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PUPILS' EARLY EXPLORATIONS OF THERMOIMAGING TO INTERPRET HEAT AND TEMPERATURE

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Abstract. *In thermodynamics teaching, pupils have been found to confuse temperature and heat, and to conceive touch as an infallible thermometer. This study explored the potential of combining the sense of touch with infrared (IR) thermal imaging on pupils' understanding of heat and temperature. Eight 7th-grade pupils (12-13 years old) worked in pairs across three laboratory exercises (real-time IR imaging, static IR images, or thermometers) to predict, observe and explain (POE) the temperatures of different objects. An anomaly between perceived 'coldness' and measured temperature was induced among the pupils, but they did not manage to resolve this cognitive conflict. The pupils observed the objects getting warmer and increasing in temperature, but did not explain the experiments as involving a heat flow from their bodies to the objects. Successful explanation might require a combination of thermal imaging and the explicit introduction of a simple heat-flow model.*

Key words: *cognitive conflict, heat, multisensory experience, predict-observe-explain (POE), temperature, thermal imaging.*

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Introduction

The present study explores the potential of combining the sense of touch with real-time thermoimaging in a guided discovery predict-observe-explain (POE) (White & Gunstone, 1992) exercise with eight 12- to 13-year-old 7th-graders, prior to exposure to any formal teaching of thermal science. Recent work indicates that thermoimaging by use of infrared (IR) cameras could enhance and support pupils' inquiry and reasoning about heat transfer and related thermal concepts (Xie, 2011; Xie & Hazzard, 2011). We hypothesise that when augmented with pupils' touching of objects of different temperatures, the combined visuotactile experience could provide a perceptual platform for building meaningful conceptions of thermal phenomena by rendering the concepts actively 'visible'. Furthermore, apart from the representational form of temperature along a colour scale, IR cameras provide real-time visual data, thereby eliminating the traditional steps of first recording and then plotting data. In particular, pupils were asked to account for the fact that metal feels colder than wood at room temperature. The study is the first part of a broader research programme exploring the use of modern visualization technologies in learning thermal concepts in school physics education.

Predict-Observe-Explain as an Approach to Guided Discovery Learning

Discovery- and inquiry-based approaches to science education have been proposed to stimulate learning and motivation in curricular development (e.g. Rocard et al., 2007). Such approaches entail that pupils should be encouraged to discover natural phenomena, rather than merely being told about them, and that science learning should involve inquiry into pupils' own questions related to such phenomena. However, discovery- and inquiry-based education has not been left without criticism. For instance, Mayer (2004) argues against 'pure' discovery learning, where pupils are merely left to investigate scientific phenomena without guidance, while Kirschner et al. (2006) provide evidence that minimal guidance approaches simply do not lead to good learning outcomes. In response, Hmelo-Silver et al. (2007) claim that inquiry-based approaches often encompass extensive guidance and scaffolding, and the 'guided discovery' approach developed by Brown and Campione (1994) is a case in point. Accordingly, learners require scaffolding in the form of carefully designed environments and teaching intervention in combination with continuous assessment of learning progress.

In a POE exercise (White & Gunstone, 1992), pupils are first asked to predict what will happen with respect to a particular event, often a physical experiment or demonstration. Next, they are encouraged to observe and describe in detail what happens as they experience the phenomenon. Finally, they are stimulated to explain their observations against the background of their predictions, where any particularly interesting discrepancies are followed up. The POE teaching design provides a structure for directing pupils' attention to a particular phenomenon, where they are expected to observe and explain rather than being told what happens, thereby adhering to the ambitions of guided discovery.

Cognitive Conflict and Learning Science

Cognitive conflict as a consequence of a perceived anomaly has been put forward as an important step in inducing conceptual change, which is defined by Posner et al. (1982) as "fundamental changes" in a learner's set of conceptions of a phenomenon, closely related to Piaget's (1929) notion of "accommodation". According to Posner et al., "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" (p. 214). Accordingly, a cognitive conflict is pivotal in adjusting an existing conceptual ecology. Albeit so, research (e.g. Linn & Eylon, 2011; Smith, diSessa, & Roschelle, 1993) has recognised the usefulness of pupils' existing ideas as productive *resources* for knowledge integration with scientific ideas. This contrasts with the view of mere replacement of previous "misconceptions" with correct science concepts, but also places emphasis on careful curricular design. In this spirit, much research has recently been directed towards exploring how technology-based learning environments influence students' integration of pre-existing ideas into a coherent scientific worldview (e.g. Linn & Eylon, 2011).

Multimodal Processing of Information: Tactile and Visual Perception

Learning can be enhanced by building connections between sensory modalities (Moreno & Mayer, 2007). For example, in comparison with receiving visual information alone, combining auditory and visual information leads to superior knowledge transfer (known as the *modality effect*) (Mayer, 2005). Recent research has referred to a *visuohaptic modality effect*, which suggests that knowledge integration might also be promoted by simultaneously coordinating vision and touch (Schönborn, Bivall, & Tibell, 2011). Such an effect could be a means to disambiguate heat and temperature concepts. 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, with vision usually dominating. Studies investigating different types of "intermodal conflict" (e.g. Hershberger & Misceo, 1996) have revealed varying dominance, and in some cases, the visual and tactile senses weigh the perceived intermodal information almost equivalently (e.g. Lederman & Abbott, 1981). The visual information generated on the screen of a thermal camera is a graphical supplement to a human's already existing perception of the world. Here, in augmenting tactile interaction with real-time thermal imagery, both processes coexist in a combined real and computer-visualized space.

Human perception of temperature through touch is by no means an accurate thermometer. Heat and cold receptors in our skin do not react to temperature, *per se*, but to *changes* in skin temperature, and it is the thermal conductance and heat capacity of different materials that determines our percep-

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tion of what material an object may be composed (Jones & Berris, 2002). Given that without any visual experience of 'invisible' phenomena such as 'heat flow', learners will naturally rely on tactile perceptions to comprehend phenomena, inadvertently reinforcing beliefs such as some materials being intrinsically colder than others. Since human knowledge construction is closely linked to sensorimotor interactions in the world (e.g. Barsalou, 2008), we also of course rely on somatosensory experiences to learn science (e.g. metals really do feel colder than plastic at room temperature). Therefore, learners will often construct their understanding of thermal phenomena by depending heavily on what they have felt but not seen. Nevertheless, even if one could suddenly be able to see such phenomena, one would have to learn to interpret new visual input in this context; a requirement that in itself would demand novel visual literacy skills (Schönborn & Anderson, 2006).

Conceptions and Misconceptions of Heat and Temperature

Science education research has identified a broad range of challenges in learning thermal science, including misconceptions or alternative conceptions of heat and temperature held by students at different ages (Sözbilir, 2003; Yeo & Zadnik, 2001) The following three reported conceptions constituted the *target misconceptions* of this study, since they can be assumed to be held by many 12- to 13-year-olds, the age at which physics commences as a formally taught subject in Sweden, and IR cameras might be expected to help address them:

- The tactile sense is a good thermometer (Clark & Jorde, 2004; Yeo & Zadnik, 2001).
- There is no difference between heat and temperature (Erickson, 1985).
- Some substances are naturally colder than others, e.g. metals are inherently cold (Brook, Briggs, Bell, & Driver, 1984; Erickson, 1985).

Overall, Erickson (1985) suggests that pupils fail to interpret touching different objects at room temperature in terms of heat transfer, but instead attribute *ad hoc* inherent properties to the materials, such as metals feeling cold due to their ability to "attract" cold. Lewis and Linn (1994) even found that adults experiencing that materials of the same temperature may feel different to the touch often question the accuracy of the deployed thermometers, indicating the strong reliance on the sense of touch in their judgment. Additional relevant student 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, very cold or very hot, also when surrounded by objects of less extreme temperatures (Clark, 2006; Lewis & Linn, 1994).
- Heat and cold are opposite fluid substances (Brook et al., 1984).

Model-Based Science Education and a Simple Heat-Flow Model

Gilbert (2004) argues that a well thought out use of models and modelling may provide a route to more authentic science education than what is typically found in our science classrooms. It would be characterised by the representation of processes in science, showing its element of creativity and providing insight into the nature of satisfactory explanations of phenomena in the world-as-experienced. The field of thermal science and its historical development offers many opportunities for model-based science education. An example is to follow in the footsteps of Joseph Black, as he disambiguated the notions of 'temperature' and 'heat' in the 18th century, and introduced 'latent heat', in developing a model for the constant temperature as heat is added to systems undergoing phase change, e.g. ice melting into water. Another example, and perhaps even more relevant to the current study, would be to introduce a simple macroscopic model of heat flowing from an object of higher temperature to an object of lower temperature with which it is in thermal contact, until thermal equilibrium is established. As a reaction to reported misconceptions of heat and temperature, Erickson (1985, p. 59) has proposed the following regarding metals feeling cold at room temperature:

> If pupils were able to 'see' this phenomenon 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.

Accordingly, Arnold and Millar (1996) developed a model-based teaching sequence that focuses on the interrelationship between 'temperature', 'heat' and 'thermal equilibrium', adopting 'heat' as the main extensive thermal quantity, which is stored in and flows from warm objects. Similarly, Linn and Eylon (2011) have relied primarily on a macroscopic 'heat flow' model in the development of Grade 8 thermal science within their *Knowledge Integration framework*. Furthermore, Rosebery et al. (2010) report a teaching intervention on thermal phenomena in Grade 3-4, centred around a poster in class expressing, "Heat always flows from objects at a higher temperature to objects at a lower temperature" (p. 333). After a series of inquiry-based exercises, pupils were found to apply the heat-flow model to their bodies following a school fire-drill performed on a cold day, arguing that they needed their coats to trap their body heat.

Use of Thermocameras as a Tool for Enhanced Learning

An IR camera detects infrared radiation, which is emitted from all solid and liquid objects, and renders corresponding temperatures of the objects' surfaces. Vollmer, et al. (2001) have suggested the application of infrared technology to visualize thermal phenomena in teaching. Atkins, et al. (2009) studied a science museum exhibit that involved IR technology. They found that detailed task instructions were inhibiting for the visitors, who tended to explore the IR camera functions in imaginative ways separately from the provided instructions. With prices of IR cameras continuously decreasing, their application is becoming rapidly feasible for educational laboratory exercises. In addition, a recent development has seen FLIR (2014) debut the first smartphone attachable IR camera. Xie (2011; Xie & Hazzard, 2011) has argued that IR technology presents powerful learning opportunities for visualizing unobservable thermal processes. For instance, an IR camera allows learners to *see* thermal conduction through metal (See Figure 1). In this way, pupils are no longer restricted to only 'seeing' heat flow in their mind's eye, but can physically see the phenomenon in real time. However, studies on the use of IR cameras in education are scarce, and no empirical research has been published on their use in secondary physics teaching.

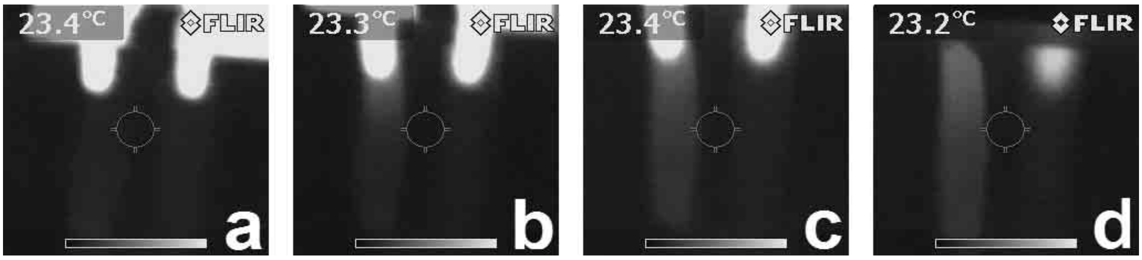

Figure 1: Sequence of thermographs displaying heat flow in a knife (on left) and a piece of wood (on right) during and after thumb contact.

(a) At the moment when thumbs are placed in contact with the objects. (b) After one minute of thumb contact. (c) After two minutes of thumb contact. (d) After thumbs have been removed. Notice the uniform temperature distribution on the knife compared to the localised 'heat spot' on the piece of wood.

Purpose of the Study

The study aims to investigate pupils' explorations of thermal imaging technology in relation to ideas of heat and temperature, corresponding to the following research questions:

- What are pupils' conceptions of heat and temperature prior to physics teaching of thermal phenomena?
- What is the potential of a POE approach that combines the sense of touch with thermal imaging in pupils' interpretation of thermal phenomena?

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Methodology of Research

Pupils and Study Context

Learners without prior exposure to any formal teaching of heat participated in the study in order to explore to what extent novel versus traditional measurement equipment influenced understanding of thermal concepts. Eight (n = 8) Grade 7 (12- to 13-year-old) participants (four boys and four girls) who attended a typical municipal secondary school in Sweden participated in the study. The school prides itself in being technologically innovative and welcomes research initiatives that explore novel educational approaches. The ethical requirements stipulated by the Swedish authorities for conducting educational research were strictly adhered to. Pseudonyms are used in the text to render the participants anonymous.

Data Collection

The data collection sequence was as follows. First, the eight pupils responded to an individual written pre-test. Second, the pupils were paired randomly, and each of the four pupil pairs was assigned to and performed a specified POE exercise. Third, the eight pupils completed an individual written post-test. Fourth, the pupils were debriefed by receiving a 20-minute lecture on the purpose of the study, including an explanation of the concepts involved.

Written Pre-/Post-Test

The written pre-/post-test (see Note at end of paper) comprised three open-ended and three closed multiple-choice items, which all aimed to probe pupils' understanding related to the target misconceptions. Items were adapted from international science education literature and published concept instruments (see Andersson, 2006; Paik, Cho, & Go, 2007; Yeo & Zadnik, 2001) to ensure a high content and construct validity for exploring pupils' understanding of heat-related phenomena. The pupils took approximately 10-15 minutes to complete the pre- and post-test on each occasion.

Practical POE Laboratory Tasks

Three laboratory predict-observe-explain (POE) tasks (White & Gunstone, 1992) were designed, namely an *IR-camera*, an *IR-static*, and a *thermometer* exercise (see Figure 2).

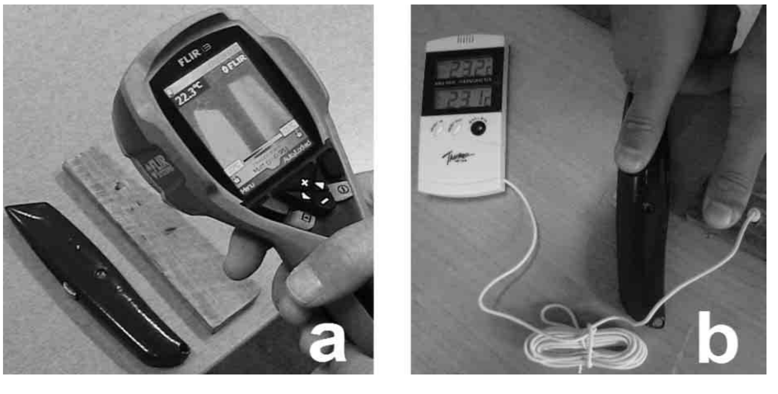

Figure 2: Photographs of the equipment used in the laboratory POE tasks.

(a) A thermocamera is directed at a metal knife and piece of wood showing the corresponding real-time IR display that is viewed by the user. (b) The temperature of each object during thumb contact is shown being measured with a digital thermometer.

In the *IR-camera* task, the pupils interacted with a *FLIR i3* infrared camera that renders real-time coloured thermal images of objects, and displays the temperature with a precision of 0.15 °C. For the study, the emissivity coefficient of the IR camera was set to 0.95, close to the emissivity of the knife paint coat (0.96) and identical to that of wood (0.95), as listed by The Engineering Toolbox (2012), ensuring adequate temperature readings. The *IR-static* exercise required the pupils to interpret static coloured paper-based images generated from the same camera, while interaction with *thermometers* constituted the traditional laboratory exercise. For this exercise, an outdoor metal temperature probe connected to a digital thermometer with a precision of 0.1 °C was used.

To make the POE exercises authentic, the pupils investigated objects that they would encounter in everyday life: a painted sheet-metal utility knife, a piece of wood, and a woollen beanie. Each respective POE exercise required the pupils to predict, observe and explain three phenomena: 1) objects at room temperature; 2) pupils placing their thumbs in contact with objects for two minutes (see Figure 1 for a grey palette version of the thermal imaging); and 3) objects placed outdoors on an autumn morning. Of these three components, 1) was intended to induce cognitive conflict, 2) provided the opportunity to "see" heat transfer, and 3) was used for knowledge transfer across contexts. The actual coloured thermographs associated with the IR-camera and IR-static laboratory tasks used in the study together with the laboratory instructions for the IR-camera group are available to the reader as supplementary material (see Note at end of paper).

For the POE tasks, two pupil pairs carried out the IR-camera exercise, and one pair each conducted the IR-static and thermometer exercises. Although no time constraint was set, the pupils spent approximately 20 minutes on each POE exercise. Each pair's execution of the POE tasks was video-recorded. Authors KS and JH monitored the POE tasks and intervened with conceptual questions when the need arose, such as when pupils' verbal utterances and interaction waned or became unfocused.

Data Analysis

All participants communicated in Swedish. Author JH, of Swedish mother tongue, and bilingual with English, transcribed the video recordings verbatim and translated the Swedish written and oral utterances into English. JH and KS analysed the Swedish dialogue of the original transcripts, and collaborated in communicating the data in English as presented in the Results of Research. The analysed data corpus consisted of learners' written responses to the pre-/post-test, video recordings of the POE tasks, IR-camera screenshots taken by the pupil-pairs, verbatim transcripts, and field notes penned by KS and JH.

Analysis of the data proceeded as follows. First, responses to the pre-/post-tests were coded to determine which target alternative conceptions were exposed by the pupils. Second, the transcripts were qualitatively analysed by identifying and constructing themes from the data relating to heat and temperature (Lincoln & Guba, 1985). The videotapes were also analysed for any patterns related to the pupils' interactions with the equipment, objects and with each other. Third, emergent themes from the POE data were contrasted with the findings from the pre-/post-test data. All three authors discussed the nature of the emergent themes, and agreed on representative dialogue excerpts and interpretations of them.

Results of Research

The findings of the study are presented in three sections. Firstly, the pupils' exposure and engagement of conceptions of heat and temperature are described from two perspectives: i) the pre-/post-test, and ii) pupils' dialogue in the laboratory exercises. Secondly, the pupils' behavioural interactions with the equipment, investigated objects and with each other are presented. Thirdly, cognitive conflict scenarios from pupils' dialogue are revealed.

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Pupils' Exposure and Engagement of Heat and Temperature Concepts

Identifying the Pupils' Conceptions of Heat and Temperature Before and After the Laboratory Tasks

The pupils' responses to the pre-/post-test were used to probe their 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-/post-tests. In total, the pupils answered 4 items correctly in the pre-test (17 %) and 3 correctly in the post-test (13 %). As a whole, this result suggests that the pupils' overall conceptual understanding of heat as measured by the closed-response items did not improve from interacting with the POE laboratory tasks. Collectively, this result also demonstrates the general lack of a scientific conceptual understanding of heat and temperature among the pupils in this study.

In addition to the closed items, free response questions related to the pupils' conceptions of thermal phenomena were employed. One such free response test item asked the pupils to explain what was meant by the terms 'heat' and 'temperature' in as much detail as they could. In the pre-test, three of the pupils gave the following responses:

> Pelle: Heat is warm. Temperature is like a "degree" for how warm it is outside or in the body.
> Sven: 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.
> Lisa: Heat is something that is around all the time everywhere. Temperature is a particular number of degrees.

Several of the pupils conceptualised temperature as being related to how 'warm' or 'cold' something is, often connected to a measure or "degree". The conceptualisation of heat was more varied. Pelle provided a brief description of heat as associated to 'warm', 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 is spatially distributed, possibly a sign of a conceptual commitment to a substance ontology of heat (Chi, Slotta, & De Leeuw, 1994).

The Pupils' Thermal-Related Conceptions During the POE Laboratory Tasks

Metals are Colder than Wood. Apart from their emergence in the pre-/post-test, the pupils' conceptions of temperature were also exposed during the laboratory exercises. For example, the excerpt below shows the pupil pair of Karin and Anna making predictions related to the temperatures of the piece of wood and the knife. As they talk, they touch the objects:

> 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?

The pupils rely heavily on their sense of touch in predicting the temperature of the wooden and metal objects, relating to the target misconception that our sense of touch is a good thermometer (Clark

& Jorde, 2004; Yeo & Zadnik, 2001). In this excerpt, Karin and Anna both touch each of the objects and speak in terms of how cold they feel. 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 the target misconceptions of materials' inherent temperatures (Brook et al., 1984; Erickson, 1985).

Metals Get Much Warmer than Wood. The pupils also discussed how sensitive different objects are to changes in temperature. This is exemplified by Karin and Anna's predictions concerning what will occur when they place their thumbs in contact with the wooden and metal objects in task 2 of the exercise:

> 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. /…/
> Karin: Actually, I think so, too. This [touches the knife] got very warm [when they touched it briefly].

Anna predicts that the metal would be more sensitive to a temperature change than the piece of wood. Karin agrees with this idea, and relates it to the pair's recent experience of touching the knife and perceiving it to get "very warm". Subsequently, when the pair performed the experiment with the IR camera, they confirmed that the metal increased in temperature more than the wood, but not by as much as they had predicted:

> 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… /…/ But we were wrong. That [the metal] only pulled away by one degree… /…/
> JH: It did not pull away as much as you thought it would…? /…/ 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 pre-test] 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.

Here, Anna conceptualises the "warming up" process of the wooden and metal objects in terms of "pulling away", i.e. related to a rate of change of temperature, possibly as an upward spatial movement on a temperature scale. Secondly, when Anna is probed to explain the observed outcome that the knife got warmer than the piece of wood, she relates this interpretation to her previous experiences, both in recalling a pre-test item describing a wooden and a metal spoon submerged in hot soup 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. This awareness of the sensitivity of metal to temperature change is also shown when Anna advises Karin not to hold the piece of metal for too long when they later perform task 3 outdoors, in order not to influence the measurements. The pupils' explanations 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.

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Heat as a Substance. In the following exchange, Lisa and Maria, the other pair interacting with the IR camera, explain why the knife feels cold in task 3.

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… /…/ 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 the cold better…

Lisa engages the idea of heat being "contained" or "held" in the beanie for a long time, while Maria expresses that the knife is a good recipient "absorber" of cold. This implies a substance conception of heat, in parallel with the findings of Erickson (1985), for example. 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.

In addition, the following excerpt is taken from Kalle and Sven's work with task 2 in the IR-static exercise. While analysing the IR-static images, they reflect upon what would have happened to their thumbs immediately after having been in contact with the objects:

Kalle: The [My] thumb gets colder. And the thing 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…

In this exchange, Kalle uses the word 'heat' adequately as a noun in conceptualising heat transfer from his thumbs to the objects. 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…

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. Lewis and Linn (1994, p. 668) 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", reflecting a misconception of temperature as an extensive quantity. However, in Sven's case, he appears dissatisfied with this manner of expression, 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 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. The application of the idea of heat as a substance residing in or flowing out from warm objects was not very common in the current study. Kalle, in this exchange, and Lisa, in her pre-test response, are two of the few cases where the pupils got close to expressing the idea of heat as substance-like. The pupils seemed to struggle to engage *any* extensive quantity involved in thermal processes, be it energy or heat, lending support to the need to use heat flow approaches to introductory teaching of thermal science (Arnold & Millar, 1996; Linn & Eylon, 2011).

Nature of the Pupils' Interactions with the POE Tasks, Equipment and each other

Overall, all pupils – in particular those who interacted directly with the IR cameras – engaged with the tasks and equipment in a confident way. The IR camera came across as fascinating, and the work with the exercises showed clear evidence of a "wow factor" (Chandler, 2009) at play. When it comes to interpretation of the measurement data, however, the pupils rarely made full use of the two-dimensional colour display of the IR camera, in terms of still images or dynamically in real time on the screen. The pupils tended to use the IR camera as a thermometer, rather than focusing on the displayed infrared imagery. For instance, in task 2 Karin has held her thumbs in contact with the metal and wooden objects for about a minute, when Anna proceeds to conduct measurements with the IR camera:

> Anna: That… the piece of metal… it's been like a minute now… it is about 24 degrees… /…/ And the piece of wood 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…

The two of them focus on reading the temperature numerals on the screen of the IR camera at the locations where the screen cursor was directed. This interaction was not unique to the pairs interacting with the IR camera, and was in fact similar to the way Lasse and Pelle worked with the digital thermometers. Consider the following interaction where Lasse touches the wood with his thumb and Pelle touches the knife in task 2:

> 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. /…/ Pelle: Mine rises all the time. It's 23.3 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 is 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, as they were not used to interpreting IR images.

Emergence of Cognitive Conflict Scenarios

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The video data also showed evidence of certain anomalies being exposed during the pupils' conduction of the tasks, suggesting how cognitive conflict scenarios could be induced and created upon pupils' thermal explorations during the 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 a 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:

> 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…? /…/
> 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 their sense of touch as a thermometer, and are baffled by the apparent contradiction observed. This excerpt reveals the creation of an anomaly of the conflicting multisensory input in the form of the tactile perception of the cold metal, but seeing through the IR visual display that the temperature of the metal is in fact the same as the temperature of the surroundings. As 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 they used the digital thermometer or the IR camera as a way out of their conundrum. In an attempt to resolve the anomaly, Karin puts forward the tentative explanation that the knife has 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; preliminary evidence for the induction of a cognitive conflict. The frustration of not being able to provide an explanation is captured most succinctly when Anna reflects upon the observations after having completed task 2 by asserting, "But metal really is just colder!". 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, 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". For the IR-camera pairs in particular, a salient affective and emotional dimension associated with experiencing the anomaly was observed. Overall, the anomaly was observed in all four pairs in varying ways of expression, but none of the pupils managed to resolve the issue by developing a convincing explanation.

Discussion

In the following discussion, the research questions are revisited in the light of the results of the study and against the background of the presented literature.

What are Pupils' Conceptions of Heat and Temperature Prior to Physics Teaching of Thermal Phenomena?

The results support the existing literature that 12- to 13-year-olds often hold two conceptions in relation to heat that are not entirely in line with the scientific view: that our sense of touch is a good thermometer; and that metal is inherently cold. Temperature is seen as a measure of how hot (or cold) objects are.

In addition, the pupils in this study do not conceptualise warming of objects with their thumbs in terms of heat transfer, and only rarely embrace a substance-like conception of heat in these particular contexts. From a science education perspective, at first glance, the finding may not come across as very alarming. Indeed, the conception of heat as a substance has been put forward as a misconception and an obstacle to grasping the interpretation of heat as a process depending on molecular motion (Chi et al., 1994; Erickson, 1985). However, the pupils in the current study make only very limited use of *any* thermal extensive quantity and the word 'energy' is not used at all. They do not seem to have a suitable word available for what it is that may be transferred from their hands to colder objects, and therefore have difficulties seeing the phenomenon of heat flow even when facilitated with an IR camera.

Given the pupils' seemingly limited preconceptions and resources for interpreting thermal phenomena, the introduction of a simple heat flow model seems to be an appropriate educational step to take. If they had been explicitly introduced to the idea that heat spontaneously flows from objects of higher temperature to objects of lower temperature, they might have been able to apply this model to the transfer of heat from their warm bodies to colder objects. This basic macroscopic model could later serve as a conceptual foundation for a more advanced understanding of heat in terms of molecular motion.

What is the Potential of a POE Approach that Combines the Sense of Touch with Thermal Imaging in Pupils' Interpretation of thermal phenomena?

The findings of this work demonstrate the induction of a cognitive conflict between pupils' existing conceptions of heat and their experience of perceiving the IR-camera output. The pupils in this study recognised the anomaly in the discrepancy between their sense of touch and the IR-camera and thermometer readings. In contrast to some adult participants in the study by Lewis and Linn (1994), they did not resort to questioning the accuracy of the equipment. Experiencing anomaly has been put forward as an important step in adjusting conceptions (Posner et al., 1982), and it has been acknowledged that people often ignore such anomalies (Dunbar, Fugelsang, & Stein, 2007). In this respect, having manifested a cognitive conflict among the pupils even with a brief intervention is a promising first step.

The pupils interacting with the IR camera were intrigued by the colourful dynamic images along the lines of the "wow factor" associated with innovative technology (Chandler, 2009). Even though they failed to resolve the anomaly, affective impact remains a significant factor towards bringing about conceptual change (Pintrich, Marx, & Boyle, 1993).

Apart from the pupils experiencing the cognitive conflict, in line with Erickson (1985), we had also hoped that they would be able to resolve the conflict by explaining the processes in terms of a heat flow from their thumbs to the investigated objects. However, they did not manage to resolve the experienced cognitive conflicts. From a teaching perspective, it may be seen as a disappointing result with respect to the potential of the implementation of novel IR technology in revolutionising pedagogical practice, but it is nevertheless an interesting research finding, with respect to better understanding the pre-conditions of learning thermal concepts. One possibility is that the task was just too challenging for the current age group. In fact, Andersson (2008) has reported that only 3 % of Swedish ninth-graders explained differences in felt coldness in terms of a heat flow from the hands. In contrast, however, Rosebery, et al. (2010) managed to show the potential in purposeful teaching of a heat-flow model to considerably younger pupils.

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Conclusions and Implications

This study indicates that combining real-time visual and tactile modalities in the current pedagogical context provides the opportunity for pupils to experience cognitive conflicts about thermal phenomena. Actively prompting such conflict can promote cognitive assimilation and accommodation processes to facilitate pupils' construction of abstract, yet core scientific concepts. Albeit so, the POE-based approach was not sufficient for reconciling pupils' intuitive ideas of thermal phenomena and conflicting temperature readings. Hence, exploiting IR technology as a vehicle for learning in the studied age group should be framed within a carefully designed teaching sequence, for instance by introduction of a macroscopic heat flow model as outlined here (Arnold & Millar, 1996; Linn & Eylon, 2011).

As for application in regular physics teaching, other than acquiring an IR camera, it is worthwhile investigating to what extent viewing and interpreting video clips might be a cost-effective way of accessing IR-imaging technology. In fact, video clips posted on *YouTube* on the use of IR cameras in practical laboratory exercises, show differences in thermal conductivity for instance, as manifested when holding one's thumbs in contact with metal and foam objects (Xie, 2012). However, physical manipulation combined with real-time visual feedback from IR cameras holds a promising potential for presenting thermal phenomena. In addition, disambiguation of heat and temperature might well be one area of learning for which physical, sensory input plays an important roll (Zacharia & Olympiou, 2011), including inducing a cognitive conflict between the perceived 'hotness' and measured temperature, which goes beyond what is possible through computer simulations alone (e.g. Clark & Jorde, 2004).

Apart from introducing a heat-flow model, another way of providing more direct guidance and scaffolding might be to intervene in more detail during pupils' conduction of the laboratory exercises. For instance, when the pupils hold their thumbs to the objects of different materials, we could explicitly direct attention to the gradually changing colour along the length of the knife and ask: "why is the colour changing?" or even "what is flowing?" Then again, as recognised by Atkins, et al. (2009), instructions that are too detailed might stifle any discovery-spirited intentions of providing IR technology to students or laypeople.

Given our findings, the following points will inform future empirical research:

- Investigating what specific types of guidance and scaffolding (Hmelo-Silver et al., 2007) would be advantageous in supporting pupils' 'seeing' heat flow, and discerning extensive quantities such as 'heat' and 'energy' involved in heat conduction.
- Exploiting dynamic real-time multimodal interaction and visualization. If educators have the desire for pupils to build the conception of heat as something that flows as a first step towards grasping extensive thermal quantities, the pupils will have to actively 'see' it flowing. Real-time IR imaging may promote multisensory referential connections between haptic and visual perceptual channels (Moreno and Mayer 2007).

This study was conducted with a limited number of participants and cannot readily be generalised to other pupils or to other school contexts. In addition, our collection of data was brief and performed as an event not part of the pupils' day-to-day science curriculum. Nevertheless, the exploratory research approach showed how this group of pupils conceptualised a thermal phenomenon, and experienced a conflict between perceived 'coldness' and temperature readings through interaction with IR technology.

Note

Permanent web link to the supplementary material referred to is available at:
http://www.ep.liu.se/PublicationData/diva-103668/SupplementaryMaterial-103668.pdf

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