must be specifically informed by research in order to be conducive to conceptual understanding.

Purpose of the study

The purpose of the study was to explore how IR imaging technology might influence pupils' conceptual understanding of heat and temperature. Specifically, we posed the following research questions:

- What are pupils' conceptions of heat and temperature prior to any formal physics teaching of thermal phenomena?
- How does interpretation of thermal images influence pupils' understanding of heat and temperature, compared to traditional laboratory approaches?

- To what extent can a non-guided discovery approach that combines tactile input and thermal imaging technology foster conceptual change about heat and temperature?

Methods

The methodological framework developed and applied in this study was designed with the intention of striking a balance between creating an inquiry-based discovery learning environment *and* at the same time, an appropriate study context for acquiring empirical data in response to the posed research questions. The overall data-gathering methods employed in this study consisted of generating and analysing learners' responses to written items, and observing their execution of practical exercises in three different laboratory task conditions.

Pupils and study context

Learners without prior exposure to any formal physics teaching of heat were purposefully sought to participate in the study. In this regard, since one central tenet of the study was to monitor to what extent traditional (e.g. thermometers) in comparison with novel (e.g. IR visualization) laboratory approaches influenced pupils' understanding of thermal concepts, we wished to investigate learners' prior conceptual ecologies, and evaluate the impact of a discovery learning approach for developing macroscopic conceptions of heat. The study was conducted in 2011 with eight Grade 7 (12- to 13-year-old) participants (four boys and four girls) who attended a typical municipal secondary school in Sweden. The school prides itself in being technologically innovative and welcomes research initiatives that explore novel educational approaches. Ethical requirements stipulated by the Swedish authorities were adhered to, and necessary informed consent was obtained from the participants and their parents.

Data collection

The sequence of data collection in the study was performed as follows. First, each of the eight pupils responded to a written pretest. Second, pupils were paired randomly, and each of the four pupil pairs was assigned to a specified task condition, and performed a corresponding laboratory exercise. Third, each of the eight pupils completed a written posttest. Following the data-collection, pupils were debriefed by receiving a 20 minute lecture on the purpose of the study, which included a scientific explanation of the concepts under investigation. Finally, all pupils who were not exposed to the IR technology during the study received the opportunity to interact with the camera used in the data collection.

Written pre-/posttest

The written pre-/posttest (see Appendix I) consisted of three open-ended and three closed-response (multiple-choice) items, which specifically aimed to probe pupils' understanding related to the identified target misconceptions about heat. Since one goal of the study was to obtain data related specifically to the identified target misconceptions, items were adapted from published international science education literature. This ensured a high content and construct validity of the items for investigating pupils' understanding of heat-related phenomena. In addition, we also intended the items to include knowledge transfer ability, often seen as the yardstick for demonstrating the meaningful learning of a concept

(Mayer 2002). Out of the three open-ended items (see items 1-3 in Appendix I), item 2 was adapted from Paik, Cho and Go (2007). Two multiple-choice items (items 4 and 5 in Appendix I) were adapted from Yeo and Zadnik's (2001) thermal concept test instrument, while the last one (item 6 in Appendix I) was developed by Andersson (2006). The pupils took approximately 10-15 minutes to complete the pre- and posttests, respectively.

Practical POE laboratory tasks

In the spirit of a discovery learning and inquiry-based approach, and indicative of "authentic scientific practice" (e.g. de Jong and van Joolingen 1998), we designed the laboratory tasks around a predict-observe-explain (POE) framework (e.g. White and Gunstone 1992; Xie and Hazzard 2011). Three separate POE laboratory exercises were designed, namely an *IR-camera*, *IR-static*, and *thermometer* condition. Each POE practical exercise was formulated to systematically investigate and compare pupils' interaction with traditional and novel measurement equipment, in the process of predicting, observing, and explaining a macroscopic account of heat-related phenomena. In the *IR-camera* task, pupils interacted with a *FLIR i3* infrared camera that renders dynamic real-time thermal images of objects (Fig 1). The *IR-static* condition required pupils to interpret static paper-based images generated from the same camera. Pupils' interaction with digital *thermometers* constituted the 'traditional laboratory' condition, and was also viewed as the 'control' condition (Fig 1).

[Insert Fig 1 about here]

In order to add a degree of authenticity to pupils' linking of their thermal-related conceptions with real experiences, the pupils investigated objects that they would encounter in everyday life, namely: a painted sheet-metal utility knife, a piece of wood, and a woollen beanie. The design of each respective laboratory exercise in each of the three conditions required pupils to predict, observe and explain heat and temperature phenomena related to: 1) the objects at room temperature; 2) pupils placing their thumbs in contact with the objects for two minutes; and 3) the objects placed outdoors on an autumn morning. Components of the laboratory task set-ups are illustrated in Fig 2. As an example, the laboratory instructions for the IR-camera groups are provided in Appendix II. The emissivity coefficient of the IR camera was set to 0.95, close to the emissivity of the knife paint coat (0.96) and that of wood (0.95), as listed by The Engineering Toolbox (2012). This setting ensured that the colours depicted in the IR images were valid and reliable measures of the observed temperatures.

[Insert Fig 2 about here]

For the POE practical task, each pair of pupils was assigned to one of the three conditions. Since potential data to be obtained from pupils' use of the thermal imaging technology was of high interest to the current research, two pupil pairs were assigned to this condition. Before commencing with each respective POE task, pupils were provided with pre-instructions and relevant information (see Appendix II). Pupils spent approximately 20 minutes on each POE exercise, and each pupil-pair's complete execution of the tasks was video and audio recorded. Authors KS and JH monitored the POE tasks and intervened with conceptual questions when the need arose, such as when pupils' active verbal utterances and interactions with the equipment and objects waned, ceased, or became unfocused.

Data analysis

All eight participants responded to the written pre-/posttests in Swedish and communicated in Swedish during the laboratory POE tasks. Author JH, of Swedish mother tongue, and bilingual with English, transcribed the video recordings verbatim and then fully translated the Swedish written and oral utterances into English. The English translations were treated as the data. Overall, the analysed data corpus consisted of learners' written responses to the pre-/posttest items, videotaped recordings of pupils performing the laboratory tasks, IR-camera screenshots taken by the pupil-pairs in the IR-camera condition, verbatim transcripts generated from the videotapes, as well as researcher-generated field notes penned by KS and JH.

A mixed deductive-inductive approach was used to analyse the data, which proceeded as follows. First, learners' responses to the pre-/posttests (Appendix I) were scored, coded and analysed deductively to determine and establish whether, and which of, the target alternative conceptions were present in pupils' conceptual ecologies before, and after, performing the laboratory tasks. Second, the POE transcripts generated from pupils' execution of the laboratory tasks were qualitatively analysed by inductively constructing themes from any patterns that emerged naturally from the data (e.g. Glaser and Strauss 1967; Lincoln and Guba 1985). In parallel with the latter iterative process, we also analysed the videotapes for any patterns of interest related to pupils' behavioural interactions with the respective apparatus and with each other, upon conducting the POE tasks. Third, any emergent themes from the POE data were contrasted with the findings from analysis of the pre-/posttest data. In this respect, we purposefully searched the transcripts, and observed the video recordings, for evidence of pupils' active engagement of any of the target alternative conceptions deduced from the pretest during their scientific reasoning processes. As a way to check the consistency of the analysis, all three authors discussed the nature and content of any themes (and corresponding verbatim quotes or behaviours) that were obtained from the data.

Results

The findings of the study are presented in three sections. Firstly, we present a description of pupils' exposure and engagement of heat and temperature concepts. This was unpacked in two ways, namely: i) By measuring pupils' conceptions of heat and temperature *before* and *after* they conducted the laboratory exercises (revealed by the written instrument), and ii) By exploring three episodes in the data that present dynamics surrounding pupils' engagement of exposed conceptions across the *IR-camera*, *IR-static*, and *thermometer* laboratory task conditions. Secondly, salient themes with respect to the nature of pupils' behavioural interactions with the different practical task artefacts and with each other, across the three laboratory conditions are presented. Thirdly, data related to the emergence of cognitive conflict scenarios during pupils' conduction of the laboratory tasks are revealed.

Pupils' exposure and engagement of heat and temperature concepts

Measuring pupils' conceptions of heat and temperature before and after the laboratory tasks

The data generated from the written probes (Appendix I), were treated as the measure of pupils' conceptual understanding of heat and temperature, before and after performing the laboratory tasks.

The eight pupils individually responded to three closed items in each of the pre-/posttests (items 4-6, Appendix I). Out of a possible maximum of 24 correct answers in each of the pre-/posttests, the pupils answered 4 correctly in the pretest (17 %) and 3 correctly in the posttest (13 %). As a whole, this result suggests that pupils' overall conceptual understanding of heat as measured by the closed-response items did not improve following exposure to the inquiry-based heat and temperature laboratory tasks. Altogether, only 7 of the total 48 written closed item responses (15 %) were answered correctly, across both the pre- and posttest. Collectively, this result demonstrates the general lack of a scientific conceptual understanding of heat and temperature amongst the pupil sample under investigation in the current study.

Overall, our analysis of the pre-/posttest closed responses revealed that the most prevalent alternative conception in the group of participants was that "objects of different temperature in contact do not reach thermal equilibrium". This suggests that this line of reasoning was clearly entrenched in pupils' conceptual ecologies related to heat and temperature. One of the closed-items used to measure pupils' understanding of heat-related phenomena was as follows:

> Jan announces that she does not like sitting on the metal chairs in the room because "they are colder than the plastic ones."
> a. Jim agrees and says: "They are colder because metal is naturally colder than plastic."
> b. Kip says: "They are not colder, they are at the same temperature."
> c. Lou says: "They are not colder, the metal ones just feel colder because they are heavier."
> d. Mai says: "They are colder because metal has less heat to lose than plastic."
> Who do you think is right?

Analysis of responses to this item delivered in the posttest showed that of the three correct answers, two of them were obtained from pupils who interacted with the thermal technology in the "IR-camera" condition, while the other was obtained from a pupil who viewed static thermal images in the "IR-static" group, and no correct post-test answers to any of the closed items were delivered from pupils in the thermometer group.

In addition to the closed items, we employed free response questions that aimed to elicit "open" and "what comes to mind" responses related to pupils' conceptions of thermal phenomena. One such free response test item (item 1, Appendix I) asked pupils to explain what they think was meant by the terms 'heat' and 'temperature' in as much detail as they could. The following data are examples of four different pupils' responses to this item across the pre- and posttest:

> *"Temperature shows how warm or cold it is and heat is that it is warm."* (Anna, IR camera, post-test)
>
> *"Heat is warm. Temperature is like a 'degree' for how warm it is outside or in the body."* (Pelle, thermometer, pre-test)

"Heat is something that makes things warm, for example if one person is out playing football and if it is warm outside then you get warm yourself and that is heat. Temperature is something that tells us how warm or how cold it is." (Sven, still IR images, pre-test)

"Temperature is a particular 'degree' and heat is something that can be anywhere and there is no limit as to how warm it can get." (Lisa, IR camera, post-test)

Analysis of the responses above demonstrates that several pupils conceptualised temperature as being related to how 'warm' or 'cold' something is, and often alluded to a measure or "degree", although this designation was not only constrained to 'warm' objects alone. The conceptualisation of heat was more varied. As evidenced in the data above, Anna and Pelle provided very brief descriptions of heat as associated to 'warm', but in contrast to temperature, their utterances did not encompass ideas of 'cold'. These conceptions are reminiscent of the findings previously reported by Erickson (1985) among 12-year-olds. In Sven's account, heat is perceived as the cause of 'warmness' in 'making things warm' and also seen as identical to the phenomenon of 'being warm'. Finally, Lisa expressed that heat can be spatially distributed, possibly a sign of a substance ontology, and that heat in itself can 'get' infinitely warm.

Dynamics of pupils' thermal-related conceptions and reasoning patterns exposed and engaged during the POE laboratory tasks

Episode 1: Metals are colder than wood. Apart from their emergence in the written free response data, pupils' conceptions of temperature were also exposed during the practical laboratory exercises. For example, the excerpt below shows the pupil-pair of Karin and Anna making predictions related to the temperature of the piece of wood and knife (item 1a, Appendix II). In conjunction with the verbal utterance below is the behavioural action of Karin touching the piece of wood and Anna touching the piece of wood and the knife:

Anna: I think… the wood is… ehh, twenty… or nineteen [degrees Celsius]
Karin: [touches the wood] Well, it feels quite, like, smooth…
Anna: [touches the wood] It feels like… average…? Well, it feels like…
Karin: [touches the wood] …a bit colder…?
Anna: [touches the wood] A bit colder. It feels… mild, so to speak! [laughter] /…/ And then, there's the metal… [touches the metal]… It feels much colder, I think.
Karin: [touches the metal] Yes.
Anna: [touches the metal] It could be about… five.
Karin: Fifteen…?
Anna: [touches the metal] No, not fifteen! It feels like it's about five degrees. Five degrees. It feels as if it's about, maybe… 10?
Karin: Yes.
Anna: Somewhere around there.

The interaction shows pupils' heavy reliance on their sense of touch when it came to ascertaining the temperature of the wooden and metal objects. Specifically, Karin and Anna both physically touch each of the objects and talk in terms of how cold 'they feel' they are, prior to their predictions of the temperature of each respective object. While doing so, they appear confident in relating their sensory experiences to the Celsius scale. The wood feels "smooth", "mild" or "average", and their prediction of 20 °C points to a belief that it is somewhere in the region of room temperature. In contrast, the metal feels colder and considerably lower temperatures are predicted, in resonance with one of the target misconceptions regarding the inherent temperature of different materials (Brook et al. 1984;

Erickson 1985). Using the sense of touch as a thermometer was used consistently by all groups in all three exercises and reflects application of another of the target misconceptions, which also supports previous findings of Clark and Jorde (2004) and Yeo and Zadnik (2001).

Episode 2: Metals get much warmer than wood. Another salient line of reasoning that emerged during the laboratory tasks concerned pupils' discussions surrounding how sensitive different objects are to changes in temperature. In this regard, the datum below traces Karin and Anna's formulation of a prediction concerning what would occur when they placed their thumbs in contact with the wooden and metal objects (item 2, Appendix II):

> Anna: I guess that… the piece of wood, when we touch it with our thumbs… [points to the wooden and metal objects] that the piece of metal is going to get much warmer than the piece of wood.
> JH: Yes.
> Anna: And then, well…
> Karin: Actually, I think so, too. This [touches the knife] got very warm [when they touched it briefly in task 1].

Here, the excerpt above shows Anna's view that the metal would be more sensitive to a temperature change than the piece of wood. Karin agrees with this notion, and relates it to the pair's recent experience of touching the knife and perceiving it to get "very warm". The exchange exposes the conception that metal is more sensitive to temperature change than wood. Subsequently, when the pair performed the experiment as part of the IR-camera condition, they found that the metal increased in temperature more than the wood, but not by as much as what they had predicted. Consider the following interaction:

> JH: So, what was your… how is this [the observed temperatures of the metal and wood following contact with thumbs] connected to your predictions…?
> Anna: It still was very similar… I thought that it would be much more different.
> Karin: Yes.
> JH: Difference between…?
> Anna: Well, the metal and the wood… /…/ the piece of wood… like a bit warmer… but this [the metal] would pull away…
> JH: Yes.
> Anna: But we were wrong. That [the metal] only pulled away by one degree…
> Karin: Yes.
> JH: It did not pull away as much as you thought it would…?
> Anna: No.
> JH: What is the reason… if you want to explain… why did the knife get warmer than the piece of wood? /…/
> Anna: Well… if you have a wooden spoon and a metal spoon in a pot [example related to item 2 from pretest] then, there is, like, material in this [refers to the metal knife] that gets warmer, or something… when you have this [wooden piece representing the spoon]… the wooden spoon gets warm, right… but not as warm as… this one [shows knife in reference to metal spoon] gets extremely warm… /…/ Like, for example, a hair straightener… because it gets really, really warm when you straighten your hair.

Upon analysis of the exchange above, we first see how Anna conceptualised the "warming up" process of the wooden and metal objects in terms of "pulling away", i.e. relating to a rate of change of temperature, possibly analogous with an upward spatial movement on a temperature scale (e.g. on a mercury thermometer). Secondly, when Anna was probed to explain the observed outcome that the knife got warmer than the piece of wood, she related this interpretation to her previous experiences, both in recalling the similar pre-test item describing a wooden and a metal spoon submerged in hot soup (Appendix I, item 2) and to her everyday experience of the "hotness" of metal hair straighteners. It appears that she conceptualises metal as a substance that can "get warm easily" but also easily "gets cold", i.e. being more sensitive to temperature changes in comparison to wood. Incidentally, this awareness of the sensitivity of metal to temperature change is also manifested when Anna advises Karin not to hold the piece of metal for too long when they later perform task 3 outdoors (Appendix II), in order not to bias the measurements.

Similarly, after obtaining measurements with the digital thermometers (in the thermometer condition) when his thumbs are first placed in contact with the metal and wooden objects, and then removed (item 2, Appendix II), Lasse concludes that the temperature of the metal "rises and sinks much quicker than [for] wood". The pupils' explanations offered here are consistent with the findings of Clark (2006) and Lewis and Linn (1994), who found that pupils interpret metals as having extreme temperatures. However, in contrast, the realisation of the participants in this study that metals are sensitive to temperature change may serve as a constructive anchoring conception for more advanced thermal concepts, such as thermal conductivity and heat capacity of different materials.

Episode 3: Engaging conceptions of heat as a substance. Consider the following exchange obtained from a pupil-pair in an IR-camera condition when explaining why the knife felt cold in response to item 3 (Appendix II):

> Lisa: But the knife feels colder than it [really] is.
> JH: So it's the knife that is a bit strange?
> Lisa, Maria: Yes.
> JH: …in a way you didn't think it would…?
> Lisa: Mhm.
> JH: Yes. Can you explain what that depends on… do you think?
> Lisa: Maybe the beanie holds the heat longer, or something…
> Maria: Mhm.
> JH: The beanie holds the heat better?
> Lisa: Yes. So it's maybe still warm… from when it was, like, inside… or something… maybe…
> JH: They have been outside pretty long.
> Lisa: Okay, I see…
> Maria: The knife takes up [absorbs] the cold better…
> Lisa: Mhm. But when the knife… once the metal gets cold, it's like cold for long… very cold.

Analysis of the datum above suggests that Lisa engaged the idea of heat being "contained" or "held" in the beanie for a long time. On this note, Maria contrasted this reasoning with the properties of the knife, which was construed as a good recipient "absorber" of cold. This implies a substance conception of heat, in parallel with other work by Erickson (1985) and Lautrey and Mazens (2004).
In particular, in support of findings from Brook et al. (1984), this pupil pair reveals conceptions of "heat" and "cold" akin to being two *different* kinds of substances that can be held within and transferred between objects. However, in this context, in contrast to the examples seen above where metal was viewed as sensitive to temperature changes, in this instance, metal is assumed to have a stable temperature once it has become cold. Interestingly, Lisa engaged her idea that the beanie had retained heat from when it was indoors upon trying to explain why it feels warm outdoors. Even though the idea of thermal equilibrium – that

objects in thermal contact tend towards the same temperature – was not expressed explicitly by the participants, in line with previous research (Clark and Jorde 2004; Yeo and Zadnik 2001; Lewis and Linn 1994), Lisa's exposure of the idea of the beanie 'still' being warm when placed outside may mirror a precursor of the concept.

In addition to the datum above, the following excerpt is taken from Kalle and Sven while they responded to task 2 (Appendix II) in the IR-static condition. While analysing the IR-static images, the following is what transpired while they explained to each other what would have happened to their thumbs immediately after having being in contact with the wood and metal objects:

> Kalle: The [My] thumb gets colder. And the thing [metal or wooden object] you hold, it gets a bit warmer…
> Sven: …where you had the thumb, it gets warmer…
> Kalle: Mhm [Yes], it gets a bit warmer, because you push the heat from…
> Sven: Yes, and then…
> Kalle: …the thumb gets colder…

The datum above serves as another example of pupils' use of the word 'heat' as a noun during the laboratory exercises, which implies attaching some-or-other substance quality to the interpretation of heat. Moreover, as part of the same utterance sequence, Kalle and Sven provide a further example of the idea of something flowing from one object to another, as exemplified in the following exchange when asked by author KS to explain their observation of their thumb heating the metal:

> Kalle: Well, the metal gets… a bit warmer…
> Sven: …because the temperature in the hands, it, like…
> Kalle: …the temperature in the hands… if you put your thumb [on a metal object] and press on it… then the thing [object] gets warmer.
> KS: Why?
> Sven: Er, the temperature in the body, it, like… it ends up on the metal… or, like this… the metal gets warmer when you touch it…

The excerpt above suggests that Sven attempts to construe the process in terms of some kind of substance transfer from the thumb to the metal, expressed in the sense of 'temperature in the body ending up on the metal', as if it has some material property that can be extracted. With respect to this finding, Lewis and Linn (1994) have reported a similar pupil response to why metal feels cold, in which one pupil stated: "Body temperature is going to the objects that feel cold", whereupon the authors consider this reasoning as an example of using scientific terms inappropriately, and reflecting a misconception of temperature as an extensive quantity. However, in Sven's case, he appears dissatisfied with this way of expressing himself, and rephrases himself in a way that he is more confident with, as the metal getting warmer when it is touched by the thumbs. Speaking of temperature as something that ends up somewhere else could come across as strange in everyday language. In our interpretation, searching for a suitable term for what may flow from the thumb to the metal, and without access to formal concepts of either 'heat' or 'energy', Sven seems to use 'temperature', a noun related to thermal phenomena, only reluctantly. In general, in the context of what happened when the participants touched the objects with their thumbs, the most common ways of expressing the experience was in terms of the objects 'getting warmer' or 'warming up' and of the temperatures 'going up', and not in terms of some entity flowing from here to there. In contrast to the findings of Lautrey and Mazens (2004), albeit among 8-year-olds, the conception of heat as a substance residing in or flowing out from warm objects, corresponding largely to the abandoned caloric theory of heat, was not very common in the current study. Lisa's idea in her posttest response of heat as spatially located, "something that can be anywhere", is one of the few cases that got close to the idea of heat as substance-like. On this note, it can be seen as promising that the pupils are not hindered by any caloric-like conceptions of heat, which is well known to be an obstacle to grasping a thermodynamics account of thermal phenomena. However, the pupils seemed to struggle to engage *any* extensive concept involved in thermal processes, be it energy or heat, lending support to Arnold and Millar (1996).

Nature of pupils' interactions with the inquiry tasks, artefacts and each other

Data obtained from pupils' interactions during the practical task across the IR-camera, IR-static, and thermometer conditions revealed interesting aspects regarding how the pupil-pairs approached the tasks, how they interacted with the equipment and task artefacts, and how they conversed with each other. Such data revealed dimensions related to the nature of pupils' processes and actions associated with executing the discovery and inquiry-based tasks.

Confidence in interacting with novel equipment

The pairs that recorded measurements during either the IR-camera or thermometer conditions did so in a confident way, without much hesitation or fear of attaining a 'wrong' answer. Actually, Lisa and Maria immediately immersed themselves into obtaining measurements with the IR camera without reading the task instructions (Appendix II) very carefully, nor spending much time on making predictions before performing the measurements, or explaining the observed results. At times, they had to be encouraged by the researchers to spend more time reflecting upon different components of the tasks before continuing. For instance, consider the following interaction obtained when Lisa uses the IR camera to observe what occurred when Maria touched the objects with her thumbs in task 2:

> Maria: Should I put my thumbs on…? [puts her thumbs on the objects]
> Lisa: Mhm [picks up the IR camera, and places it back on the table]
> KS: Wait, wait. [points to the IR camera] What does the instruction say? /…/
> JH: If you describe the patterns that have appeared…
> Lisa: It becomes, like, blue… But we were supposed to check when she removes [her thumbs]… what happens then… /…/ What is meant by 'pattern'?
> JH: Well, or what the colours look like, so to speak… for the two objects…
> Lisa: Well, they're blue… That [points to the knife] is warmer… the piece of metal is warmer…
> Maria: [than] the wood…
> Lisa: Yes. Should we remove them?
> Maria: Yes, let's do that… [She removes her thumbs. The temperature scale recalibrates automatically.]
> Lisa: [Directs the IR camera to the objects] It is… [laughter] It got really warm on the piece of wood! And look at that! [directs the IR camera to the knife and laughs]
> Maria: [touches the piece of wood briefly and laughs] That's cool!
> Lisa: Yes, that's cool!

Although the datum above clearly provides confirmation of the pair not being familiar with performing laboratory work in a "methodical" or "recipe-like" manner, their diving straight into the task at hand with enthusiasm and motivation surely correlates well with the intention of any discovery or inquiry-based educational approach. On this note, a high level of motivation, curiosity and excitement is clearly apparent. This datum certainly supports the assertion that the pair was enthusiastic about interacting with the equipment and excited about the dynamic images that were generated. In this regard, such interaction is a clear case of the 'wow factor' (Chandler 2009) at play, which bodes well for the promises of discovery in learning. When it comes to the measurements, the temperature range was large during the time that both the hands and the two objects were in focus (20-37 °C). Therefore, the background and the two objects were displayed largely in blue while Maria held her thumbs in contact with the objects, and it may have been difficult to discern the subtle changes in temperature upon heating. The temperature scale recalibrated when she removed her thumbs, resulting in the "cool" images where the knife and the piece of wood appeared richer in contrast.

Overall, the participants were very confident in their interaction with the equipment, even though it was their first encounter with IR technology in this context. During the measurement, Lisa had used the screenshot functionality on the IR camera to take static pictures of the IR dynamics when Maria held her thumbs to the knife and piece of wood. After the measurement, author JH requested whether he could have a look at the still images:

> JH: You can click on that [clicks a button on the IR camera to display the pictures that were taken] then you get back to the objects…. /…/ There you can click… no, that was a 'delete'… maybe that was not very good…
> Lisa: Maybe the arrows… [laconically]
> JH: Yes, precisely… That [image] is a bit interesting… here you see… that [points to the image] is the piece of wood… /…/
> Lisa: The knife is kind of the same temperature… the whole…
> JH: Yes, you could see it in that way. /…/
> Lisa: And then you push there? [points to a button]
> JH: 'Close'. So, then you are back to measuring again.

The utterances above suggest that Lisa was not at all afraid of exploring the functionality of the IR camera, and appears familiar with taking still pictures and managing the recorded images when viewing them, behaviours which probably mirror her experiences with modern hand-held technology.

Interpretation of output from the measurement equipment

Apart from providing evidence of the confidence in the use of the equipment, the preceding excerpt also shows that when Lisa was encouraged by the researcher, she could describe the temperature pattern of the knife in terms of the whole knife having the same temperature. However, this manner of describing the two-dimensional colour image displayed on the IR camera either in terms of still images or dynamically in real time was rather uncommon among the pupils. There were no observed instances where the pupils interpreted the images as if something was being transferred or flowed from the thumbs to the objects. Instead, pupils often tended to use the IR camera as a thermometer, rather than as a piece of equipment that renders infrared imagery. An example of this interaction is presented from an exchange in task 2 whereupon Karin had held her thumbs in contact with the metal and wooden objects for about a minute, and Anna proceeds to conduct measurements with the IR camera thereafter:

Anna: That… the piece of metal… it's been like a minute now… it has [is] about 24 degrees…
JH: The knife?
Anna: Yes. And the piece of wood has [is] 23…
JH: So, it looks as if… you said that the knife has become a bit warmer… one degree warmer than the piece of wood…?
Anna: Mhm. /…/ Okay, maybe it has been two minutes now…
Karin: Yes. Okay. [Removes thumbs]
Anna: The piece of metal is 24 degrees… point 1… and the piece of wood is 22… point 4… something like that…

The datum above provides evidence suggesting that the pair particularly focused on reading the temperature numerals on the screen of the IR camera at the locations where the screen cursor was directed (see Fig. 2b, 2d and 2f). This interaction was not unique to the IR-camera condition, and was in fact similar to the way Lasse and Pelle interacted with the digital thermometers in the thermometer condition. Consider the following interaction where Lasse touches the wood with his thumb and Pelle touches the knife (item 2, Appendix II):

Lasse: Mine [the thermometer reading of the piece of wood] rose a bit.
Pelle: Mine [the thermometer reading of the knife] went down. Now it rose by two [tenths of a degree]
Lasse: Mine is 21.8.
Pelle: Mine is 22.9, no, 23.0.
KS: Discuss with each other. What do you see? /…/
Pelle: Mine rises all the time. It's 23.3 now.
KS: More [discussion]!
Lasse: Mine is 22.1.
KS: Good!
Pelle: Mine got up. It's 23.6 now.
Lasse: Strange. Yours [the knife] is warmer, but it feels colder.

Here, Lasse and Pelle approached the thermometer readings as a sort of competition between increasing temperatures. The process of becoming warmer appears to be interpreted in terms of increasing temperature.

One possible explanation for the similar measurement approaches of these two groups is that performing thermometer readings appeared the most obvious observation to make and focus on, while the offered infrared functionality of the IR equipment was often ignored. Complementary explanations could be that dynamic two-dimensional colour images demand increased cognitive processing and that the pupils were not acquainted with visual representations of thermal phenomena. Further reinforcement of this explanation may be supported by the observation that pupils had difficulty understanding what was meant by the expression 'temperature pattern' in the laboratory task sheet. The calibration of the IR camera to automatically adjust to the temperature range of the objects being measured may have also added to the difficulty of the interpretations.

Such possible processing challenges in interpreting the IR images was evident particularly for Sven and Kalle, who interpreted printed still IR images as part of the IR-static condition. In this regard, the data suggested they had difficulties realising that the first image given to them illustrated that the knife and the piece of wood actually had the same temperature, but they seemed to take for granted that the knife would be colder. Gradually, they got better at interpreting the visual representations of the thermal phenomena as the exercise progressed. However, in the final outdoor exercise (Appendix II, task 3), they mismatched the physical dark blue colour of the beanie with the colour coding display on the IR camera, and superficially interpreted the beanie to be considerably colder than it actually was. In light of this finding, Lowe (e.g. Lowe 1993) has demonstrated that novice pupils often construct superficial mental models of scientific phenomena that are based largely on salient visual features of a display, rather than on the underlying knowledge of what the visual markings intend to represent. In this regard, novices tend to organise their information-processing of visual displays on surface-features alone.

Overall, the results suggest that although the pupils were confident in handling the technology, it was challenging for them to interpret the measurement output without any direct guidance from the researchers. A consequence of this result is that providing a discovery learning environment in this context cannot go without some kind of scaffolding in order to bring about meaningful learning.

Emergence of cognitive conflict scenarios across the task conditions

In addition to the findings related to pupils' exposure and engagement of heat-related concepts, and their interactive behaviours with the equipment across the conditions, the data also showed evidence of certain anomalies being exposed during pupils' conduction of the tasks. We suggest that such data provides an indication of how certain cognitive conflict scenarios could be induced and created upon pupils' exploration during the discovery-based POE tasks.

The pupils experienced that the metal knife felt colder than the piece of wood, both at room temperature and outdoors during a chilly autumn day, but that the two compared objects were shown to have similar temperatures when measured with an IR camera or digital thermometer. Below, the associated bewilderment of this anomaly is expressed by Karin and Anna when they obtained their first measurement of the temperatures of the knife and piece of wood during task 1 (Appendix II):

> Anna: [she directs the camera] Okay, the piece of wood is 20… yes, 20 degrees. 19, 20, so we were right. /…/ And then, there's the piece of metal… [she directs the camera] we have… it's 21 degrees! [giggles] Yes, it is. That's what it says… /…/ That is strange!
> Karin: That's maybe because we touched it, too. /…/
> Anna: But here [IR image on camera] it says that it [the knife] is 22 degrees.
> Karin: Wow! This… [touches the piece of wood and the knife]. But now, this [the knife] has got warmer!
> Anna: Let's feel… [touches the knife] But it is still colder [touches the knife and the piece of wood]
> Karin: Yes, a bit colder, but…
> Anna: I think that this [touches the piece of wood] feels like, well, normal… This [takes the knife] feels very cold. Yes.
> JH: Can you explain… next step here [points to the instruction sheet] 'explanation'… how does it fit together…? Your predictions… this [points to the knife] was supposed to be about 10… this [points to the piece of wood] was supposed to be about 20… but what do you see with the heat camera…?
> Anna: I think that is because… wood, it has, like... this [picks up the knife] is so hard… or, well… [giggles, puts the knife back onto the table] I really don't know why!
> Karin: Me neither!

In a similar fashion to what was observed by this pair previously during the exercise, Anna and Karin rely heavily on utilising their sense of touch as a thermometer, and are clearly baffled by the apparent contradiction observed from the scientifically accurate readings on the IR camera. This datum reveals the creation of an anomaly of the conflicting multisensory input in the form of the tactile perception of the cold metal, but observing through the IR visual display that the temperature of the metal is in fact the same as the surrounding temperature. It should be noted, however, that opposed to the findings of Lewis and Linn (1994) among adults performing similar laboratory exercises on the temperature of metal, the participants of the present study never questioned the readings of the equipment, whether in the digital thermometer condition or in the IR camera condition as a way out of their conundrum. In an attempt to resolve the anomaly, Karin puts forward the tentative explanation that the knife had actually become warmer due to the fact that they had touched it, but Anna remains unconvinced of this notion. Clearly, the knife still feels colder.

At the close of the exchange, the pair resigns to not being able to provide an explanation for the contradictory results. In this respect, the datum provides firm evidence for the clear construction of a cognitive conflict. The frustration of not being able to provide an explanation is probably captured most clearly when Anna reflects upon the observations after having completed task 2 by asserting, "But metal really is just colder!". From a conceptual point of view, she expresses the notion that a particular material has a certain natural temperature associated with it, regardless of the circumstances, in support of one of the central target misconceptions of interest to this study. This also reinforces results reported by Brook, et al. (1984) and Erickson (1985), but seemingly in contrast to her earlier conveyed idea of metals being associated with "changing temperature easily".

All four pupil pairs experienced the anomaly between perceived 'coldness' and temperature readings. For instance, in Lasse's final remark in the excerpt in the previous results section, we saw that he was able to relate the readings of the thermometer to the physical sensation of the knife feeling colder than the piece of wood and realise that it was "strange". However, a more pronounced cognitive conflict was induced in the IR-camera condition. In this regard, the anomaly appeared much more intriguing to these pairs and there seemed to be a more affective and emotional dimension associated with experiencing the anomaly via the real-time IR visualization. If so, this event can be exploited not only for engendering pupils' motivation about scientific phenomena, but as a multisensory experience that provokes pupils at a deeper level of inquiry. When Anna and Karin completed their outdoor laboratory exercises (item 3, Appendix II), they had still not come to terms with the impact of the conflicting sensory input, as portrayed in the following exchange:

> JH: But why is it that they [the piece of wood, the knife and the beanie outdoors] still seem to have the same temperature?
> Anna: It's probably because it's outdoors… so it's cold… But that… when we touch them with our hands… it gets much warmer [touches the objects]… or warmer… and this [the knife] gets cold and hard and 'yuck'… well…
> JH: What do you think? [looks at Karin]
> Karin: But I think about the same… that, like… this [the knife] feels really cold… well, I don't know… /…/
> JH: But still, they have the same temperature…
> Anna: But I don't understand why.
> Karin: Me neither…
> JH: It's just hard to understand…
> Karin, Anna: Yes.

At the close of the exercise, the pupil-pair still resorted to their tactile sense as the ultimate source of validity of their observation, yet could not provide satisfactory explanations. Overall, the anomaly was observed in all four pairs in varying states of expression, but none managed to resolve the issue by developing a convincing explanation for solving the incongruity in perceived temperature.

Discussion

In framing the discussion of this paper, we first revisit the research questions in light of the results that emerged against the presented literature, followed by drawing conclusions and formulating implications for practice and future research.

Revisiting the research questions

What are pupils' conceptions of heat and temperature prior to any formal physics teaching of thermal phenomena?

The results support the existing literature that three target misconceptions concerning heat – that our sense of touch is a good thermometer, that metal is inherently cold and that heat and temperature are roughly interchangeable – are held among 12- to 13-year-olds, and that they certainly are robust.

In addition, the pupils in this study do not conceptualise warming of objects in terms of heat transfer, and do not readily embrace a substance-like conception of heat, as something that resides in warm solid objects and can flow from one object to another. From a science education perspective, at first glance, the finding does not come across as very alarming. In fact, the conception of heat as a substance has been put forward as a robust misconception that provides an obstacle to grasping the interpretation of heat in thermodynamics among older pupils (Erickson 1985). In thermodynamics, internal energy or thermal energy typically plays the role of being an extensive property of an object, which can effectively be conceptualised as a substance residing in warm objects; the warmer or the bigger the object, the more energy it contains. However, in the case of the pupils in the current study, they make only very limited use of such substance-like quantities and the word 'energy' is not used at all. They do not seem to be in possession of a suitable word for what it is that may be transferred from a warm to a cold object, and therefore have difficulties seeing this phenomenon even when facilitated with an IR camera. This scenario possibly parallels the situation in the history of science before Joseph Black distinguished the intensive quantity 'temperature' from the extensive quantity 'heat' (Müller 2007).

How does interpretation of thermal images influence pupils' understanding of heat and temperature, compared to traditional laboratory approaches?

The findings of this work demonstrate the induction of a cognitive conflict between pupils' existing conceptions of heat and their experience of perceiving the thermal information generated by the IR camera. It is at this junction that the conflict between the visual information and pupils' existing beliefs about heat can be exploited in laboratory settings.

We had hypothesised that the pupils would experience cognitive conflict in a way similar to what happened when they performed the experiments. In other words, they recognised the anomaly in that their sense of touch and the IR camera and thermometers gave different readings of what they believed to be the temperature, and in contrast to some of the participants in the study by Lewis and Linn (1994), they did not resort to questioning the accuracy of the equipment.

This recognition of anomaly is the first crucial step in inducing conceptual change (Chinn and Brewer 1993; Posner et al. 1982), and it is acknowledged that such anomalies are not always easy to induce (Dunbar et al. 2007). In this respect, having brought students to an active cognitive conflict in the current context is a result in its own right.

Although cognitive conflict arose across all three of the conditions, it was more pronounced in the IR camera condition. Here pupils appeared more intrigued by the anomaly and they appeared to be more emotional as to the nature of the anomaly. In contrast, the pairs in the thermometer and static conditions appeared less disturbed and concerned by the anomalous data. One possible explanation for this is that perceiving the anomaly as a multisensory visuohaptic experience has a stronger perceptual impact in the form of combining the dynamic richness of the 2D colour image rather than merely 'reading off' a temperature reading on a thermometer or making 'offline' comparisons with static images. In this way, the conflict that arose in the IR camera condition was associated with an affective impact, a dimension which has been found to be a significant factor towards bringing about conceptual change (Pintrich et al. 1993).

Apart from setting up conflict, we had also hoped that participants would devise explanations involving heat flowing from the thumb to investigated objects, in order to explain why the knife felt colder and why the thumb that had touched the knife was colder than the one that was held in contact with the piece of wood. However, the pupils did not manage to resolve the anomaly. From a teaching perspective, it may be seen as a disappointing result for any direct quick-and-dirty implementation in revolutionising pedagogical practice, but it is nevertheless an interesting research finding, with respect to formulating and better understanding the pre-conditions for conceptual change.

To what extent can a non-guided discovery approach that combines tactile sensory input and thermal imaging technology foster conceptual change regarding heat and temperature?

This study provides some evidence to suggest that discovery learning on its own may not always be enough to induce conceptual change of abstract science concepts. Our study shows that introducing innovative technology in the form of IR cameras alone is not sufficient for learning aspects of heat.

The trend of discovery and inquiry-based approaches to teaching and learning has not been left without criticism. For instance, Mayer (2004) argues powerfully against pure discovery learning, where pupils are left to investigate physical and social phenomena in the world without guidance. Similarly, Kirschner, Sweller and Clark (2006) categorise inquiry-based learning and discovery learning as examples of minimal guidance approaches which simply have not led to good learning outcomes. However, in a response to Kirchner et al., Hmelo-Silver, Duncan and Chinn (2007) claim that inquiry-based approaches typically encompass extensive guidance and scaffolding of the learning process. The approach to 'guided discovery' developed by Brown and Campione (1994) is another case in point. Hence, the current consensus position seems to be that for effective learning, learners need guidance and scaffolding in the form of carefully designed learning environments and continuous assessment of the progress of their learning, combined with intervention by teachers and more experienced peers when required. In support of this notion with particular regard to exploiting augmented simulation in science education, a study by Dunleavy et al. (2009) has corroborated that to gain from such learning contexts, pupils have to be facilitated and scaffolded in the skills necessary for effective exploitation of modern augmented learning technologies.

Lastly, Dunbar, Fugelsang and Stein (2007) have provided neurocognitive evidence to suggest that when humans receive input that is inconsistent with a plausible theory, areas in the brain associated with learning are not necessarily activated and learning may even be actively inhibited. Provocatively, they conclude that, "from the perspective of science education these data clearly show that just presenting pupils with anomalies will *not* produce conceptual change". The search for effective ways to convert anomalies into coherent thought structures remains one of the holy grails of modern conceptual change research.

Conclusions and implications

The results presented in this paper serve as an early indication that mixing real-time visual and tactile modalities in the defined pedagogical context provides the opportunity for pupils to create cognitive conflicts about thermal phenomena. Actively prompting such conflict can contribute to laying the foundation for promoting cognitive assimilation and accommodation processes to facilitate pupils' construction of abstract, yet *core* scientific concepts. Moreover, the findings also suggest that adopting a purely discovery approach *alone* is limited in remediating robust misconceptions about heat and temperature uncovered in this study, which also continue to remain entrenched in the science education literature. Hence, an implication of the results is that designing educational contexts for exploiting IR technology as a vehicle for conceptual change must be supplemented with meaningful research-based guidance. On this score, the following points of departure shall inform future empirical inquiry:

1. Establishing the degree to which cognitive dimensions such as pupils' visual literacy skills (e.g. Schönborn and Anderson 2006) with respect to reading the graphical markings on the IR images, such as the blue-green-red colour scale, influence the interpretation of the infrared data (cf. Kali and Linn 2008). Promoting such visual literacy includes the qualitative mapping between the temperature "numerals" and the colour-scale IR patterns, as well as interpreting the automatic rescaling of the IR display.
2. Investigating what specific types of guidance and scaffolding (Hmelo-Silver et al. 2007) would be necessary to support pupils 'seeing' heat flow, and to discern extensive quantities such as 'heat' and 'energy'. Given the demanding level of abstraction associated with thermal phenomena, Matthews' (2004) comment on Galileo's study of the pendulum becomes highly relevant: "Despite people seeing swinging pendulums for thousands of years, no one, not even the great Leonardo da Vinci who studied pendulum motion, saw what Galileo 'saw'".
3. Exploiting dynamic real-time multimodal interaction and visualization, rather than still images. If educators have the desire for pupils to build the conception of heat as something that can 'flow' as a first step towards grasping extensive thermal quantities, they will have to actively 'see' it flowing, by reconciling conceptions with perceived experiences of the phenomena, in line with Kang et al. (2004). Utilising real-time IR imaging could accelerate this process by exploiting multisensory referential connections between haptic and visual perceptual channels (Moreno and Mayer 2007).

In conclusion, in line with the general premise of constructivism in starting from what the learner already knows (Ausubel 1968), Kang et al. (2004) suggest that any science teaching approach aimed at inducing cognitive conflict in learners must be coupled to first establishing pupils' pre-instructional conceptions. Doing so allows educators to define and understand the nature of pupils' potential conceptual obstacles, before considering and designing strategies for conceptual change. In this regard, this study has revealed some of the target misconceptions that could be candidates for conceptual change.

The results also suggest that if IR imaging is to be used in science teaching, interaction with the equipment should be preferably carried out in real-time, rather than with static images. Since interpretation of the static images requires a repertoire of content specific cognitive and visual skills that novice learners would not necessarily have at their immediate disposal, explicit instruction or carefully designed guidance would be required for effective teaching.

We acknowledge that the data revealed in this study was obtained from a limited number of participants. In addition, our collection of data was performed as an event not part of the pupils' day-to-day science curriculum. Nevertheless, the exploratory spirit purposefully adopted in this study provided us with rich data for analysing how pupils conceptualise heat and temperature, and how experiencing the anomaly of perceived 'coldness' and temperature readings through interaction with IR-technology could be conducive to the quest toward effective strategies for conceptual change.

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Fig. 1 Photographs of the equipment used in the laboratory task exercises in each of the *IR-camera* (a) and *thermometer* (b) conditions

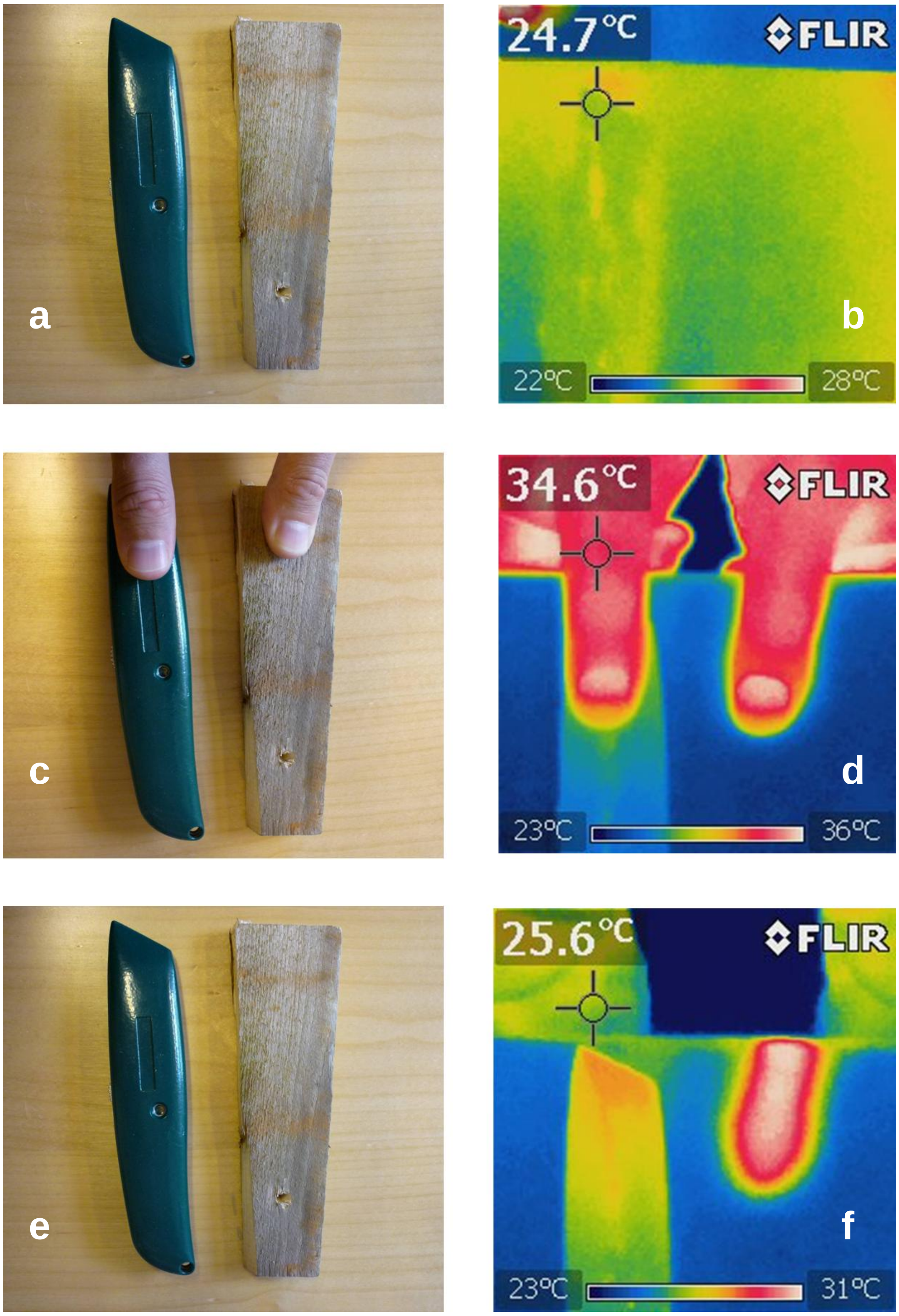

Fig. 2 Photos of the indoor laboratory set-up: a) knife and piece of wood; b) IR image of knife and piece of wood; c) thumbs in contact with objects after one minute; d) IR image of thumbs in contact with objects; e) objects after thumbs have been removed; f) IR image of objects after thumbs have been removed

APPENDIX I – Pre-/posttest

1. During your physics class, you are asked to explain what is meant by ‘heat’ and what is meant by ‘temperature’. How would you respond? Provide as much detail as you can.

2. A wooden spoon and a metal spoon are placed in warm soup. What will the temperatures of the spoons be after some time has passed?

3. Glowing embers of wood have a temperature of 400 °C or greater. Lisa claims that you can step upon the embers with your bare feet without burning yourself. Is she correct? Motivate your answer.

4. Sam takes a can of cola and a plastic bottle of cola from the refrigerator, where they have been placed overnight. He quickly inserts a thermometer into the cola can. The temperature reads 7°C. What are the most likely temperatures of the plastic bottle and the cola it holds?
    a. They are both less than 7°C.
    b. They are both equal to 7°C.
    c. They are both greater than 7°C.
    d. The cola is at 7° C but the bottle is greater than 7°C.
    e. It depends on the amount of cola and/or the size of the bottle.

5. Jan states that she does not like sitting on the metal chairs in a particular room because “they are colder than the plastic ones” in the room.
    a. Jim agrees and says: “They are colder because metal is naturally colder than plastic.”
    b. Kip says: “They are not colder, they are at the same temperature.”
    c. Lou says: “They are not colder, the metal ones just feel colder because they are heavier.”
    d. Mai says: “They are colder because metal has less heat to lose than plastic.”

    Who do you think is right?

6. Hanna conducts an experiment with ice. In the evening she places a mug containing water outdoors. A thermometer is placed in the water. By morning, the water has frozen solid and the thermometer reads -25 °C. It was a cold night! She returns the mug containing the ice into a freezer, which has a constant inside temperature of -18 °C. What will happen to the temperature of the ice in the mug as time passes?
    a. It will decrease below -25 °C (even further below 0).
    b. It will remain at -25 °C.
    c. It will increase, but not as far as -18 °C.
    d. It will increase to -18 °C.
    e. It will increase above -18 °C.

APPENDIX II – laboratory manual (real-time IR camera version)

1. **Objects at room temperature**
    a. *Prediction.* There are two objects of about the same size on the table, one made of wood and one made of metal. They have been left in the room at a room temperature of approximately 22 °C for a day. Touch them quickly. What do you think the temperature of the wooden object is? What do you think the temperature of the metal object is?
    b. *Observation.* Direct the IR camera towards the objects so that you can see both the wooden object and the metal object at the same time on the camera display screen. What are the temperatures of each object?
    c. *Explanation.* Explain your observations above and how they relate to your prediction. Discuss aloud between yourselves.

2. **Objects in contact with thumbs and after contact**
    a. *Prediction.* One of you will now touch the two objects simultaneously with your two thumbs, keep your thumbs in contact with the objects for two minutes, and then remove them. How will the temperature patterns of the two objects look during the time your thumbs are in contact with the objects? How will the temperature patterns of the two objects look afterwards? How will the temperature pattern on each thumb look afterwards?
    b. *Observation.* One of you holds your thumbs just above the two objects and the other directs the IR camera so that you can observe both thumbs on the camera screen. Touch the two objects at the same time and maintain contact for two minutes. While you do so, describe the temperature pattern that you observe on the camera. Lift your thumbs and keep the camera pointed at the two objects. Describe the temperature pattern. Then, point the camera to the surface of your two thumbs that were in contact with the objects. Describe the temperature pattern on the surface of your thumbs.
    c. *Explanation.* Explain your observations and how they relate to your prediction. Discuss aloud between yourselves.

3. **Objects outdoors**
    a. *Prediction.* Three objects of about the same size, one made of wood, one made of metal, and a woollen beanie, have been placed outdoors, and have remained there since this morning. Touch them quickly. What do you think the temperature of the wooden object is? What do you think the temperature of the metal object is? What do you think the temperature of the woollen beanie is?
    b. *Observation.* Direct the IR camera so that you can see all three objects on the camera screen at the same time. What are the temperatures of each object?
    c. *Explanation.* Explain your observations and how they relate to your prediction. Discuss aloud between yourselves.