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RESEARCH

Thermal Cameras as a Semiotic Resource for Inquiry in a South African Township School Context

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Inquiry-based approaches to science education are central to recent South African primary and secondary school curricula, but have been found challenging to adopt in disadvantaged township contexts. It is therefore important to find ways of introducing inquiry-based approaches, where pupils are encouraged to investigate phenomena they are interested in and to engage in true dialogue, as opposed to teacher-led triadic dialogue. We typically experience thermal phenomena through the sense of touch, but infrared (IR) cameras provide an additional opportunity to experience heat-related phenomena through the visual sense. Previously, in a Swedish context, we have found that hand-held IR cameras allow for strong pedagogical affordances and inspire pupils to engage in inquiry in the area of thermal science. In the present case study, grade 7 and 8 pupils (13–14 years old) in two South African township schools were introduced to IR cameras during predict-observe-explain (POE) exercises on heat conduction. The results revealed that if pupils had a sufficient conceptual understanding of heat conduction beforehand, they were capable of engaging in true dialogue in relation to the exercises and interpreting the thermal camera visual imagery. However, if pupils did not show such understanding, it was tempting for them and the facilitator to resort to triadic dialogue.

Keywords: science education; thermal cameras; heat conduction; township schools

Introduction

Many contributions to science education research literature over the last five decades have demonstrated that inquiry experiences can provide positive and meaningful opportunities for developing pupils' conceptual understanding (e.g. Minner, Levy & Century, 2010). The South African Curriculum and Assessment Policy Statement (CAPS) contains a clear directive that teaching should incorporate inquiry-based instruction, where learning is guided by students' own questions and curiosity (Department of Basic Education, 2011). However, educational research (e.g. Clark & Linder, 2006; Ramnarain, 2016) has indicated that teachers and students at schools in disadvantaged areas in South Africa find it very challenging to adopt inquiry-based approaches. Aspects of our previous work in a Swedish context (Haglund et al., 2015, 2016; Schönborn et al., 2014) have concerned the use of hand-held infrared (IR) cameras (also known as thermal cameras) in the development of practical activities for teaching thermal science. These activities aim to stimulate student inquiry and have been implemented at various educational levels spanning from pre-school through to tertiary contexts. Thermal science has always been a core component of international science curricula, and a topic of intense educational research (e.g. Linn & Eylon, 2011). With ideas such as temperature, heat, energy, and its relevance to topics such as climate change, it is an area of science education that transcends physics, chemistry and biology.

To date, one salient finding in our investigations is that pupils and students of all ages find interaction with thermal cameras very engaging and stimulating – the activities seem to catalyse instant "what if" explorations (Haglund et al., 2016). Another finding is the encouraging meaning-making power offered by simple thermal camera laboratory tasks, such as an exercise in heat conduction using ceramic and plastic cups (Haglund et al., 2015, 2016; Schönborn et al., 2014). Such tasks can be analysed from the point of view of multimodality in the science classroom (Jewitt et al., 2001). In this case, thermal imaging technology affords learners an opportunity to engage with thermal phenomena through vision, as a complement to their sense of touch. Furthermore, interaction with a thermal camera is often associated with pupils "talking science" (Lemke, 1990) and expressing themselves in various new modes of communication that are otherwise uncommon in traditional science classrooms.

Subsequently, a natural hypothesis emerged as to whether these observations would transfer to other contexts, especially those in which inquiry approaches were highly desired but remain a distinct challenge.

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In response, in the last two years, we have been involved in collaboration between research groups in South Africa and Sweden, with the overall aim to investigate how thermal cameras can stimulate and support inquiry-based teaching in grade 7–8 science education in South African township classroom contexts. This paper investigates how thermal cameras can be used as a semiotic resource for meaning-making of thermal phenomena. The study raises the following research question:

- How do grade 7 and 8 pupils engage in predict-observe-explain tasks about thermal phenomena with an IR camera using different modes of meaning-making and communication?

Theoretical Background

Conceptual understanding of heat conduction and the role of thermal cameras

Heat conduction is the phenomenon of transfer of energy from an object of higher temperature to an object of lower temperature with which it is in immediate contact. Science education research has found that it is challenging for learners to understand heat conduction (e.g. Engel Clough & Driver, 1985; Erickson, 1985; Lewis & Linn, 1994), and that the notions of heat and temperature are often conflated (Wiser & Amin, 2001). In addition, heat has many meanings, as it may refer to the overall domain of thermal phenomena, the process of energy transfer from an object of higher temperature to an object of lower temperature, or the amount of energy involved in that transfer, which may cause confusion.

If one touches a piece of metal that has been left at room temperature (20–25°C) for some time the metal feels cold, since one's hands exhibit a typical temperature of about 33°C. In contrast, if one touches a piece of wood at the same temperature, it feels warmer. It is therefore not surprising that many learners think that metal has an inherently lower temperature than wood, even if both materials have the same temperature (Engel Clough & Driver, 1985). During science instruction, the phenomenon is explained as due to a difference in heat conductivity between the materials. Metals are good heat conductors, while wood is a good insulator. A higher rate of heat transfer occurs from one's hands to the metal than to the wood, and hence metals feel colder. However, when it comes to exploring scientific ideas such as heat, the sense of touch can be misleading – human perception of temperature through touch is facilitated by warm and cold receptors in our skin that do not react to the temperature of an object *per se* (i.e. exactly as a thermometer would), but rather to changes in skin temperature due to heat transfer to, or from, the skin (see Jones & Berris, 2002).

Recent developments in hand-held IR camera technology present a potential solution to such challenges by providing the opportunity to directly observe thermal phenomena (see **Figure 1**). Images from thermal cameras are produced by detecting the radiation emitted from objects and transforming them into a visual representation of the surface temperature. In essence, the visualization technology renders the otherwise invisible infrared world as a visual mode of communication. Real time images are displayed in the form of a colour scale where warmer objects appear red and colder objects blue. In turn, the visually intuitive nature of the imagery makes it attractive to inquiry-based approaches in science education.

Even with the aid of infrared cameras, however, Swedish grade 7 (Schönborn, et al., 2014) and grade 10 pupils (Haglund et al., 2015) have been found to struggle with interpreting how a metal object that feels colder than another object made of wood can be at the same temperature, and have even questioned the accuracy of the IR-camera measurements. Pupils need access to an explanatory model of heat transfer from their hands to the objects, rather than perceiving their sense of touch as an accurate thermometer. In addition, the understanding of heat conduction is highly dependent on the cultural context and personal experiences of the learners. Rosebery et al. (2010) found great variance in the manner a class of primary school children in the USA engaged with thermal phenomena, depending on whether they grew up locally. For example, a boy that had recently emigrated from Haiti was intrigued to investigate how water froze to ice when observed during the winter, which added another dimension of interpretation to the classroom discussions. Similarly, experiences of heat conduction from insulating a corrugated iron home in a South African township context is different to experiences of holding snowballs in Sweden.

Figure 1: The multimodal affordances of interacting with a thermal camera and rendered IR images include the possible coordination of visual, tactile and verbal modes of communication.

Science teaching in a South African context

Science in the South African secondary school curriculum

In the last decades there has been an international movement that promotes science teaching approaches where students are encouraged to pose their own questions in relation to natural phenomena, and given more responsibility for how to investigate these phenomena through *inquiry-based science education* (e.g. Rocard, et al., 2007). In a South African context, CAPS promotes inquiry-based learning approaches to science teaching (Department of Basic Education, 2011). For example, the curriculum states, "Science is a systematic way of looking for explanations and connecting the ideas we have. In Science certain methods of inquiry and investigation are generally used. These methods lend themselves to replication and a systematic approach to scientific inquiry that attempts at objectivity" (p. 8).

The Grade 7–9 South African Curriculum promotes the understanding of thermal phenomena through concepts such as heat transfer processes (e.g. radiation and conduction), energy and insulation (Department of Basic Education, 2011). However, it is a very challenging and abstract area of science for students to understand. One source of the difficulties is that many terms used to communicate the idea of heat are known from their use in everyday life but mean something quite different in scientific discourse (Wiser & Amin, 2001). For example, in scientific terms, heat is the *process* of energy transfer or the amount of energy transferred, where one cannot engage the everyday idea that a hot cup of coffee *has* a lot of heat.

Challenges to inquiry-based approaches in a South African township school context

Apart from the conceptual demands associated with understanding abstract thermal concepts such as heat transfer, research has found it particularly challenging to implement pupil-centred inquiry-based methods in township schools. One compelling example of the complexities and challenges involved is presented in a case study by Clark and Linder (2006) that explored a township school science teacher's implementation of a new learner-centred curriculum following the dissolution of Apartheid in South Africa. The challenges faced in adopting a complete shift in teaching style, with the emphasis on encouraging students to "take more responsibility for their own learning", is captured in the following quote obtained from the teacher:

> I am not used to teaching in this manner and the students are not used to being taught in this way! This puts a lot of pressure on me as a teacher and the students to adopt styles of teaching and learning which we are not used to (Clark & Linder, 2006, p. 30).

Recent research by Ramnarain (2014) has shown that although science teachers in township and rural schools view the potential benefits of inquiry-based approaches positively, a lack of resources, large classes and learners' limited experiences of inquiry are obstacles impeding inquiry-based learning in these contexts. Additional factors identified as preventing the integration of inquiry in township schools include low teacher confidence, lack of competence and limited professional development in strategies associated with inquiry approaches. As a consequence, teachers tend to revert to direct didactic approaches to teach science concepts (e.g. Ramnarain, 2014; Ramnarain & Schuster, 2014).

Painting the educational context with the teacher's reflections

As a central feature of this study, the first author, who also facilitated the reported intervention, documented his reflections on his personal experience of the challenges of teaching in township schools that are expected to follow national curricula, which aligns with previous descriptions by Clark and Linder (2006) and Ramnarain (2014):

> In my capacity as a young and fresh high school science teacher, I would not trust that the large number of learners in the science classroom could do inquiry based practical work on their own. I used to believe in carrying out the demonstrations from the front for the learners while they were watching. The lack of support from the department of education, and very limited resources that the school had at the time forced me as a teacher to think less about the potential that the learners would possess. The daily experiences of constant burglaries to the school laboratories could force the science teachers to keep every single apparatus behind lock and key. However, science was taught effectively and the hard working learners were doing well under the conditions mentioned above.
>
> Science education in the township schools is overwhelmed with challenges that include management issues at district and school levels. Township high schools are constantly phasing science out as it is perceived to be the most difficult subject and that learners often fail. The first priority of principals of well performing schools is to maintain the high-performance status of the school. Since science is perceived to be the most challenging subject, combined with the belief that teachers are underqualified, it is tempting to omit it from the curriculum so as to maximise learners' pass rates. As a consequence, there is a high rate of exit off the system for greener pastures and that makes it hard to find substitutes. At classroom level, the science teachers follow the same CAPS document but interpret it differently. I find that many primary and high school teachers do not read the document thoroughly to understand what it means to them based on their context. They would rather skip the necessary parts of the document, giving excuses that include a lack of adequate resources, etc., instead of implementing what best fits their context in innovative ways.

In addition, he provides the following reflections on his role as a teacher trainer, working with preparing teacher students for the challenging future as science teachers in township schools:

> The most interesting, but also most challenging times of my life are when I do my job as a teacher trainer. For example, a group of the in-service teachers that attended the training in the form of a two year program always come forth with complaints that include a lack of resources to teach and carry out practical work, no support, etc. In response, the course seeks to make them become better science teachers by involving classroom visits and support. I make it very clear that this is a journey worth taking though we do not expect it to bring solutions to all the problems teachers encounter. Experiences that are acquired from the course are implemented into school teaching. However, when the course is completed, it is concerning that some of the qualifying teachers are being reshuffled in their schools due to shortages in the other non-science departments.

Semiotic perspectives on multimodal meaning-making in science learning

Making meaning through different modes of communication

Social semiotics is concerned with the investigation of *sign systems* in social processes of *meaning-making* (Kress et al., 2001). In terms of a science learning context, Lemke (1990) asserts that teaching, learning, and "doing" science are social processes that involve various communities, a central one of which is the school classroom. A fundamental component of the semiotic perspective used to explore learning are *affordances*, described as the meanings that can be communicated through different *modes of communication* (Kress, 2010). Various modes (e.g. spoken words, written text, visual images, physical models, and gestures), impact, influence and are used to make meaning (Jewitt et al., 2001). Different modes – and the interplay between them – serve different functions in the meaning-making process (Jaipal, 2010).

Coordinating, transforming and transducing semiotic resources across modes to acquire scientific understanding

Constructing meaning with representations in the classroom often calls for the coordination of multiple modes that are embedded as *multimodal representations* communicated within and across language, images, symbols, interactions, and collaborations (Tang et al., 2014; Davidsen & Christiansen, 2014). It follows, that the process of learning is multimodal in the sense that it occurs by combining visual, actional, tactile and verbal modes of communication, and involves the transformation of information across different modes of communication, such as from spoken words to visual images (e.g. Jewitt et al., 2001). Acting on a *multiplicity* of modes of communication and pursuing transformations between them is fundamental to science learning – indeed, a growing research area on the role of *multimodality* in science education concerns exploring how students make use of different multimodal representations to construct scientific understanding (Airey & Linder, 2009; Jewitt et al., 2001; Tang et al., 2014).

Bezemer and Kress (2014) refer to the process of *transduction* as involving the "movement" of semiotic material from one (or more) mode(s) to another. Learning science draws heavily on the transduction of information across different modes, including transforming a teacher's particular mode of communication to a different mode that a pupil may use during a particular task (e.g. Jewitt et al., 2001). Given that different modes are suited to different learning tasks in different ways, and also place different cognitive and representational demands on pupils (e.g. Jewitt et al., 2001), Airey and Linder (2009) assert that acquiring scientific understanding in a discipline relies on exhibiting *fluency* between different *semiotic resources*. A semiotic resource can be regarded as an instantiation of a mode with a particular communicative purpose in a discipline, such as a graph that displays how two variables relate to one another through the image mode. Furthermore, semiotic resources that are appropriate for the teaching and learning of some particular educational content can be characterised as having high *pedagogical affordance* (Airey & Linder, 2017). In this regard, the pedagogical affordance is specific to a particular semiotic resource, for example a particular diagram of the refraction of light, and not necessarily shared across all resources that rely on a common mode.

Touch as a semiotic resource for learning

One recent development from a semiotic perspective has been on the role of *touch* and its use "as a resource for making meaning" (Bezemer & Kress, 2014, p. 84). Specifically, these developments aim to explore whether, and if so how, touch serves as a mode of communication in a social semiotic multimodal framework (Bezemer and Kress, 2014; Jewitt, 2017). In contrast with the somewhat privileged use of spoken and written language to communicate many scientific phenomena, when it comes to interpreting thermal phenomena, the sense of touch serves as the primary means for interacting with the physical world. However, as we have seen, our touch is sensitive to heat exchange between our skin and the surroundings, rather than to temperature *per se*. This means that two objects that consist of materials with different thermal properties, such as heat conductivity, heat capacity and density, are perceived differently – one perhaps as colder than the other – even if they are at the same temperature. It follows, that since touch is a limited semiotic resource in this regard, it needs to be coordinated with other resources as part of a multimodal communication of heat concepts. In particular, measurement of temperature with thermometers and visual temperature display with IR cameras are important complements to touch in this respect.

Perils of triadic dialogue in promoting a "talking science" classroom

According to Lemke (1990), "talking science" involves far more than merely talking about science content. It involves observing, comparing, hypothesising and questioning, and many other activities that are mediated through a *language* of science that exists as part of a system of meaning-making resources. Lemke points out that a typically salient social aspect of classroom dialogue is what he terms *triadic dialogue* – a form of exchange that occurs as a triad of "moves" comprising a *teacher question*, followed by a *student answer* and then closing with a *teacher evaluation.* Studying forms of discourse involved in triadic dialogue during collaborative classroom interaction has gained much traction from the point of view that it has been shown to play a significant role in the co-construction of knowledge, but at the same time stifles students' own initiative-taking and creativity (Nassaji & Wells, 2000). Unfortunately, triadic dialogue provides students with limited opportunities to talk science; it is the teacher that controls the process and performs most of the talking. Instead, Lemke (1990) argues that classroom teaching should strive for students' involvement in different forms of *true dialogue*, where they are encouraged to pose their own questions, engage in collaborative inquiry, and develop complex lines of reasoning. In the context of the current study, however, resistance to abandoning teacher-centred triadic dialogue patterns, is part of the challenge of adopting inquiry-based teaching approaches in many South African schools.

Methods

Study context and participants

The investigation was conducted as part of a case study of school science education development efforts in township schools. In the teaching in focus in the current study, the first author participated as a researcher while conducting an infrared camera based teaching intervention. The present investigation was conducted in the context of Grade 7–8 natural science education at two schools in a South African township. One school was a high school that recruits gifted learners, and the other a traditional township primary school. From the period October 2015 to May 2017, four separate groups, comprising 33, 77, 20 and 10 pupils (13–14 years-old) participated in the case study, respectively.

Multimodal laboratory tasks

In semiotic terms, thermal cameras afford the experience of seeing the temperature of solid and liquid surfaces towards which the camera is directed. A multimodal experience is also offered when the dynamic visual mode is combined with touching the surface, or grasping an object, which allows for the coordination of two modes to interpret a thermal phenomenon. Further modes of communication such as verbal responses as well as bodily interaction with the camera itself can also contribute to the multimodal experience (see **Figure 1**).

A hand-held FLIR C2 camera (**Figure 1**, left) was used to perform predict-observe-explain (POE) (White & Gunstone, 1992) activities in the classroom. Literature has shown the POE approach to foster opportunities for pupils to "talk science" (Lemke, 1990). The two primary activities conducted in the classroom comprised pouring hot water into cups of different material and thickness (a ceramic mug and a thin plastic cup), and making thumb and hand contact with wooden and metal objects (a piece of wood and a carpet knife). The overall aim of the tasks was to elicit counterintuitive multimodal experiences as a means for pupils to confront examples of so called alternative conceptions, such as metals being inherently colder than other materials (e.g. Erickson, 1985), or human touch being an accurate thermometer. By observing equal temperature values of different materials at thermal equilibrium, and observing differences in heat flow through a thermal conductor and insulator, it was hypothesised that collaborative interaction with the thermal camera could serve as a semiotic resource for engaging, talking about, and interrogating these patterns of reasoning.

The first author participated in the dual role of facilitator and field researcher in nine classroom sessions (see **Figure 2**). All dialogue took place in English, the primary language medium of science instruction at this school level, although this was the second or third language for many of the pupils. Using the knife and wood experiment as an example, a typical session took the following form. The pupils were first introduced to the features and functionalities of the thermal camera prior to commencing the activity. The pupils were then asked to touch and *predict* the respective temperatures of the wood and knife. After the group members made their predictions, the facilitator directed the thermal camera to the two objects (in many sessions, the real time camera image feed was also projected onto a large screen), and asked the group to *observe* the infrared imagery and corresponding temperature of the object surfaces and to revisit, or expand upon, their temperature predictions. Following this, one of the pupils was encouraged to volunteer to make thermal contact with the objects using each thumb for a few minutes, while another pupil (or the facilitator depending on the context) directed the camera toward

Figure 2: Examples of different events that occurred during the multimodal laboratory POE tasks. Pupils provide temperature predictions of a metal and wooden object (left). Pupils point the camera toward the thumbs of a peer while observing contact with a knife and piece of wood (right).

the thumb contact with the objects. Following the observations, the pupils were asked to *explain* the events that they had observed, in light of their originally generated predictions. This involved discussion guided by the facilitator on comparing different pupils' observations and explanations.

Data collection

The POE activities, actions with the IR camera, group interactions, and interactions between the facilitator and the participants were video and audio recorded with (depending on the session context) a combination of tablet computer, hand-held and tripod-mounted video cameras, and fully transcribed verbatim in English. In addition, pupils (or the facilitator) took IR screenshot images. Lastly, field notes were penned by the facilitator immediately after many of the sessions.

Analysis of the data

In this study, we present and concentrate on three exchanges (or episodes) drawn from the collection of POE sessions. We have purposefully selected these data since they provide compelling exemplars of different forms of multimodal coordination, and demonstrate the interplay between different semiotic resources and modes of communication during the pupils' and the facilitator's dialogue about heat.

An in-depth qualitative analysis of the data involved a reciprocal to-and-fro between video clips and transcript text, and among the researchers. In conjunction with this approach, a *multimodal semiotic analysis* was deployed as a lens to investigate the interplay between various modes of communication during the activities, group interaction and dialogue, with a particular focus on the role of visual and tactile investigation of the phenomenon and the learners' spoken language. The multimodal analysis was guided by using the methods reported by, *inter alia*, Lemke (1990), Jaipal (2010), Jewitt et al. (2001), Tang et al. (2014), and Airey and Linder (2017) to inform an overall treatment of the data that aimed to:

- Describe how the different modes were used to communicate thermal concepts, understanding and related reasoning,
- Explore the pedagogical affordances of infrared cameras as a semiotic resource,
- Analyse the dialogue between the facilitator and the pupils in the investigation of the phenomenon of heat conduction, with a focus on patterns of triadic dialogue or true dialogue (Lemke, 1990).

The analysis was also conducted in parallel with continuous insight from the first author's previous reflections and experiences from being a teacher trainer, as well as a teacher in the South African township context for 19 years. These insights helped our interpretations of the data to be as authentic as possible to the context at hand serving as an example of an innovative classroom intervention in the township context (e.g. Clark & Linder, 2006).

Results

The findings of the study are presented in the form of analysis of selected dialogue excerpts where the first author introduces groups of learners to the practical investigation of heat conduction by means of an IR camera with the POE approach in the capacity of facilitator. In the two first episodes, he encouraged a group of grade 8 learners from the high school with gifted learners to predict which one of two objects is the coldest and then to observe the phenomenon with an IR camera and explain it. In a third episode, a group of grade 7 learners from the traditional primary school were asked to explain the same phenomenon.

Grade 8 learners predict whether wood or a metal carpet knife is coldest

The learners are shown a piece of wood and a metal knife and are asked by the facilitator to predict which one of the two objects is the coldest:

> Facilitator: And then, this activity, I just want to hear from you, which one is cold, colder than the other if I show you the wood or the metal between the two? Which one feels cold?
> L1: Looks or feels cold?
> Facilitator: Hmm?
> L1: Which one do we think feels cold or...?
> Facilitator: Yes
> L1: Oh, I think err, the..., the metal knife is the, is much colder than the wood because the metal knife is a good absorber or should I say a conductor of any temperature around it. So, I think it absorbed the room temperature and I think it's the one that is colder than the wood.
> Facilitator: Is it?
> L1: Yes
> Facilitator: Ok, what do you think?
> L2: Err the... metal knife
> Facilitator: Speak up please
> L2: I think the metal knife is the coldest
> Facilitator: Colder than the wood, the piece of wood?
> L2: Yes

In introducing the task of predicting which one is colder, the facilitator first asks which one *is* colder and then which one *feels* colder. L1 asks for a clarification, and receives a confirmation from the facilitator that it is a matter of which one feels the coldest. L1 then argues that the metal knife is the coldest, since it acts as a good conductor of the surrounding temperature. L2 supports his line of argument and also believes that the metal knife is colder than the piece of wood.

With the interpretation of the task as relating to which object feels coldest, the prediction of L1 is adequate. A metal knife at room temperature, which is lower than that of the hands, feels colder than a piece of wood. However, L1 seems to believe that the metal has assumed the (relatively low) room temperature and therefore feels cold, since it is a good conductor. In arguing that metal is a good absorber or conductor of temperature, L1 uses adequate vocabulary from thermal science but seems to confuse temperature with heat. Heat, not temperature, is an entity conceived as being absorbed by or conducted through metals. The facilitator goes on to ask the other learners to make predictions:

> Facilitator: Do you also share the same view?
> L3: No, I think they are both at the same temperature
> Facilitator: They are at the same temperature
> L3: [Nodding]
> Facilitator: So, nothing is colder than the other
> L3: Yes
> Facilitator: At the same temperature… room, at the same room temperature?
> L3: Yes, at the same room temperature

L3 does not agree with L1 and L2. By reframing the problem from which object feels the coldest to a matter of temperatures, he predicts that they are at the same temperature. The facilitator probes whether L3 thinks that they are both at room temperature, and this is confirmed by L3. This indicates that L3 interprets the situation as two objects being in thermal equilibrium with the surrounding room, regardless of how they feel, in line with the taught physics at this level of education. The facilitator asks for more predictions in the group:

> Facilitator: What do you think?
> L4: I think the wood is colder than the metal knife because the wood cannot conduct heat well
> Facilitator: The wood cannot conduct heat well. Hmm!
> L5: I think they both have the, the temperature, the room temperature because they are not coming into contact with actually…
> L2: Heat
> L5: …heat or, or something that's…
> Facilitator: Ok, from your hand?
> L5: Yes
> Facilitator: Ok, from your body temperature?
> L5: Yes

Here, based on his physics knowledge that wood is not a good conductor of heat, L4 predicts that the wood is colder than the metal. Since metals feel cold at room temperature, this is counterintuitive, but not entirely illogical. For example, if the objects had been recently taken out of the freezer, the piece of wood could have been increasing in temperature at a slower rate before reaching equilibrium, and thereby have a lower temperature. L5 agrees with L3 in thinking that the objects are at the same temperature, since they have not been in contact with something warm.

As a result, three different predictions emerge amongst the learners: the piece of wood being the coldest, the metal knife being the coldest, or both objects being at the same temperature. From the point of view of POE, this is a very dynamic situation with different predictions and associated justifications. The scene is set for observing what the outcome of the POE experiment will be.

Grade 8 learners observe with an infrared camera and explain the studied phenomenon

The real-time IR camera imagery is projected onto a screen so that all learners can see it. The facilitator points the camera to the piece of wood:

> Facilitator: Let's take a look on the board and as I do it, show it err… on the piece of wood, the IR camera on the piece of wood, what do you see on the board?
> L3: Blue
> L2: Blue
> Facilitator: Besides the colour, yes the colour is blue, it happens to be blue ok… and because it happens to be blue, err… what does it say about the heat?
> L3: It's cold
> L4: It's cold, it's 24
> Facilitator: We talk of it as cold… ok, and then what does it say in terms of the temperature? Have a look at the temperature.
> All: 24 degrees Celsius
> Facilitator: Ok, and then let's see the next one. What temperature is that… of the metal knife?
> All: It's 25 degrees
> Facilitator: So 24 and 25, are they the same thing?
> All: No

In **Figure 3**, it can be seen that the piece of wood appears as dark blue against the background of the table that is light blue. The knife beside it is green and blue, and the part of the table underneath is red and yellow (possibly due to contact with a warm object before the exercise). When the facilitator points the IR camera to the piece of wood, the learners immediately attend to the observation that it is blue. Next, he asks what the blue colour has to say about the heat as a phenomenon. L3 responds that the blue colour means that the piece of wood is cold. L4 adds that the temperature is 24°C, reading off the numerical value displayed at the top left corner of the screen.

When the facilitator points the IR camera to the knife and asks about the temperature of the knife, the learners read off the numerical value. They attend to the fact that the value, 25°C, is different from that of the piece of wood, at 24°C. A teacher could be tempted to argue that the temperatures are roughly equal, in line with the interpretation of the situation as one of thermal equilibrium, but the facilitator leaves the learners' response without commenting further.

In this short episode, we see how the learners quickly coordinate the rendered colour and numerical temperature reading on the screen, and interpret the piece of wood as being cold due to the blue colour. With a multimodal perspective on social semiotics (Kress, 2010), the blue colour is by convention associated with cold in many everyday contexts (e.g. symbols on water taps). The interpretation may be seen as a case of rapid transduction between modes, from colour, through the sense of touch (the imagined feeling of cold), to the visible numerical value, all expressed through spoken language.

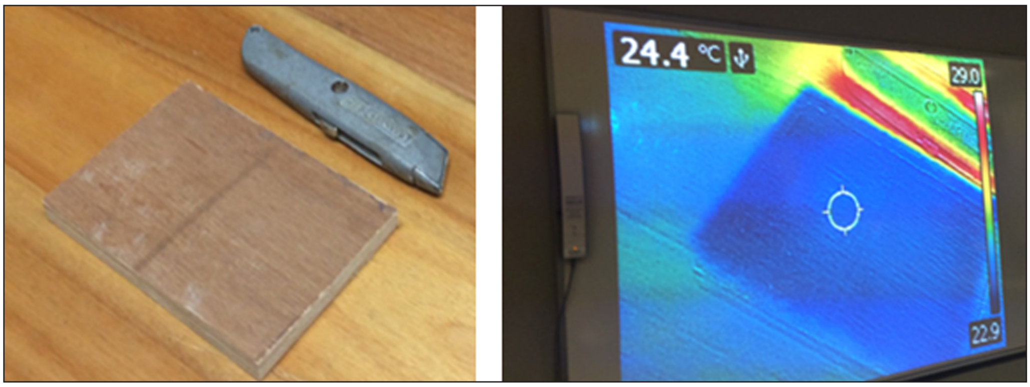

Figure 3: Snapshot of the piece of wood and the metal knife (left); snapshot of the projected IR image of the two objects on a large screen.

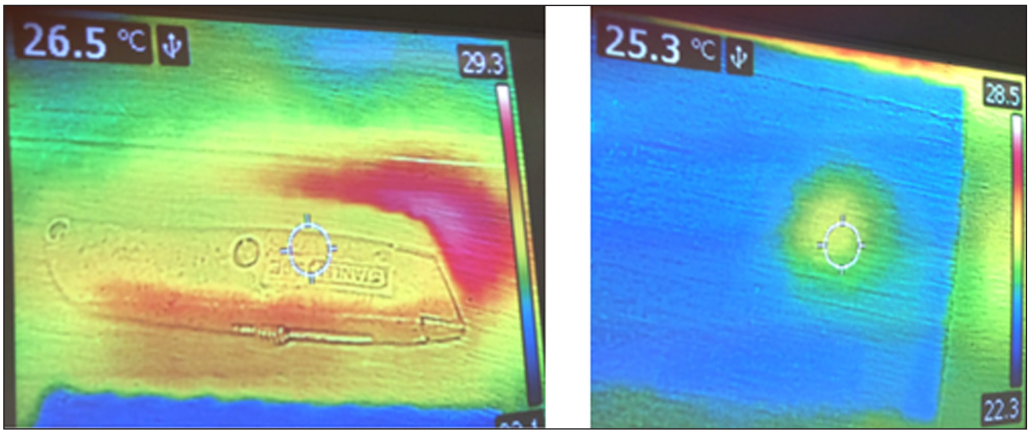

Figure 4: Snapshots of the projected IR images of the objects after a learner has held his thumbs in contact with them for 2 minutes. The knife has been heated evenly (left); the temperature of the wood has increased at the area of local thumb contact (right).

Now, the facilitator asks one of the learners to place his thumbs in contact with the two objects for about 2 minutes. Afterwards they observe the objects again (see **Figure 4**), and the facilitator turns to the explain phase of the POE task.

> Facilitator: Luckily we can see where the thumb was placed in the wood, in the piece of wood. Can you tell me about the difference between the two?
> L3: Yes
> Facilitator: What is the difference between the two?
> L3: I've noticed that the metal takes in the heat while the wood ignores it. If you can see there, there was the place, the area where I placed my thumb, the wood didn't conduct the heat, it just ignored it while the metal took it...
> Facilitator: from your thumb...?
> L3: ...from my thumb, yes

As we saw earlier, L3 predicted that the objects would be at the same (room) temperature, in line with the taught physics explanation. Here, he interprets the evenly increased temperature of the knife in terms of "the metal takes in the heat". In contrast, the wood did not conduct heat but "just ignored it". This is intriguing, given the clear, albeit localised spot where the temperature of the wood increased due to the thumb contact. In conclusion, he shows an adequate conceptual understanding of the phenomenon that is closer to a scientific interpretation than revealed in other groups, although expressed in a rather idiosyncratic way.

The overall impression is that the grade 8 learners were able to interpret the outcome of the experiment. This was achieved through coordinating a range of different semiotic resources, including the "messy", dynamic projected colour images from the IR camera, visual numerical values, and the sense of touch.

Grade 7 learners explain the studied phenomenon

After having conducted the same experiments with a group of grade 7 learners in the traditional primary school, including a learner holding the objects for 2 minutes, quite a different pattern of communication ensues. The learners noticed how the temperature of the thumb in contact with the metal knife decreased to 29°C, whereas the temperature of the thumb in contact with the piece of wood only decreased to 32°C:

> Facilitator: So, let us look at the temperature where your thumb was placed on the... on the metal. It was lower than that of the thumb that was placed on

> the wood. I am still interested to know… why is that? Would you like to say something? [Looks at pupil to the left (L1)]
> L1: I want to say that the metal is cold [smiles]
> Facilitator: Yeah…
> L1: …and the piece of wood is warmer than the metal.
> Facilitator: Yes. And so, the temperature now… are different… the temperatures, you have seen them…
> L1: [Nods] Yes, they have different temperatures.
> Facilitator: So, why are these temperatures different? I want to hear from you… what is the reason for them to be different? Is it because you believe the temperature is… of the metal… is low? The metal is cold, is that the reason?
> All: Yes.
> Facilitator: Oh… [sounds surprised] So because it is cold… does that cold have anything to do with the temperatures dropping when you put the thumbs… on these two objects…?
> All: Yes.
> Facilitator: Is it? [sounds sceptical]
> All: Yes.

Even though the learners have just observed with the IR camera that the objects initially had roughly the same temperatures, and that the metal increased in temperature by being heated by the thumb, L1 maintains her description that the metal is cold. The learners' interpretation of the phenomenon is dominated by the sense of touch, according to which the metal feels cold, so that the visual impression from the colour image and numerical reading of the IR camera is not taken into account. The facilitator is not satisfied by this explanation, and he asks a series of questions that commence as open questions, such as "So why are these temperatures different?", but develop into a more closed format: "The metal is cold, is that the reason?" The learners respond in chorus, but the facilitator reacts to the learners' statements with a surprised and sceptical tone. Next, he tries to change the learners' interpretation of the situation by shifting the focus to how quickly the two objects "take away the heat" from the hand:

> Facilitator: How fast does each of the objects take away the heat… from your hand…? Which of the two takes heat much faster than the other? [two of the learners raise their hands] Yes, [L2?]
> L2: The metal knife… The metal… [struggles to find the words]
> Facilitator: …metal knife, yes…?
> L2: The metal knife take…
> Facilitator: …take heat…
> L2: The metal knife take the heat more faster than the wood…
> Facilitator: …than the wood…? [L2 nods] Because you've seen from the camera…?
> All: Yes.
> Facilitator: …how that happened…?
> All: Yes.
> Facilitator: Okay, so do you all believe, then, that it takes the heat much faster than…
> L5: …the wood.
> Facilitator: …the wood, right…?
> Facilitator: Yes.

From the perspective of comparing how quickly the objects "take" heat from the hands, L2 responds that the metal knife "takes heat" faster than the piece of wood. The facilitator confirms the interpretation by pointing to the observations made with the IR camera, according to which the knife increased in temperature. This time, the learners' chorus response seems to satisfy him. Having established that the metal takes more heat, however, the facilitator returns to the matter of which object has the highest temperature:

> Facilitator: But, let's go back. Do you still believe these two objects are the same temperature?
> All: No!
> Facilitator: They are not?
> All: Yes! [they smile]
> Facilitator: Meaning, even if the temperature of the room is the same… but they won't be the same temperature…
> All: Yes.
> Facilitator: But I want to say, these are the same temperature. [L3, L4 and L5 shake their heads].
> L5: I think it's no…
> Facilitator: Err…, you saw from this camera! It showed you. Remember on the camera, you could read… the temperature. You could read the temperature… of these two objects!
> L4: Yes…

The facilitator tries to explain that the two objects had the same temperature (of the surrounding room) before the experiment of contact with the thumbs, but the learners do not accept this explanation. They still believe that the temperatures of the two objects are different. From the previous utterances, we can assume that they believe that the metal is colder. The facilitator expresses frustration that the learners seem to have forgotten the initial observation that the objects were at room temperature. He takes the initiative to observe the objects again with the IR camera:

> Facilitator: I want to show… [Points the camera to the knife so that the learners can read the temperature] What temperature was this?
> L4: 25,9 Celsius.
> Facilitator: And this one? [points to the piece of wood, so that the learners can read off the temperature again]
> Learners: 24… 25,0 degrees Celsius.
> Facilitator: And this other one [points to the knife] …unless we touched it.
> Learners: 25,8… 25,6 degrees Celsius.
> Facilitator: 25,7. Which is… 25 and 25 is the same thing.

> Learners: Yes.
> Facilitator: …the temperature of these objects is the same! [they smile] It *is* the same! Isn't it the same…?
> L4: I can't believe…
> Facilitator: Come again. I want to show you. Bring on your thumbs again… Place your thumbs here. Just to show you… [conducts the experiment of placing thumbs on objects again]

When checking the temperatures of the two objects again, the facilitator points out that they have roughly the same temperatures. In fact, the temperature of the knife is slightly higher than the temperature of a piece of wood, because of the previous heating by the thumb. The learners acknowledge the observation, but L4 expresses that he cannot believe that this is the case. At the end of the exercise, the learners have not been able to reconcile how metal can feel colder than wood when both materials are at room temperature.

Discussion

The findings of the study are discussed by revisiting the posed research question, followed by a discussion of the educational implications of the work and limitations of the study.

How do grade 7 and 8 pupils engage in predict-observe-explain tasks about thermal phenomena with an IR camera using different modes of meaning-making and communication?

Both groups of learners associated the blue colour on the IR-camera screen with cold, following a common everyday convention (Kress, 2010), and coordinated the colour with the numerical temperature reading. In this respect, they quickly transduced between different modes of meaning-making in interpreting the phenomenon. The learners managed to interpret the IR imagery in an intuitive way, which aligns well with our previous findings (e.g. Haglund, et al., 2015).

However, the groups of learners differed in the degree to which they managed to integrate what they saw on the IR-camera screen with their sense of touch and previous experiences of the thermal properties of wood and metals. With their deeper content knowledge and greater experience in inquiry approaches to science teaching, the 8th graders came to interpret the phenomenon as a case of heat conduction between their hands and the objects that they touched. In this interpretation, the IR-camera measurement of roughly equal temperatures of the objects beforehand cohered with their sense of touch. In this way, access to the IR camera helped the students form a richer interpretation of heat conduction. In other words, for these learners, the IR camera can be argued to exhibit high pedagogical affordance (Airey & Linder, 2017) in studying this phenomenon.

In contrast, throughout the exercise, the 7th graders were convinced that the metal was colder than the piece of wood. They assert this, because it feels colder. When the facilitator pointed to the IR-camera images, the learners paid attention to the colours and temperature readings, but without access to a model representing heat conduction from their hands to objects they held, their interpretations were dominated by their sense of touch, and they did not manage to incorporate the IR images into their explanations. The difficulty in coordinating temperature measurements with the sense of touch aligns with previous research on students' understanding of heat conduction in practical activities. In this regard, adults have been found to question equal thermometer readings of an object that feels warm and another that feels cold (Lewis & Linn, 1994), and similar results have been found with IR cameras (Schönborn, et al., 2014).

Educational implications and limitations of the study

Given the prominence of the sense of touch in our experience of thermal phenomena, it can be challenging for learners to coordinate what they see in a thermal image with what they perceive with their hands. Without access to a model of heat conduction between their hands and objects they touch, they tend to trust their experience that what feels cold has a low temperature (Lewis & Linn, 1994; Schönborn, et al., 2014). Therefore, for effective teaching of heat conduction, it is not sufficient to provide learners with an IR camera alone. They have to be provided with a theoretical model of the phenomenon, together with teacher support, in order to be able to integrate the visual and tactile modes of communication and investigation in an adequate way. At the level of 7th and 8th grade teaching, the central idea is that heat and temperature are different concepts, which can be conveyed by the model of heat flow from objects at higher temperatures to objects at lower temperatures (Arnold & Millar, 1996).

In allowing the 8th graders to explain their observations on their own, in somewhat idiosyncratic terms, the facilitator's interaction and the learning environment as a whole encouraged them to "talk science" (Lemke, 1990). This is all the more impressive as many of the learners do not have English as a first language. The study indicates that under favourable circumstances, such as a school with high standards for admission, well prepared learners and a skilled teacher with experience from teacher training, and combined with the rare opportunity to work in small groups, learners in South African township contexts are able to engage in meaningful dialogue on science phenomena when given the opportunity.

However, the example of the interaction between the facilitator and the 7th graders also shows that it is easy to adopt a pattern of triadic dialogue (Lemke, 1990), where learners carefully attend to and respond to every sentence the teacher utters, without being able to place exchanges into a larger understanding of the topic at hand. When the frustration built up as the learners did not respond in the way the facilitator had hoped, even as an experienced teacher who is convinced of the advantages of inquiry approaches, the facilitator reverted to a traditional type of teaching, which all the pupils are familiar with. He turned to posing closed questions to which the learners could respond "yes" or "no" in chorus, and signalled when he was not happy with the response, for example by asking "Is it?" with a sceptical or surprised voice to induce further exchange.

With regard to limitations of the study the 8th graders were asked which object was the coldest, the wood or the metal, which could be considered by some to have been unfair, since they were at the same temperature. It was also left unclear as to whether they should say which object felt cold or looked cold (presumably with the IR camera), which may have contributed to early confusion. The study also suggests the potential limitations of conducting research in the dual role of facilitator and investigator. Nevertheless, in this case study, the joint inter-researcher analysis helped identify such teaching challenges, and at the same time, highlighted the important role of the teacher in the learning process.

Competing Interests

The authors have no competing interests to declare.

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