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From Thermosensation to the Concepts of Heat and Temperature: A Possible Neuroscientific Component

Angel Ezquerra [1*], Ivan Ezquerra-Romano [2]

[1] Science, Social Science and Mathematics Education, Universidad Complutense de Madrid, Madrid, SPAIN
[2] Dept. of Cognitive, Perception and Brain Science. University College London, London, UK

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ABSTRACT

Alternative conceptions in physics are ideas held by people regardless of their age, ability, sex, race and religion. The persistence and universality of these misconceptions suggest that there must be a common underlying factor found in all human beings. In this work, we suggest how the structure and arrangement of our thermosensory system shapes and constrains the creation of the concepts of heat and temperature. Firstly, we outline the main characteristics of alternative conceptions in physics. Then, we describe the neurobiology of thermosensation. The proteins sensitive to temperature changes can be classified as hot- and cold-sensitive. The nervous system maintains mostly this separation in hot- and cold-fibres and thermal information is integrated in specific areas of the central nervous system. Therefore, it seems that the neurobiological structure predisposes us to categorise stimuli into hot and cold. Understanding the relationship between alternative conceptions and the structure of the nervous system can improve the abilities of teachers to deal with students' ideas. In particular, this knowledge could decrease the frustration of teachers, since they would understand that human physiology is a determinant factor. Therefore, they should not expect to easily modify their students' alternative conceptions.

Keywords: conceptualisation, alternative conceptions, thermosensation, heat and temperature, neurosciences

INTRODUCTION

Organisms possess an array of responses that drive them to stay at an optimal temperature or protect them from extreme conditions. Responses can be classified as: automatic (sweating, shivering etc.) and behavioural (spreading out, shrinking, etc.). Humans, like other species, have a thermosensation system which transduces and carries the external and internal thermal information to the brain. However, humans show a broad repertoire of highly elaborate responses such as wearing clothes, starting a fire or building an air conditioning system. These complex actions are planned and executed based on our mental representation —our concepts— of the environment; in this case, the concepts of heat and temperature.

In early stages of development, these ideas (heat, cold, temperature…) are used to resolve limited situations in daily life and they help people predicting and understanding natural phenomena (Norman, 1983). These spontaneous ideas often diverge from accepted explanations (Hewson & Hewson, 1988). However, they frequently are the starting point for understanding concepts of physics, even though they are generally counterproductive and insufficient for comprehending the theoretical approach of a phenomenon (Pfundt & Duit, 1994). A remarkable example is the concept of cold, which does not relate to anything useful in thermodynamics. Cold does not exist *per se*, it does not represent any physical magnitude. Nonetheless, the term cold, as an opposite entity of heat, is a well-known misconception (Wiser & Amin, 2001).

A noteworthy observation is that these intuitive concepts appear in a universal ordered sequence in the building process of concepts. In development, there exists a progression in their complexity (Driver & Easley, 1978). This

✉ angel.ezquerra@edu.ucm.es **(*Correspondence)** ✉ ivan.romano.14@ucl.ac.uk

Contribution of this paper to the literature

- This theoretical work proposes a new approach in the study of alternative conceptions: identifying the neurophysiological bases of misconceptions.
- A novel explanation about how the neurophysiology of the thermosensation system shapes the conceptualisation of heat and temperature.
- It is proposed that the ubiquity of the structure of the nervous system explains the persistence and universality of some alternative conceptions.

sequence was called conceptual trajectory by Driver (1989). She also observed that this progression -or chain of knowledge- is common to different educational systems and cultures. Each step of this path is called an alternative conception (Driver and Easley, 1978; Hewson, 1981; Abimbola, 1988).

Historically, alternative conceptions were detected in scholarly contexts. Researchers collected a wide array of misconceptions from various educational sources: textbooks (Doige & Day, 2012), children's ideas (Driver, Guesne, & Tiberghien 1985), teachers' knowledge of science (Davis, Petish, & Smithey, 2006), cultural or language-based (Lee, 2001, 2007), and the methodologies and the language used (Borg, 2015). These misconceptions, detected in children and teenagers, are also held by adults and experts regardless of their sex, race, religion, ability, and cultural boundaries (Abrahams, Homer, Sharpe, & Zhou, 2015; Lewis & Linn, 1994).

Moreover, it has been observed that some alternative conceptions currently held by students are similar to the explanations of natural phenomena proposed and believed by previous generations of scientists and philosophers (Conant, 1957; Matthews, 1994). They are also found in social contexts (Thijs & Van Den Berg, 1995). Misconceptions are common to millions of people (Wandersee, Mintzes, & Novak, 1994).

Furthermore, it has been detected that many preconceptions predate educational life, transcend the actions carried out in classrooms (Williams, 1999) and remain surprisingly inflexible throughout life (Clough & Driver, 1985). They are tenacious and resistant to change and to extinction (Chiappetta & Koballa Jr, 2006; Driver & Erickson, 1983). The persistency and universality of these conceptions suggests that there must be a general factor which is common to all human beings. Some researchers have proposed that the way our senses work, which is common and persistent in healthy humans, shapes the development of scientific ideas (Driver, 1985; Vosniadou, 1994; Wenning, 2008). Recently, it has been proposed that misconceptions might arise from perceptual ambiguity or from ineffective representations of the perceptual and physical variables involved in a task (Kubricht, Holyoak & Lu, 2017).

In the last 20 years, our understanding of the underlying neurophysiological mechanisms of transduction and transmission of physical stimuli has increased substantially. This neurophysiological knowledge might help explaining how our sensory organs shape the development of scientific ideas. In this work, we suggest how the structure and arrangement of our thermosensory system (physiological level) shapes and constrains the creation of the concepts of heat, 'cold' and temperature (cognitive level). We have found connecting links between the experimental results in the literature of both alternative conceptions and the thermosensory system. The procedure followed was divided in three parts. Firstly, the alternative conceptions about heat and temperature were analysed and their characteristics were categorised. Moreover, a contrasted and peer-reviewed literature review about the neurobiology of the thermosensory system was carried out (Ezquerra-Romano & Ezquerra, 2017). Finally, we systematically compared the general characteristics of alternative conceptions with the way each component of the thermosensory system works. This was a study of how thermal information is transmitted through the nervous system, including how information is transduced, modified and transmitted, and how these processes shape the formation of alternative conceptions.

FROM HOT- AND COLD-OBJECT TO HEAT AND COLD

Scientists have collected and defined the general characteristics of misconceptions of heat and temperature (Clough & Driver, 1985; Harrison, Grayson, & Treagust, 1999; Kesidou & Duit, 1993; Lewis & Linn, 1994; Linn & Songer, 1991). A sequence in the appearance of these topics throughout a child's development has been established (Albert, 1978; Driver, 1989; Piaget, 2007). Therefore, it seems that individuals consistently go through a series of steps ─a chain of concepts─ to develop their own abstract concepts.

The chain of concepts (see **Table 1**) starts at an early age, when children consider there are only two realities to describe the thermal state of any item: hot- and cold-objects (Albert, 1978; Erickson, 1979). Furthermore, children only use these terms when they encounter the sensations that these objects arise on their skin (Albert, 1978). They perceive objects that, among other traits (shape, colour…), are hot or cold. Therefore, the states hot- or cold-object are considered to be irreducible realities, which are inseparable from objects.

Table 1. Conceptual trajectory of the notions of heat and temperature throughout childhood

Age	Alternative conceptions on heat and temperature	Authors
2-4 years old	Children consider there are only two types of realities which describe the thermal state of items: hot- and cold-object.	Albert, 1978
	Children seem to be unable to detach the concepts of hot and cold from objects and, consequently, they cannot consider these notions as separate identities from objects.	Erickson, 1979
4-6 years old	Children start to develop the concept of thermal source They learn from their personal experiences such as radiation (sun) and the contact with daily thermal sources.	Albert, 1978
5-6 years old	Children begin to express their ideas about thermal sources as objects which warm up or "cool down" other objects.	Albert, 1978 Erickson, 1980
7-8 years old	Some children already realise that "things get hot/cool down" and they consider heat and cold as an extended entity.	Albert, 1978
	They assume the existence of two entities called heat and cold and these entities go from one body to another.	Erickson, 1985
	Children usually begin to express the existence of a scale, which ranges from cold to heat, and they point out that temperature can be cold or hot.	Tiberghien, 1985 Clough & Driver, 1985

The initial notion of hot- or cold-object leads to the conception of source of heat and cold (Albert, 1978). Specifically, children start by identifying and recognizing daily sources of heat and cold through their personal experience. They eventually consider themselves as objects that are heated or cooled by sources. It seems that we all assume the existence of an entity that passes from one body to another (Erickson, 1980, 1985). This tendency to think of a thermal entity as a 'substance' that flows from place to place arises as a spontaneous model in most individuals. This model, which is also currently held by students (De Berg, 2008), is very similar to Lavoisier's concept of heat: *caloric* (Driver, Rushworth, Squires, & Wood-Robinson, 2005).

Later in development, hot and cold ─together with cool, warm and others─ are organised to form a qualitative scale of temperature (Brook, Briggs, Bell, & Driver, 1985; Erickson, 1979; Tiberghien, 1985). On the other hand, there also exist more factors that influence the transfer of heat such as thermal conductivity or the kind of contact between surfaces. Here, we specifically focus on the transduction and transmission of stimuli and their relationship with the creation of concepts of heat and temperature.

THERMOSENSATION: FROM PROTEINS TO THE BRAIN

As mentioned above, some authors have suggested that a possible explanation that underlies the formation of alternative conceptions could be the nature of sensory systems. However, the neurophysiological understanding of the thermosensory system has been limited. It has been only in the last 20 years that techniques have allowed scientists to study the intricacies of this sensation.

In this section, we introduce some key notions of the neurophysiology of the thermosensory system. We also explain how these biological features could contribute to the development of the concepts of heat and temperature.

Molecular Level

Transduction of external and internal conditions is essentially mediated by proteins, called Transient Receptor Potential ion channels (TRPs), which are embedded in the neuronal membrane (Patapoutian, Peier, Story, & Viswanath, 2003). 28 TRP channels have been identified so far (Pedersen, Owsianik, & Nilius, 2005). Some of them, called thermoTRPs, are extremely sensitive to temperature changes.

These channels open or close due to temperature variations, and this dictates the internal and external concentration of ions (see **Figure 1**). Consequently, cells depolarise in reaction to shifts in temperature and a generator potential is established. In sensory neurons, when the generator potential reaches a threshold, an action potential is generated. Accordingly, the initial change in ionic concentration caused by a temperature shift is transduced into a signal that is coded in the firing frequency of neurons. This signal travels to the spinal cord and from there to the brain.

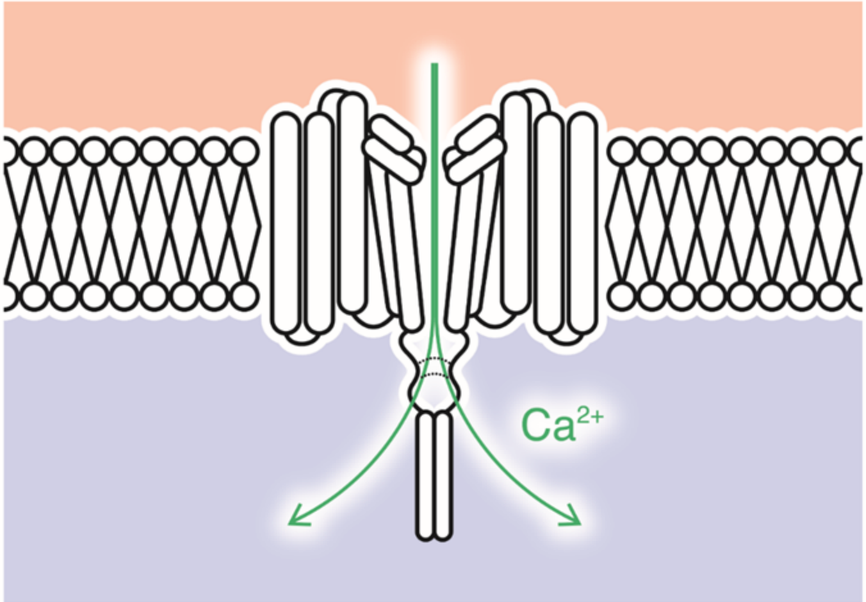

Figure 1. Schematic representation of a thermoTRP in its open state. The hydrophilic core of the neck domain is represented by the dotted lines. This structure provides the metastable behaviour. Modified from Arrigoni et al. (2016); Shaya et al. (2014) and Voets et al. (2005)

Furthermore, physiological studies on thermosensitive proteins have revealed that each TRP protein works at a particular temperature range and has its optimal point of activation within this range (Patapoutian et al., 2003; Voets et al., 2005). The channels identified so far can be classified as either heat- or cold- sensitive. A neutral range between 30ºC-36ºC has been also defined. Therefore, temperatures below this range are experienced as cold stimuli, whereas, above it, hot stimuli are felt (Lv & Liu, 2007). Additionally, noxious stimuli in the hot range have been defined when the skin is over ~ 43ºC and under ~ 17ºC in the cold range (Davis & Pope, 2002; Patapoutian et al., 2003). A nonlinear relation between temperature increases/decreases and channel activity has been also observed (Andrew & Craig, 2001; Xu et al., 2002).

Evidence presented above shows that humans do not have a unique temperature detection device (a thermometer), but a family of sensors. These sensors behave non-linearly, open within a particular range of temperature and have a probabilistic behaviour. Therefore, the overlapping activation and responsiveness of these receptors, as well as the complex interaction of the neurons involved in this process, determines our capacity to feel temperature: our range of perception and our sensitivity to change.

Thus, when our skin contacts with an object that is at a different temperature, a thermal gradient is established. Consequently, the temperature of the TRPs shifts, which results in the opening (or closing) of the channel. Then, sensory neurons depolarise (or hyperpolarise) and a signal is triggered (or not). But, we can only feel a part of the whole thermal range: innocuous cold from ~17ºC to ~30ºC, innocuous hot from ~36ºC to 43ºC, and a neutral zone between 30ºC and 36ºC. Out from our sensitivity range, we can only feel pain and our tissues are damaged. Therefore, the arrangement of the thermosensory system (hot- and cold-sensitive TRPs) seems to predispose us to categorise the thermal state of bodies in hot- or cold-objects.

Neuronal Level

ThermoTRPs are found in the free nerve endings of afferent neurons (Schepers & Ringkamp, 2010). These thermosensitive afferent neurons have been classified according to their receptor type found in their membrane. Therefore, in the innocuous range, there are neurons with either cold or hot receptors, so innocuous cold and hot stimuli are independently transduced and transmitted to the central nervous system. Noxious cold and heat are mainly mediated by multimodal neurons (activated by other noxious stimuli) (Schepers & Ringkamp, 2010). It seems that the body has evolved to group pain and noxious stimuli separately from precise and more accurate innocuous stimuli (Ezquerra-Romano & Ezquerra, 2017).

Furthermore, thermoreceptors are situated at different levels in the human skin. Cold receptors are found in the epidermis at a depth of 0.2 mm (Dhaka, Earley, Watson, & Patapoutian, 2008), whereas hot receptors are found deeper, at about 0.5 mm (Lv & Liu, 2007). Due to the difference in depth, the response time to thermal stimuli differs for each type of receptor. Therefore, temperature increases (and decreases) faster in cold receptors than in hot receptors. Consequently, the detection time of hot receptors is slower than cold receptors (Lv & Liu, 2007).

Moreover, thermosensitive afferent neurons can be also classified into different kind of fibres. Specifically, innocuous hot sensitive fibres are mainly C fibres (LaMotte & Campbell, 1978), which are the slowest conducting fibres (Lv & Liu, 2007). In contrast, cold sensations are mediated by Aδ and C-fibres (Lv & Liu, 2007; McKemy, Neuhausser, & Julius, 2002). Aδ fibres conduct faster than C fibres (Lv & Liu, 2007).

In summary, hot and cold thermoreceptors are situated at different depths in the skin, which results in distinct activation times. They are also grouped in specific fibres, which means that they are transmitted at different speeds. Therefore, the separation of the thermal range into hot and cold is seen at both the molecular and the neuronal level. As explained above, it appears that our physiology predisposes us to categorise the thermal information into hot- or cold-objects.

Another important characteristic is that the amplitude of the action potential is the same for any stimuli in any neuron. The information is coded by the number of depolarisation peaks per unit of time, not by the amplitude of the spike. Therefore, a sudden change in temperature causes a high firing rate that indicates a strong signal. In particular, hot-sensitive neurons increase their firing rate when temperature rise and decrease their activity when temperatures decrease; the opposite is true for cold thermoreceptors (Lv & Liu, 2007; Schepers & Ringkamp, 2010). Therefore, thermosensitive neurons show the strongest firing rate during and immediately after the temperature change. After the transient change in firing rate neurons return to a steady level; they adapt to long lasting stimuli (Hensel, Strom, & Zotterman, 1951). Additionally, cold-sensitive neurons take longer to reach their peak frequency compared to hot-sensitive neurons (Lv & Liu, 2007). This modulation of the signal, as well as the overlapping activation and responsiveness of thermoTRPs, allows our nervous system to establish a scale within thermosensation. Therefore, we can distinguish between hot-, lukewarm-, chilly- and cold-objects.

Another factor that should be considered is that humans are warm-blooded animals. Consequently, when someone contacts with a small object (hot or cold) there is an initial thermal gradient, which could trigger action potentials in our thermosensory neurons. However, the object will immediately heat up or cool down, since its mass is smaller than our body and its temperature will tend to equalize ours. Therefore, the thermal gradient disappears and the firing rate decreases. In contrast, when an individual touches a large mass that maintains or even increases (or decreases) its thermal gradient over time, the initial firing pattern is more likely to maintain or even increase. This might explain why some objects are felt as thermal sources and why people feel heat or cold flows from an object to their skin.

It should be noted that there are other properties of objects such as thermal conductivity and heat capacity that might influence the process explained above. For instance, two bodies at the same temperature, but with different thermal conductivities act differently on our thermosensory system. People will tend to feel metallic objects as "intrinsically cold" and winter gloves as "intrinsically hot" (Potvin, 2011). Other variables specific to liquids such as evapotranspiration might also contribute to the development of the concepts of heat and temperature. However, this is out of the scope of this work.

Central Nervous System Level

Innocuous and noxious temperature-sensitive neurons synapse in the superficial laminae of the dorsal horn with neurons that project to the thalamus and brainstem (Patapoutian et al., 2003). The separation of hot and cold information seen at the molecular and cellular level has been also found in the spinal cord and even in some areas of the brain (labelled-line hypothesis) (Craig, 2002; 2003). However, it has been observed that the hypothalamus and the brainstem send projections to these laminae, which suggests that at this stage the signal is already modified and modulated by higher-order brain areas (Holstege, 1988). Readers are referred to the review by Ezquerra-Romano and Ezquerra (2017) for a more detailed account of the thermosensation system from the molecular to the central nervous system level.

Research into the Drosophila brain has provided evidence of a clear segregation of cold- and hot-sensing neurons. Specifically, cold-sensing neurons project to a glomerulus at the lateral margin of the Proximal Antennal Protocerebrum (PAP), while hot-sensing neurons target a separated glomerulus in the same area (Gallio, Ofstad, Macpherson, Wang, & Zuker, 2011). It is important to note that they do not overlap. This organisation forms a thermotopic map in the Drosophila's PAP that displays a functional representation of temperature in the brain.

A recent study identified the higher brain areas in Drosophila where thermosensory information converge (Frank, Jouandet, Kearney, Macpherson, & Gallio, 2015). A similar mechanism has been suggested in mammals, and the brain areas in humans and primates that become more active with temperature information and variation have been identified (Gallio et al., 2011). Temperature neurons that ascend via the spinal cord project axons to the thalamus, specifically, to the posterior part of the ventromedial nucleus (Davis et al., 1999).

Furthermore, there are projections that carry thermal information from the thalamus to the right anterior insular, the hypothalamus, the anterior cingulate cortex and the orbitofrontal cortex. These projections further process thermal information (Craig, 2002). They split or bring together different aspects of the information flow. However, hot and cold information separately reaches the spinal cord and thalamus. Therefore, the information reaching these areas has already been funnelled by our nervous system. The patterns of activity elicited in the brain would not be a direct representation of external conditions, but an impression of the information that has already been transduced and processed by sensory neurons.

Moreover, the feeling, awareness and perception of temperature have been proposed to emerge from the synergic integration and interaction of the homeostatic centres with the thermal representation in insular, anterior cingulate and orbitofrontal cortex (Craig, 2002). In addition, a recent imaging study shows that cortical activation in specific areas is associated with explicit physical knowledge (Mason & Just, 2016). Speculatively, the distinct patterns of neuronal activity that encode information of cold, cool, warm and hot might constitute our internal organisation of sensations. This classification would result in the physical concept of temperature.

DISCUSSION

We first gathered the general characteristics of alternative conceptions, in particular those associated to heat and temperature. These intuitive ideas show a progression in their complexity during the building process of concepts. These mental structures are found in all societies and throughout people's lives. They are also resistant to most strategies aimed at taming and shaping them. Therefore, many scientists have suggested that there must be a pre-existing and common substratum that explains these characteristics (Driver, 1985; Kubricht, Holyoak & Lu, 2017; Vosniadou, 1994; Wenning, 2008).

We then considered the way in which thermal information is transduced and transmitted by cold- and hot-sensitive TRPs and afferent neurons (Ezquerra-Romano & Ezquerra, 2017). The neurophysiological arrangement (hot- and cold-sensitive TRPs and sensory neurons) might determine why we perceive hot- and cold-objects. This would result in the sensation that hot and cold are two different entities and, ultimately, in the development of two different concepts: cold and heat. Furthermore, particular patterns of neuronal activity, which code thermal information, may establish a ranking of sensations that eventually results in the physical concept of temperature.

In this work, we suggest the neurophysiological bases of misconceptions about heat and temperature. This approach has the potential to explain why alternative conceptions are resistant to change and very common among any level of expertise, group of age, gender, and culture. Our physiology is common and persistent in humans. Unless there is a pathology, our sensory systems always have the same structure. Therefore, even if we shaped the complex networks of our initial conceptual maps and learned to interrelate some concepts, we would always sense the world in the same way. Preliminary evidence appears to explain this phenomenon. A study using functional magnetic resonance imaging (fMRI) found that the same networks were activated in beginners and experts when they dealt with alternative conceptions (Masson, Potvin, Riopel & Foisy, 2014). In addition, experts' brains had activity in areas which are normally involved in inhibition. Therefore, it seems that alternative conceptions are still somehow expressed in expert's brains, but they are inhibited (Foisy, Potvin, Riopel & Masson, 2015). Further research should explore possible neurophysiological bases for other misconceptions other than about heat and temperature.

Since the thermosensation system works and develops similarly in all humans, this hypothesis could also explain why the same misconceptions are expressed in all humans at similar ages (see **Table 1**). In **Figure 2**, we represent the stages of the conceptualisation of heat and temperature and how the neurophysiology of the thermosensation system might influence each step. This interaction contributes to the existence and development of conceptual trajectories.

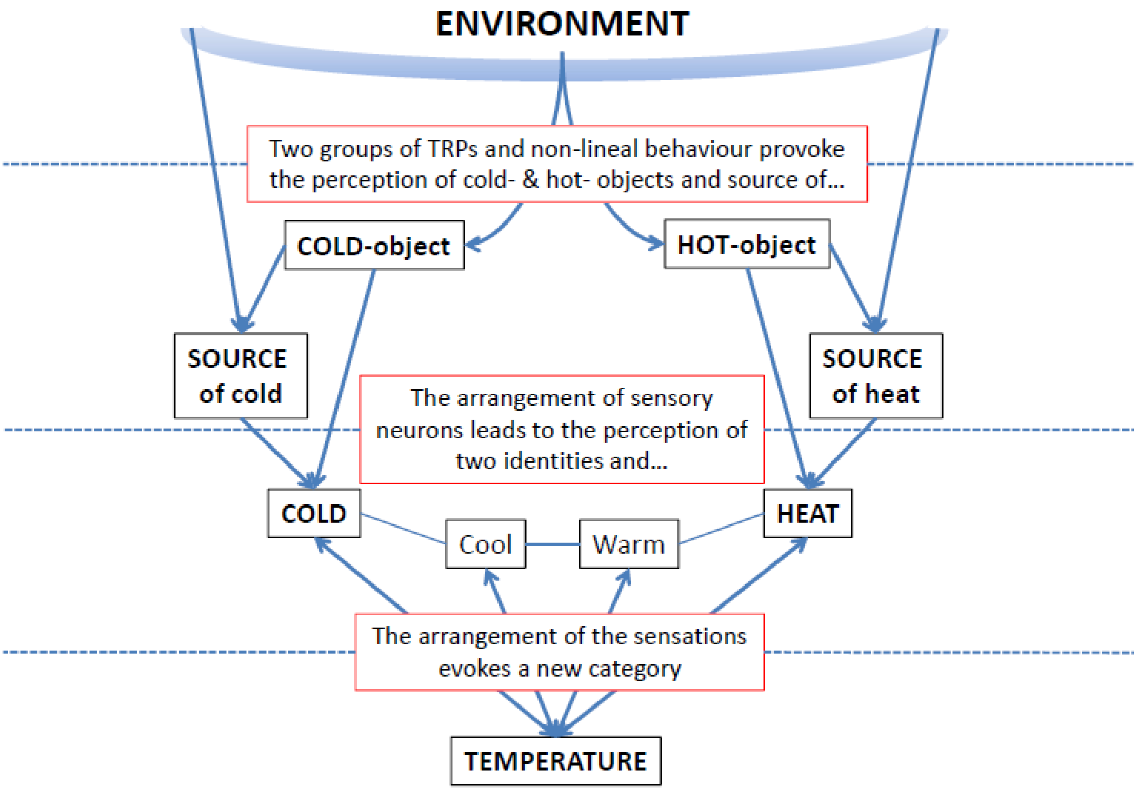

Figure 2. Diagram that represents the stages of development of the conceptualization of heat and temperature and how the neurophysiology of the thermosensation system influences each stage

There are undoubtedly many cultural, psychosocial and educational factors that influence the emergence of alternative conceptions and the development of conceptual trajectories. We do not attempt to leave these factors aside, but to complement the wide range of literature on these topics. It would be interesting to explore the interaction of all these factors and how each one contributes to the appearance of misconceptions and to the development of specific conceptual trajectories.

CONCLUDING REMARKS

To obtain the knowledge that helps us understanding the physical environment is a phenomenological (empirical) process (Chi & Slotta, 1993; DiSessa, 1993). In thermodynamics, determining and ranking each element (cold, cool, warm and hot) involves learning about the behaviour of the environment (laws of physics) and of our thermosensory system. Both learning processes occur simultaneously and interact with each other. This mechanism appears to require several steps as it is shown above. We undergo different stages to identify reiterations, verify relations and ensure the existence of standard and consistent physical rules. Therefore, this development demands time, which might explain why the concept of temperature develops later in childhood (see again **Table 1**).

From an educational point of view, the interplay defined in this article between conceptual trajectories and neurophysiology brings to light the capacities and limitations of humans in the creation of concepts. The understanding of these factors could have a ground-breaking educational value. We develop below a few ideas of the contribution and impact this approach could have on teacher's training and the teaching of science to children.

Although the precise characterization of Pedagogical Content Knowledge (PCK) is still an open issue, some key elements have already been established: the knowledge of representations of subject matter by teachers, and the knowledge of student conceptions and their specific learning difficulties (Van Driel, Verloop, de Vos, 1998). Understanding the role of physiology in the development of concepts of physics could facilitate teachers, among other things, to know and understand children's ideas about science and tackle the learning difficulties in an innovative way as explained below.

Furthermore, this neuroscientific knowledge could also decrease the frustration of teachers. The aim of teachers is to stimulate an evolution in their students' misconceptions. This task has classically been considered to be hampered by modifiable situations such as the attitude of the students, the training of teachers, the means available in the classroom, etc. In this perspective, a delay or absence of evolution in student's learning could be considered responsibility of the teaching staff. However, by understanding that human physiology is a determinant factor, teachers would realise, among other things, that student's misconceptions have an immutable component, our neurophysiology. Therefore, they should not expect to easily modify their students' alternative conceptions.

Understanding the relationship between alternative conceptions and neurophysiology can improve teachers' abilities to deal with student's conceptualisation. Teachers would be encouraged to design activities that would directly show the interplay between perception and the development of concepts. These kind of activities should aim to make students realise about the mistakes they make and the possible underlying reasons to do so. For instance, teachers could stimulate a debate about the erroneous use of the words heat and cold in daily life language. For example, it is often said in different languages that heat or cold 'comes through the window', which is a misconception reminiscent to the caloric theory explained before. However, neither heat nor cold are fluids, but a physical phenomenon of energy transfer.

An alternative activity would be to present buckets with water to students at different and known temperatures. This practical activity would stimulate a reflection of how different temperatures actually feel, since there are often misconceptions in this regad. Another suitable activity could be to present students with different materials (wood, metal, plastic etc.) at the same temperature. This practical exercise would show students the disparity between our thermal sensations and the measured temperature. This type of activities would help students becoming aware of the capacities and limitations of their senses and, therefore, to overcome their misconceptions.

Moreover, the curriculum could be also improved. It might be that some concepts such as temperature are not worth introducing early in development, since they may only frustrate students and hinder their learning process. Although they might be able to memorise and 'understand' the concepts, they might not really internalise them. Understanding the development of the nervous system and its relationship with alternative conceptions could facilitate the reflection on how and when children should be introduced to some concepts. However, the development of conceptual trajectories and the nervous system should be studied more carefully.

Humans certainly experience the world through very limited and distorted windows: our senses. They funnel information in a way that has probably been the most advantageous throughout evolution. Nevertheless, our thinking and capacity of conceptualisation are shaped and constrained by the physiology of our organism. In a broad sense, we think in the way we are, in the way our organism is physiologically assembled.

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