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ARTICLE

A Growing Body of Knowledge

On Four Different Senses of Embodiment in Science Education

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Abstract

Science deals with the world around us, and we understand, experience, and study this world through and with our bodies. While science educators have started to acknowledge the critical role of the body in science learning, approaches to conceptualising the body in science education vary greatly. Embodiment and embodied cognition serve as umbrella terms for different approaches to bodily learning processes. Unfortunately, researchers and educators often blur these different approaches and use various claims of embodiment interchangeably. Understanding and acknowledging the diversity of embodied perspectives strengthen arguments in science education research and allows realising the potential of embodied cognition in science education practice. We need a comprehensive overview of the various ways the body bears on science learning. With this paper, we wish to present such an overview by disentangling key ideas of embodiment and embodied cognition with a view towards science education. Drawing on the historical traditions of phenomenology and ecological psychology, we propose four senses of embodiment that conceptualise the body in *physical*, *phenomenological*, *ecological*, and *interactionist* terms. By illustrating the multiple senses of embodiment through examples from the recent science education literature, we show that embodied cognition bears on practical educational problems and has a variety of theoretical implications for science education. We hope that future work can recognise such different senses of embodiment and show how they might work together to strengthen the many roles of the body in science education research and practice.

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1 Introduction: the Role of the Body in Science Education

What is the role of the human body in science education? Of course, the human body features as a subject of study, for example, in biology or physical education (Almqvist & Quennerstedt, 2015; Alsop, 2011). Additionally, the body is involved in producing science phenomena, for example, in laboratories (Hardahl et al., 2019). More generally, though, science educators seem to agree on the vital relationship between physical movement and conceptual learning in science. Researchers argue that thinking about and understanding science needs embodiment both in concrete and in more abstract learning domains (Niebert et al., 2012).

On the one hand, research suggests that gestures and kinaesthetic activities facilitate the learning of physics in classical mechanics (Bruun & Christiansen, 2016). In the concrete context of classical mechanics, gestures can provide sensorimotor information that prompt idea construction (Scherr, 2008). On the other hand, some learning domains in science are among the most abstract and complex areas of human thought. Entropy, the greenhouse effect, or the theory of relativity present students with abstract concepts that are far removed from our sensory capabilities (Amin, Jeppsson, & Haglund, 2012; Niebert & Gropengießer, 2014; Steier & Kersting, 2019). To make sense of these concepts, we project patterns of sensorimotor experiences onto more abstract domains, and everyday language reflects these projections (Lakoff & Johnson, 2003). For example, we conceptualise the atmosphere as a "container to describe the flow of radiation between the inside and the outside" to make sense of the greenhouse effect (Niebert & Gropengießer, 2014, p. 283). Here, the human body and our experience of physical containment bear on the form and use of instructional metaphors of the greenhouse effect (Niebert & Gropengießer, 2014).

Despite the many merits of looking at embodied ways of learning, there is no one best way to think about the role of the body in science education (Alsop, 2011). What we usually view as a simple notion, the body, opens to a multitude of theoretical perspectives that build on different traditions and premises about science learning (e.g. Amin et al., 2015; Euler et al., 2019; Hardahl et al., 2019; Kersting & Steier, 2018; Niebert et al., 2012). Often, science education researchers use relevant concepts of embodiment and embodied cognition interchangeably or do not address the complexity of these concepts at all.

The terms "embodiment" and "embodied cognition" are used differently within different perspectives and traditions. While we refine possible meanings of these terms below, broadly, we understand "embodiment" as being concerned with the experiences that arise from having living bodies in our interactions with the material and sociocultural world. Embodiment is a fundamental aspect of lived experience, and the study of embodiment builds on the basic view that "our knowledge of the world is inseparable from our experiences of the bodies that we are" (Popova & Rączaszek-Leonardi, 2020, p. 3). We use the term "embodied cognition" broadly to refer to the processes of thinking, knowing and communicating that rely in some way on embodiment. Embodied cognition describes cognitive processes that deeply rely on features of the physical body beyond the brain (Wilson & Foglia, 2017). As a loosely knit family of research programmes, the study of embodied cognition builds on the assumption that we can improve our understanding of the mind by characterising the role of the body in cognition[1] (Wilson & Foglia, 2017).

[1] In this paper, we use the terms "mind" and "cognition" in the ordinary sense without taking a specific conceptual stance. However, we do acknowledge that there are controversies regarding different definitions of "mind" and "cognition" and that these definitions may vary quite a bit between traditions of mainstream psychology, cognitive science, and embodied cognition.

Within these broad concepts are quite different premises. Observing that embodied perspectives operate on multiple abstraction levels, from the nature of physical phenomena to more abstract concepts, we argue that it is necessary to bring clarity to the diverse approaches towards embodiment in science education. As researchers, we need to disentangle the complex experience of "having a physical body in a physical world" (Roth & Lawless, 2002, p. 336) to fully realise the theoretical and practical benefits of embodied perspectives.

Consequently, this paper aims to clarify and contextualise different perspectives of embodiment and examine the implications of these perspectives in science education research and practice. In line with Merleau-Ponty (1962) and the phenomenological tradition, we conceptualise the body in a double sense: first, as the context of cognitive mechanisms and second, as a lived, experiential structure. Building on ecological and interactionist traditions, we extend and complement this double sense of embodiment by adding two more senses: the ecological and interactionist senses of embodiment describe the relationship between the body and its material and sociocultural environment. Together, these four senses provide distinct perspectives on embodiment, and they become our organising principles to study the role of the body in science education.

To examine how different claims of embodiment and embodied cognition bear on science education research and practice, we present a series of recent examples taken from empirical studies in science education. The four senses of embodiment act as lenses to bring the use of embodied perspectives into sharper focus. We show how each sense of embodiment supports very different analytic approaches to researching science learning and prompts unique considerations for designing science education activities. Our goal is not to advocate for one sense over the other but to show that there are significant implications for adopting a particular sense even implicitly. By distinguishing these senses, we are advocating for more nuanced language around embodied cognition in science education.

2 Philosophical and Psychological Traditions of Embodiment and Embodied Cognition

Ever since Descartes famously introduced the Cartesian divide between mind and body, Western philosophers have had a keen interest in the nature of the mind and its relationship to the body. Similarly, psychologists and cognitive scientists have historically treated "the skin as the boundary of their territory and thereby embraced an organism-environment dualism (…) [where] things inside the skin constitute one domain and things outside the skin another, and the two domains are approached independently" (Michaels & Palatinus, 2014, p. 20).

However, there is a growing commitment among philosophers, psychologists, and cognitive scientists that we should understand our knowledge and our means of arriving at knowledge in terms of the relationships between mind, body, and environment (Anderson, 2003; Hutto & McGivern, 2015; Jensen & Greve, 2019; Varela et al., 2016; Wilson, 2002). Rejecting a Cartesian divide between body and mind, proponents of embodied cognition understand the mind and the world not as two pre-given entities but as mutually constituted in dynamic relationships (Popova & Rączaszek-Leonardi, 2020).

At the most basic level, the study of embodiment entails the view that our knowledge of the world is inseparable from our experiences of and through the bodies that we are (Popova & Rączaszek-Leonardi, 2020). This focus on embodied being and acting in the world promises a more holistic approach to knowledge, experience, and learning than what has traditionally been the case within cognitive science, philosophy, and psychology. Still, there remain significant differences in how embodied cognition is understood. There are a wide variety of interpretations of embodiment and embodied cognition and claims emerging from them, some of which are controversial or even contradictory (Anderson, 2003; Hutto & McGivern, 2015; Wilson, 2002).

To put our investigations onto firm grounding and to be able to unpack and contextualise the multiple senses of embodiment, we now turn to philosophical and psychological traditions of embodiment and embodied cognition. We focus on the 20th century philosophy and psychology with a particular emphasis on phenomenology and the ecological theory of perception since these two precursors of embodied cognition bear most directly on the issues in science education that we wish to explore.[2]

2.1 Embodied Experiences in Phenomenology

Within our Western tradition, phenomenology has been the philosophy of human experience (Bengtsson, 2013; F. J. Varela et al., 2016). At its core, phenomenology is the direct study of our lived experiences that are guided by intentionality: all acts of consciousness, be it perceptions, feelings, moods, decisions, memories, or imaginations, are experiences of something (Popova & Rączaszek-Leonardi, 2020).

Phenomenologists acknowledge the first-person point of view and the central role of subjectivity in our relationship with the world. Motivated by the wish to return to the "things themselves", Edmund Husserl (1965) promoted a direct examination of experience and sought to reflect systematically on how phenomena are manifest in the convergence of "things themselves" with the consciousness of the experiencer: "We cannot be conscious of an object (a tasted lemon, a smelled rose, a seen table, a touched piece of silk) unless we are aware of the experience through which this object is made to appear (the tasting, smelling, seeing, touching)" (Zahavi, 2005, p. 121).

For Husserl, the lived body is involved in intentional acts and as a subject that is reflectively aware of itself (Husserl, 1965). Although Husserl's work can be considered a first phenomenology of embodiment, the role of the body remains mostly implicit (Moran, 2017; Popova & Rączaszek-Leonardi, 2020).

Martin Heidegger (Heidegger, 1962) extended Husserl's phenomenology by introducing the notion of "Being-in-the-World". Heidegger observed that there could not be a divide between subject, object, and the world. According to Heidegger, phenomenology rejects dichotomies between mind and world, subject and object, language and reality. Although Heidegger considered thinking beings first and foremost as acting beings in the world, he largely ignored the body's active role in his account of being.

Building on Husserl and Heidegger's phenomenological tradition, Maurice Merleau-Ponty (1962) was the first to stress the embodied context of human experience explicitly. Acknowledging that bodies are the mediators of our reality, Merleau-Ponty articulated the view that

[2] We recognise, though, that other traditions have provided crucial perspectives on how we navigate, experience, and understand the world as embodied beings. Notably, in philosophy, William James' radical empiricism (1890) and John Dewey's pragmatism (1949) share a commitment to the lived experience and recognise that the world and our experiences are inseparably interlinked. In psychology, the early enactivism of Varela et al. (Varela et al., 2016) has paved the way for modern perspectives of embodied cognition that draw on the study of self-organisation.

perception always occurs in the context of (and is therefore structured by) the embodied agent in the course of their ongoing purposeful engagement with the world. According to Merleau-Ponty, “my body is the fabric into which all objects are woven, and it is, at least in relation to the perceived world, the general instrument of my comprehension” (1962, p. 273). In other words, bodily movement and bodily experiences are a way of accessing the world.

For Merleau-Ponty, embodiment has an inherent double sense: it encompasses both the physical body as the context of cognitive mechanisms and the phenomenological body as a lived experiential structure. The perspective of being doubly embodied “provides a way to escape dualism in the description of embodied experience and evens a way of reconciling a more scientific third-person stance and a first-person phenomenological one” (Popova & Rączaszek-Leonardi, 2020, p. 4).

2.2 Embodied Experiences in Ecological Psychology

The assumption that there are divides between mind and body and subjects, objects, and the world has had a profound impact on psychology, as well. Traditionally, psychology has separated the organism and environment: for contact to be had with the environment, it had to be represented in the mind (Michaels & Palatinus, 2014). As one of the original fields of embodied cognition, ecological psychology has challenged this dualist assumption.

Ecological psychology has developed from James J. Gibson’s theory of perception (1966, 1979) which attempted to reconceptualise the relation between organism and environment. By taking the organism and its environment as the minimal unit of analysis, the ecological view respects the integrity of the system under investigation. Gallagher (2017) illustrates the ecological view through an analogy:

> Saying that cognition is just in the brain is like saying that flight is inside the wings of a bird. Just as flight doesn’t exist if there is only a wing, without the rest of the bird, and without an atmosphere to support the process, and without the precise mode of organism-environment coupling to make it possible (indeed, who would disagree with this?), so cognition doesn’t exist if there is just a brain without bodily and worldly factors. The mind is relational. It’s a way of being in relation to the world. (Gallagher, 2017, p. 12)

An ecological conception of cognition offers a reconfiguration of the relationship between the inner and outer because it relates the mind to bodily functions and environmental features (Jensen & Greve, 2019). A critical ecological concept that describes this relationship is that of affordances as possibilities for action. Introduced by Gibson (1979) in his pioneering work on visual perception, affordances capture the idea that features of the organism shape properties of the environment. Ultimately, there is no divide between perception and action:

> The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill. The verb to afford is found in the dictionary, the noun affordance is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment. (…) An affordance cuts across the dichotomy of subjective-objective and helps us to understand its inadequacy. It is equally a fact of the environment and a fact of behaviour. It is both physical and

psychical, yet neither. An affordance points both ways, to the environment and to the observer. (Gibson, 1979, p. 127)

In ecological psychology, embodied experiences and the embodied nature of cognition stem from an understanding of cognition as being for a body's action. The active body shapes perceptual categories, and ultimately, activity serves as the starting point for cognition (Popova & Rączaszek-Leonardi, 2020). Thus, in the ecological view, cognition emerges in and through an organism's actions in its environment. Relations between mind, body, and environment become conditions of existence because the environment enables and restricts cognition.

2.3 Embodied Experiences in Social Interaction

When adopting an ecological stance towards embodiment, we have to specify how we understand the environment that enables and restricts cognition, because the environment comprises both material and sociocultural aspects. In much of Gibson's work, the focus lies on the naturally occurring features of the environment instead of the environment as produced by humans. However, it is crucial to acknowledge that affordances in the human world can look different compared with those of a general "organism": "The richest and most elaborate affordances of the environment are provided by other animals and, for us, other people" (Gibson, 1979, p. 135).

Gibson was aware that humans are created by the world in which they live. Still, it seems that Gibson's approach to persons was similar to his approach to objects (Pedersen & Bang, 2016). Although ecological perspectives acknowledge the mutuality among humans, they tend to neglect humans' essential sociocultural character: humans create, construct, and live their lives in relation to their societies, cultures, and historical constraints. By reducing sociocultural objects to their natural and perceivable functional properties, much of the Gibsonian tradition has neglected the person's subjectivity and the person as a sociocultural object (Pedersen & Bang, 2016). A notable exception is Reed's work (1996) that extends Gibson's ideas to aspects of human experience beyond perception. For example, Reed notes that "becoming a person is something one cannot do all on one's own; it is an inherently social process. (…) the human environment itself is the result of collective efforts and activities" (1996, p. 126).

The phenomenological tradition has met similar criticism. Varela (1994) argued that Merleau-Ponty's conception of embodiment with a focus on the lived body lacks an explicit acknowledgement of the body as a social and cultural entity:

> After all, bodies don't intend, people do; and certainly minds don't intend either, only people. People are personal agents, and, while they are enabled by their natural being, they are empowered by their social being to engage in the conversational practices of their local culture. What is missing then in Merleau-Ponty's philosophical perspective is the person. (Varela, 1994, p. 171)

In summary, the main focus in the above theories of embodied cognition has been on the relation between the individual body and its cognitive processes in interaction with the material environment (Lindblom, 2007). However, for humans, "being-in-the-world" is not an individual enterprise because the world comprises social and cultural contexts (Lindblom, 2007). Actions have social meaning, and agency takes place within a web of cultural structures (Anderson, 2003). As such, researchers have made calls to move beyond the traditional emphasis on interactions between the individual and the physical environment to encompass embodied interactions between embodied agents in their social environments (e.g. Anderson, 2003; Johnson & Rohrer, 2007; Lindblom, 2007; Still & Costall, 1991). Sociointeractional aspects of embodied cognition highlight semiotic activities such as communication, dialogue, feedback, intersubjectivity, coordination, and collaboration. Such interactions between people thus reveal a layer of complexity beyond the individual that can be crucial for science learning and meaning-making.

A natural starting point to approach the role of embodiment in social interaction is Vygotsky's theory of cognitive development (1962, 1978). Vygotsky stressed the centrality of situatedness for the development of higher mental functions. In the Vygotskian tradition, human cognition is the consequence of the intertwining of sociocultural and biological factors: cognition emerges in the developmental process of human bodies interacting with the material as well as the sociocultural world: "Every function in the child's development appears twice: first, on the social level, and later, on the individual level" (Vygotsky, 1978, p. 56). In his work, Vygotsky did not explicitly address the body or embodiment. Still, his ideas on the relationship between cognition and our social situatedness can complement the (primarily) individual perspectives of the phenomenological and ecological traditions (Lindblom, 2020).

With his approach of "cognition in the wild", Hutchins (1995) brought such sociocultural considerations specifically into the field of embodied cognition. Hutchins identified the complex task of navigating a large naval vessel to be a culturally constituted activity in which cognitive systems at different levels simultaneously manifest. "In describing the ongoing conduct of navigation tasks, it is possible to identify a number of cognitive systems, some subsuming others. One may focus on the processes internal to a single individual, on an individual in coordination with a set of tools (…), or on a group of individuals in interaction with one another and with a set of tools (…)" (Hutchins, 1995, p. 373). In his analyses, Hutchins showed how tasks were performed by (sub)system composed of people and material and symbolic artefacts in interaction. In the context of science education, Vosniadou (2007) sees Hutchins' analysis as a promising approach to "put cognition back in the social and cultural world" (p. 61) and thereby bridge the divide in educational research that has formed between cognitive and situative perspectives.

2.4 Summary: Historical Roots of Embodiment and Embodied Cognition in Philosophy and Psychology

In this section, we have presented the historical origins of embodiment in line with the phenomenological tradition in philosophy and the ecological tradition in psychology.

The phenomenologists' preoccupation with the bodily world of experience aims to describe the human experience as it is lived, that is, in practical terms of the actions and movements that having a body allows (Popova & Rączaszek-Leonardi, 2020). Merleau-Ponty moved away from "I think that" towards "I can" and put agency and interactivity at the centre of his explorations (Anderson, 2003). The body is not any other object in the world or merely a physical body; rather, the body is experienced by a particular first-person perspective (Popova & Rączaszek-Leonardi, 2020). Consequently, Merleau-Ponty introduced the double sense of embodiment that encompasses both the physical body as the context of cognitive mechanisms and the lived body as an experiential structure (Varela et al., 2016).

In parallel to philosophers, psychologists put forward an ecological framework that explains cognition as a quality of an organism-environment system. In this framework, cognition emerges from internal and external processes that are distributed across the brain, body, and environment. Thus, cognition is not restricted to our brain but an expression of our bodily agency in the world (Thompson, 2014). Agency in ecological psychology is usually understood in the context of a pragmatic sense of embodiment, in relation to undertaken action. Bodily actions shape and drive cognitive processes, and perception provides rich relational information that guides behaviour (Popova & Rączaszek-Leonardi, 2020).

Phenomenology and ecological psychology share common themes while also, and importantly, providing complementary perspectives. The relational nature of the subject-world connection through bodily mediation is a dominant feature in phenomenology and ecological psychology. In fact, to "the extent that the lived body is seen as complicit in the act of perception and action in the world, the theory of affordances bears certain similarity to a phenomenological understanding of the body" (Popova & Rączaszek-Leonardi, 2020, p. 9).

However, by and large, ecological psychology has not considered the lived and felt quality of experiences. Ecological perspectives broaden the scope of phenomenology by carefully unpacking the rich relations between organisms and their environments. However, these perspectives lack the subjectivity so prevalent in phenomenology.

While neither phenomenology nor ecological psychology denies the relevance of sociocultural aspects of embodied experiences, they do not further explore the embodied nature of social interaction either. Building on a Vygotskian approach, we can shed light on the role and relevance of embodied experiences in social interaction. By drawing on different and complementary traditions of embodied experiences in philosophy and psychology, we hope to capture the multifaceted nature of embodiment and embodied cognition better for our purposes in science education.

3 Multiple Senses of Embodiment in Science Education

Common to the various claims of embodied cognition is the understanding that cognitive processes are deeply linked to the dynamic ways in which people use their bodies to engage with the world (Anderson, 2003; Hutto & McGivern, 2015; Wilson, 2002). Still, significant differences between different such perspectives remain. Often, these differences are not adequately acknowledged, or different perspectives become blurred. Thus, we have to be careful to explicate the meaning of embodied cognition in the context of science education.

Building on Merleau-Ponty's phenomenology of perception (1962), we introduce the first two senses of embodiment: the *physical* sense of embodiment describes the body as the basis of cognitive structures; the *phenomenological* sense of embodiment describes the body as lived experiential structure. In line with the Gibsonian and Vygotskian traditions, we add two more senses of embodiment, the *ecological* and *interactionist* senses of embodiment, which take the material and sociocultural affordances of the environment into account. In the following sections, we develop and unpack these four senses.

Of course, the various senses of embodiment are not opposed or mutually exclusive (Varela et al., 2016). In fact, the same pedagogical activity could be analysed or designed by drawing on multiple senses. However, we think it is useful to disentangle these four senses as organising principles to explicate key differences and premises so they may be applied intentionally. These perspectives operate on multiple levels of abstraction, and they have different implications for what embodied cognition can look like in the context of science education. We give illustrative examples from science education research and practice to show how each sense of embodiment rests on very different premises yet contributes in essential ways to science education. For each sense, we have chosen two examples: one example to illustrate the relevance of the embodied perspective as an analytical approach in science education research and one example to illustrate the practical implications of this perspective in the context of instructional activities.

3.1 The *Physical* Sense of Embodiment: Embodiment as Basis of Cognitive Structures

The *physical* sense describes embodiment as a basis of cognitive structures. This sense builds on a physical view of the body: The body is a physical structure, and abstract cognitive states are either grounded in states of the body, or cognition can be influenced and biased by such states of the body. Our *physical* sense of embodiment captures the aspect of physiology that Anderson (2003) presents as one key aspect of embodied cognition. The mind is embodied not just because all its processes must be biologically instantiated but also because the structures of our perceptual and motor systems play a fundamental role in cognitive functions such as concept definition and rational inferences. Our *physical* sense of embodiment also aligns with the claim that cognitive processes rely on knowledge structures that emerge from body-based experiences (Wilson, 2002).

The body as the basis and context of cognitive mechanisms aligns well with the classical account of conceptual metaphors of Lakoff and Johnson (1999, 2003). Lakoff and Johnson argued that our conceptual system, to a large extent, develops from embodied experiences through interaction with the surrounding world. We form so-called image schemas as phenomenological building blocks of cognition with characteristic inference patterns that stem from repeated patterns of sensorimotor experiences (Johnson, 1987). For example, we form a container schema from the manipulation of objects, where we conceptualise a container in which objects can be located. With the image schema, we can infer that we can place objects in the container and take them out of it and that it is harder to extract objects when they are deeper in the container.

We can project the structure of image schemas onto more abstract domains through conceptual metaphor, which is reflected in conventionalised ways in everyday language. With expressions such as "I am in trouble" or "I am getting into trouble", the inferential structure of the container schema is transferred from the domain of physical objects to that of an emotional state: the deeper you are in trouble, the harder it is to get out of it. Another type of inference that follows from the container schema is the transitivity property: if an object is in container A and A is in container B, then the object must be in B, too. Here, the image schematic logic of containment maps onto set theory. Image-based reasoning is so prevalent in human thought that one can speculate whether all abstract human reasoning is a metaphorical version of image-based reasoning (Lakoff, 1990).

Lakoff and Núñez (2000) argue that even mathematics, one of the most abstract areas of human thinking, is grounded metaphorically in our embodied experiences. For example, our ability to count develops from the experience of manipulation of physical objects, and we get to understand the notion of an equation from physical balancing. More generally, the recent years have seen an active and ongoing conversation about the metaphorical basis of scientific knowledge that builds on the assumption that embodied understandings can be extended to more abstract cognitive structures (e.g. Amin, 2009; Beger & Smith, 2020).

The *physical* sense of embodiment is relevant in science education because of the inherently abstract nature of science and scientific knowledge. Many scientific concepts are intangible and far from our natural sensory capabilities. It is the transfer of inferential structure from image schemas to abstract concepts that accounts for the importance of embodiment in abstract scientific understanding. Suppose understanding of abstract concepts is grounded in our bodies. In that case, we can tailor instructional activities to students' embodied needs by grounding instructional activities and instructional metaphors in embodied sources. The following example of conceptual metaphors illustrates how the *physical* sense of embodiment can inform analytical approaches in science education research. Kinaesthetic activities in physics instruction serve as an illustration of practical activities informed by the *physical* sense.

3.1.1 Analytical Example: Conceptual Metaphor as an Analytical Approach in Science Education Research

The use of conceptual metaphor analysis in science education is an example of a theoretical approach that builds on the *physical* sense of embodiment. Conceptual metaphor analysis can identify features that make instructional metaphors fruitful in science education. The underlying motivation of this analytical approach is the insight that the transfer of inferential structures from image schemas to abstract domains is a key mechanism for learning science.

Amin (2009) analysed the use of language related to the notion of energy in the Feynman lectures (Feynman et al., 1963). He showed that this language involved heavy use of conceptual metaphors. In particular, energy is often explained as an object-like entity that can be stored in, moved to or taken away from a physical object or system, for example, using the container schema. Alternatively, we can interpret energy states as locations on a vertical scale. This implicit use of metaphorical language about energy stands in contrast to Feynman's clear introduction of the law of conservation of energy as an abstract idea. Amin argued that his analysis shows how we can use experiential, embodied resources to understand abstract concepts. Subsequently, Amin and colleagues have found further evidence of extensive use of conceptual metaphors in relation to entropy, yet another abstract science concept, in university textbooks (Amin, Jeppsson, Haglund, et al., 2012) and in students' dialogues during problem-solving (Jeppsson et al., 2013).

Daane et al. (2018) investigated the potential usefulness of adopting conceptual metaphor perspectives in teaching science. When the researchers introduced conceptual metaphor theory in teacher professional development activities, one of the teachers started to wonder: "Is it possible, I mean, is it just impossible to talk about energy without using metaphors?" (p. 1066). Daane et al. (2018) argue that teachers who are aware that thinking and talking about the concept of energy requires metaphorical language can make explicit choices about which metaphor to choose to support their students in learning about specific aspects of energy.

Niebert et al. (2012) used conceptual metaphor analysis to identify factors that make instructional analogies and metaphors effective in teaching science. By analysing metaphors that failed to convey an adequate scientific understanding, the authors identified necessary conditions for metaphors to work during instruction. One such condition is that the analogies and metaphors are grounded in embodied sources based on students' embodied experiences. For example, Niebert et al. reanalysed why a metaphor between chemical equilibrium and a school dance event, described by Harrison and De Jong (2005), did not lead to students' learning of equilibrium. In the study, the teacher compared chemical reactions to students at a dance event where pairs of students dance or break up to form new couples. Niebert et al. concluded that part of the failure is that the metaphor is very complex, building on many different elements and concepts in the target and source domains of the analogy. However, the main reason for failure is students' lack of experience of large-scale school dance events: "The intelligence with which the metaphor is constructed reveals the problem—it is constructed and not embodied. Students do not have an embodied experience with the metaphor's source domain but need imaginative skills to understand it" (Niebert et al., 2012, p. 857).

3.1.2 Practical Example: Kinaesthetic Activities in Physics Instruction

Bruun and Christiansen (2016) drew on the *physical* sense of embodiment to motivate and justify an instructional approach that uses kinaesthetic learning activities for teaching classical mechanics at the secondary and tertiary level. Noting that students' conceptions of basic physical phenomena (e.g. linear motion) are rooted in fundamental kinaesthetic experiences (e.g. image schemas), Bruun and Christiansen argued that this idea could fruitfully frame physics activities in the classroom.

Towards that end, the authors developed a series of instructional activities where students directly felt physical concepts of classical mechanics such as force, resistance, and motion. For example, students were sitting on a plastic piece and holding a rope while another student pulled the rope. Students then discussed and filled out a worksheet in which they described their kinaesthetic experiences and the physics concepts they believed were relevant to their experience. The worksheet also asked students to explain how their experiences linked to the physics concepts.

In developing these classroom activities, Bruun and Christiansen used the image schema of "effort-resistance-flow" that captures our bodily experience of exerting effort and experiencing resistance. Bruun and Christiansen argued that this image schema lies at the heart of physics since the central physical variables in many physics domains drive or describe motion. To facilitate the instructional use of image schemas, the authors distinguished between the kinaesthetic activity (that students perform in the classroom) and the kinaesthetic model (which is an idealisation of the activity useful for planning). Bruun and Christiansen introduced the notion of the "phenomenological gap between everyday experiences and the abstractions of formal physics" (2016, p. 66) to describe how kinaesthetic activities grounded in our bodies allow students to bridge this gap.

Having students link their kinaesthetic experiences to physics laws illustrates how the *physical* sense of embodiment can provide a useful entry point for students' learning of physics concepts. A central aim of this instructional activity was to make students aware of "how their intuitive experience of effort-resistance-flow situations may be conceptualised and used to work with and explain physics phenomena" (Bruun & Christiansen, 2016, p. 69). In other words, the *physical* sense of embodiment suggests instructional designs that target image schemas explicitly.

3.2 The Phenomenological Sense of Embodiment: Embodiment as Lived Experience

The *phenomenological* sense describes embodiment as lived experience. This sense builds on a phenomenological view of the body that emphasises the centrality of the first-person point of view. The body is not a mere physical structure, but it is also a lived experiential structure and part of the lived world of human experience.

The commitment to subjective experiences in the constitution of everything we do includes science, as well. Much scientific knowledge derives from experiments and observations in and of the natural world. Although scientists might think of themselves as disembodied spectators of scientific phenomena, they cannot step out of their lived bodies. Instead of being mere observers of reality, scientists are very much involved in the perception and production of phenomena through their bodily experiences:

> [I]t is, therefore, quite true that any perception of a thing, a shape or a size as real, any perceptual constancy refers back to the positing of a world and of a system of experience in which my body is inescapably linked with phenomena. But the system of experience is not arrayed before me as if I were God, it is lived by me from a certain point of view; I am not the spectator, I am involved (...). (Merleau-Ponty, 1962, p. 353)

Merleau-Ponty replaced the prevailing view of the mind as “I think” with the body’s “I can”. Thus, the body is not only a centre of experience but also a centre of agency in the world (Popova & Rączaszek-Leonardi, 2020).

The *phenomenological* sense of embodiment is relevant in science education because science is very much a practical subject. Hardahl et al. suggested that science educators often neglect the explicit education of students’ bodies and their bodily practices in the science classroom. Shedding light on bodily practices in the lab could be a way to prompt reflection that may deepen students’ awareness of what scientific knowledge entails. This conclusion is similar to the one reached by Almqvist and Quennerstedt (2015) who observed that “knowledge is very much embodied in habits, bodily reactions, actions and our being and becoming embodied” (p. 442) and that science learning is “embodied in practical, emotional and physical aspects” (p. 440).

As emphasised by Hacking (1983), science is not primarily a matter of scientists passively representing the physical world in their theories. Rather, science entails interfering in the physical world through experimentation, often enabling or creating phenomena that have never occurred spontaneously by themselves. Experiments and observations involve many activities, among them looking, checking, choosing, inferring, imaging, and imagining. Through these actions and by creating natural phenomena, scientists reason their way through experiments (Gooding, 1990). Gooding (1990) recognised that thought and act are mutually implicated. It is the mutual implicatedness of conceptual and material activities that put human agency at the centre of scientific knowledge creation in laboratory settings.

Moreover, case studies in the history and philosophy of science suggest that the first-person perspective is central to scientific activities. For example, the sketches and visualisations of physicist Michael Faraday “represent his mental imaging of embodied, multimodal perceptual interaction with objects and forces, but later these become objects of deliberative thought about their physical meaning” (Gooding, 2004, p. 584). Thus, scientific visualisations can convey natural features of human experiences, and making and manipulating images may help generate scientific knowledge (Gooding, 2006).

Therefore, the body in science education is an inquiring and researching body (Almqvist & Quennerstedt, 2015), and we can locate agency in experimental setups in the lab (Gooding, 1990). Students cannot fully understand science without developing practical knowledge and experiencing science with and through their lived bodies. Without these bodies, there are no experiences upon which science education could be based (Bengtsson, 2013). Consequently, the *phenomenological* sense of embodiment can improve instructional practices by acknowledging that authentic, bodily experiences are essential in science learning.

We now turn to the production of physics phenomena in the lab to illustrate how the *phenomenological* sense of embodiment can foreground students' lived experience. A workshop that brings particle physics to a dance studio illustrates a practical activity that invites students to identify with science concepts, thereby drawing on students' first-person perspective.

3.2.1 Analytical Example: the Body and the Production of Phenomena in the Science Laboratory

The following example illustrates how students' lived experience can guide the analysis of video data in science education research to shed light onto neglected aspects of students' learning processes that become relevant in embodied classroom activities.

Hardahl et al. (2019) took lower secondary physics laboratory classes in Denmark as a context to study how students' bodies are involved and intertwined with the production of physics phenomena. Here, producing a phenomenon meant both the making and the observation of the phenomenon. Building on the observation that we often take the purposeful functioning of the body for granted (Leder, 1990), Hardahl et al. analysed situations in which students produced physics phenomena of light and sound. The authors analysed these activities from a perspective towards embodiment that highlights the *phenomenological* sense.

Emphasising practical activities, Hardahl et al. chose "actions as situated in activities and institutions" as their unit of analysis. This choice allowed them "to see how not just talk but also the embodied ways of producing the phenomena are transformed through students' laboratory work" (Hardahl et al., 2019, p. 878). The researchers selected video segments for closer examination where bodily actions played an essential part in producing a physical phenomenon.

One such example was a group of students who used lab equipment to refract light and make various objects "invisible". This activity is a regular part of the physics curriculum in lower secondary physics education in Denmark. Students used their bodies to produce and sense the optical phenomenon of invisibility. The main task consisted in positioning their bodies towards the experimental setup (a beaker filled with water) and aligning the angle of test tubes in such a way as to make the objects in the tubes invisible. Through tinkering, students changed the relative position of bodies and materials. The different alignments between body and material were temporarily filling a gap in the students' inexperience of how to produce the phenomenon. Through bodily positioning, the lived body became part of the physics content to be learned.

Hardahl et al. demonstrated that the embodied production of scientific phenomena is an inescapable part of learning scientific inquiry. The lived bodies of students are just as much part of science as conceptual knowledge. "Producing the phenomena entails not just learning to conceptually distinguish what is there, or following a manual for a ready-made equipment, but demands bit-by-bit embodied tinkering on the part of the students, which may be more or less successful" (Hardahl et al., 2019, p. 866). To illustrate this point, Hardahl et al. presented a detailed analysis of how students "fine-tuned" their bodies to produce the optical phenomenon of invisibility in the lab.

Thus, this study illustrates how embodiment in science education can denote an experiential body in line with the *phenomenological* sense of embodiment. Hardahl et al.

conceptualised learning as a faculty of the mind and as learning how to engage and coordinate with the environment physically: Learning to produce science phenomena is learning science content. Such a view has consequences on how we conceptualise knowledge in science education. In line with the phenomenological tradition, knowledge is not limited to the head but can be an integrated part of practice (Heidegger, 1962).

3.2.2 Practical Example: Particle Physics in the Dance Studio

A recent example of teaching particle physics to middle school students in the UK presented an instructional approach that built deliberately on students' lived embodied experience. Nikolopoulos and Pardalaki (2020) developed the "Particle Dance" workshop to let students approach particle physics through the experiential and expressive means of dance. "Particle Dance" is part of CREATIONS,[3] a Horizon-2020 project that supports and coordinates European actions to develop art-based creative approaches towards a more engaging science classroom. In the workshop, dance became the means to embody and identify with elementary particles and express scientific ideas. Here, the *phenomenological* sense of embodiment sheds light on science learning through imaginary identification with science concepts.

Scientists routinely use imagination and identification strategies to facilitate their understanding of science concepts that are not directly accessible by perception (e.g. Ochs et al., 1994; Steier & Kersting, 2019; Stinner, 2003). Such acts of imaginary identification entail placing oneself into a scientific representation, embodying a scientific scenario, and empathising with aspects of natural phenomena. Examples include Albert Einstein who "imagined what it would be like to ride on a ray of light" when working on his theory of relativity (Kind & Kind, 2007) or virologist Jonas Salk who described that "I would picture myself as a virus or a cancer cell, for example, and try to sense what it was like to be either and how the immune system would respond" (Salk, 1983, p. 7). Ochs and colleagues observed that physicists assumed the perspective of physical entities to think through physics problems (Ochs et al., 1994, 1996). Embodied "interpretive journeys" allow scientists to "transport themselves by means of talk and gesture into constructed visual representations through which they journey with their words and their bodies" (Ochs et al., 1994, p. 8).

The example of "Particle Dance" illustrates how the *phenomenological* sense of embodiment can inform instructional activities that invite students to experience and express subjective involvement with science concepts. The workshop invited students to empathise with elementary particles and to perform a choreography of particle interactions. The activity highlights the centrality of each student's first-person point of view. Inspired by the names and properties of elementary particles, each student proposed a simple move to embody one particle, and then, students worked in small groups to turn their moves into a choreography of particle interactions. Nikolopoulos and Pardalaki (2020) observed that students assumed ownership of the science content by drawing on their lived bodily experiences and creating their own choreography. This observation aligns with a broader tradition in science education that uses the immediate and lived nature of drama and theatre activities to enhance learning in science education by creating a significant learning situation in the lives of students (Jackson & Vine, 2013; Ødegaard, 2003).

[3] http://creations-project.eu

"Particle Dance" also illustrates that there is no strict separation between the proposed senses of embodiment: viewing science learning through the lens of different senses points to different aspects of the learning activity. For example, we can draw on the *physical* sense of embodiment to understand how dance movements can make science content more accessible and enrich science learning. However, we need the *phenomenological* sense to illuminate learning in which students "humanise the inanimate particles" (Nikolopoulos & Pardalaki, 2020, p. 4). Viewed through this sense, we can recognise the imaginary identification with a science concept as an essential tool for science learning. In the case of "Particle Dance", imagining what it was like to be a particle and acting upon this first-person identification allowed students to create and expand the "imaginative space (…) between science, dance, and music" (p. 3) which, in turn, facilitated their science learning.

3.3 The *Ecological* Sense of Embodiment: Embodiment as Relational Co-dependence Between Body, Mind, and World

The *ecological* sense describes embodiment from the ecological perspective in line with the Gibsonian tradition of viewing the body in relation to its environment: "Just as a motion for the physicist can be specified only in relation to a chosen coordinate system, so is a phenomenal motion relative to a phenomenal framework" (Gibson, 1954, p. 310). In the ecological perspective, the brain is not the sole cognitive resource we have available to solve problems, and the brain does not bound the mind. Instead, the mind and cognition can extend into the world. The body becomes an integrated part of an extended cognitive system assembled from a broad array of resources.

Viewing the body from an ecological perspective aligns with various claims of the study of embodied cognition, namely, that we offload cognitive work onto the environment, that the environment is part of the cognitive system, and that cognition guides and is for action (Wilson, 2002). The *ecological* sense also comprises the dynamic agent-world interactions that Anderson (2003) describes as characteristic features of practical activities. According to Anderson, practical activities of agents relate to thinking and problem-solving strategies, and these strategies involve intensive interaction with the environment.

One common type of cognitive offloading uses the environment as long-term memory, for example, in the form of reference books or electronic calendars. However, many other cases illustrate how we interact with the environment to save cognitive work in more dynamic ways. For example, Kirsh and Maglio (1995) found that skilful players of the computer game Tetris tended to use an actual rotation of the blocks to find the best solutions rather than mentally computing the best solution and then executing it. Cognitive offloading is not limited to such spatial problems but can extend to more abstract and symbolic offloading, such as counting on one's fingers or paper-and-pencil problem-solving in mathematics. With the introduction of the notion of "the extended mind", Clark and Chalmers (1998) investigated where to draw the border between the individual and the environment. By showing the similarity between cognitive processes performed with or without external tools like calendars or calculators, they argued that the engagement with the tools is part of thought itself.

The *ecological* sense of embodiment is relevant in science education because it allows reframing science learning in terms of affordances. The concept of affordance is vital to relate the body to its environment via action and perception. This new vocabulary brings processes of student-environment interactions into sharper focus. With the rise of new educational technology, the role of situated tools and digital affordances is likely to become even more relevant in the future. To illustrate the analytical implications of the *ecological* sense of embodiment, we present a mixed-reality environment that invites students to enact astronomy metaphors. The offloading of cognitive work onto the environment serves as an illustration of practical activities in physics and engineering education that the *ecological* sense may inform to promote conceptual understanding.

3.3.1 Analytical Example: Metaphoricity in an Ecological Perspective

To illustrate the analytical implications of the first sense of embodiment, we have looked at how bodily experiences give rise to more sophisticated aspects of cognition in the form of image schemas and conceptual metaphors. We now return to metaphors but view them from an ecological perspective to show how the *ecological* sense of embodiment can inform new and complementary approaches to metaphoricity in science education. From an analytical point of view, the difference between the *physical* and *ecological* sense of embodiment points to the distinction between the linguistic and material mediation that metaphors can afford.

Gallagher and Lindgren (2015) argued that failing to acknowledge the differences between the use of metaphors in linguistic and action-oriented practices (in other words, differences in understanding metaphors according to the *physical* and *ecological* sense of embodiment) can impede how we put metaphors to work in actual learning situations. There seems to be a subtle but significant difference in the way linguistic and material affordances can mediate learning in educational contexts. Therefore, Gallagher and Lindgren (2015) extended the traditional cognitive linguistic view of conceptual metaphors by defining enactive metaphors. The concept of enactive metaphors builds on the idea that actions "shape the way the perceiver-thinker-learner experiences and comes to understand the world" (p.401). In this context, the term enactive does not necessarily describe a different kind of metaphor but a different kind of engagement with metaphor.

This ecological stance towards metaphors informed project MEteor (Metaphor-Based Learning of Physics Concepts Through Whole-Body Interaction in a Mixed Reality Science Center Program) that explored the implications of enactive metaphors for learning science (Lindgren et al., 2016). Lindgren et al. designed a room-sized simulation of the solar system that used floor and wall projections with a laser-based motion tracking system to create an immersive and realistic learning environment. The MEteor simulation prompted students to interact with the mixed-reality environment by using their bodies to launch an asteroid with a certain velocity. The task was to predict the trajectory of the asteroid based on planets and gravitational forces. Real-time feedback about the accuracy of their predictions cued students to adjust their movements in agreement with the law of gravity.

MEteor used a fairly literal embodied metaphor ("I am an asteroid") where the motion of one's body corresponded to the motion of the asteroid. The material and experiential affordances of the wall- and floor-projected dynamic imagery provided real-time body cues that helped students participate in the activity and learn about gravity principles. Students had to recognise these affordances and identify possibilities for action and interaction with the mixed-reality environment to perform the task. Thus, acting out the asteroid movement and predicting its trajectory was not the student's individual accomplishment. Instead, the metaphorical performance was embedded in the environmental structure of the activity. In other words, the enactive metaphor was a product of the student-environment-system: it did not solely rest in students' minds (or bodies) but was given life through the movement of the students in an interactive and responsive mixed-reality environment.

While the *physical* sense of embodiment helps us understand how embodied actions can scale up to more sophisticated aspects of cognition through conceptual metaphors and image schemas, the *ecological* sense of embodiment demonstrates the relevance of action-based enacting metaphors for learning. MEteor presents an example of how we can put enactive metaphors to work in actual learning situations. First, the enactive metaphor ("I am an asteroid") introduces students to an activity, namely, to move through the solar system in a prescribed way. This activity provides specific affordances in the form of real-time bodily cues from floor and wall projections. Second, learners are prompted to act out their understanding by metaphorically transforming these affordances. The mixed-reality simulator augments students' physical activity with digital displays of planetary movements and thereby reinforces the metaphor. The interplay between the students' embodied actions and the material affordances of the environment opens up new ways of learning physics (Gallagher & Lindgren, 2015).

In summary, the *ecological* sense of embodiment can inform an action-oriented view towards metaphors neither as figures of speech nor as figures of thought but as figures of action (Jensen & Greve, 2019). By adopting this analytical stance, science education researchers can understand metaphorical meaning as emerging from human actions and as being closely intertwined with and embedded in the environment. Learning environments that are designed for enactive participation can "reinforce what enactive theory claims to be our natural embodied stance toward the world—a stance in which perception is *for-action* and in which agents pragmatically exploit worldly affordances" (Gallagher & Lindgren, 2015, p. 402).

3.3.2 Practical Example: Offloading Cognitive Work onto the Environment in Physics and Engineering Education

When designing instructional activities, the *ecological* sense of embodiment can guide designs that allow students to offload cognitive work onto their environments. For example, a conceptual lab is an instructional approach that uses probeware in engineering and physics labs (Bernhard, 2010, 2018). Probeware systems consist of a sensor connected to a computer that collects and analyses data in real time. As an example of interactive technology in physics education, probeware has "cognitive value" because it can be used as a "cognitive tool" or a tool of knowing (Bernhard, 2018). Students can perform experiments using a range of different sensors in the lab to gather data on variables such as force, motion, temperature, light, or sound. The probeware transforms experimental data directly into a graph on the computer screen.

For example, in one of the conceptual labs, students try to follow kinematic graphs, such as velocity–time graphs, with the motion of their own bodies as they approach or move away from a motion detector (Thornton & Sokoloff, 1990). The probeware records the motion of the students and generates kinematic graphs on a screen instantaneously. Students can view the graphs in real time as they are moving. This way, the student, in interaction with the probeware, solves task about basic concepts of classical mechanics. For example, what does it mean that the velocity or acceleration is zero at a certain point in time, and how can students represent this scenario by moving their bodies? Rather than spending time on typical lab activities such as making measurements, writing data in a table, or generating a graph by hand, students can focus on interpreting the graphs that the probeware generates in real time. In other words, students can offload some of the tasks involved in generating data onto the probeware of the computer.

Bernhard (2010) pointed to the instructional potential of such exercises which focus specifically on developing students' conceptual understanding. Bernhard (2018) further emphasises that different experimental equipment provides different affordances for learning about a particular phenomenon. For example, in the study of the accelerated motion of a cart on an inclined plane, a setup with motion detectors and probeware allowed students to investigate movement both up and down the plane, and the point in time when a cart going upwards stops and starts moving downwards. In contrast, ticker tape measurements with a tape attached to the cart could only be used for motion downwards. Thus, instructional technology used in labs constrains and enables what students can discern and, ultimately, learn (Bernhard, 2018). The *ecological* sense of embodiment allows educators to become aware of these different instructional affordances in the learning environments.

3.4 The Interactionist Sense of Embodiment: Embodiment as Sociocultural Interaction

The *interactionist* sense emphasises the socially situated nature of embodied interaction (Azevedo & Mann, 2018; Hall & Stevens, 2016; Steier et al., 2019; Streeck et al., 2011). While the body as a site for *thinking* and the body as a site for *living* and *experiencing* constitute the first two senses of embodiment, the *ecological* sense emphasises the co-dependence between mind and world. However, the *interactionist* sense transcends the co-dependence between mind and material world by emphasising the sociocultural world of people working together. This sense considers the kinds of situations that occur when people are coordinating and interacting with each other and how we might experience the world through the bodies of other people. We may refer to this view as a sociocultural or *interactionist* sense of embodiment. Its value is in recognising the unique understanding of embodiment that occurs through embodied coordination of many people interacting with each other; typically, interactional resources are at work to bridge different levels of cognitive processes.

The *interactionist* sense of embodiment is relevant in science education because it emphasises the collaborative, communicative, and socially situated nature of embodied cognition. Just as we can view a body and the environment as an extension of that individual's cognitive structures, we can also think about how such structures extend across multiple individuals. From this view, thinking occurs across multiple embodied "minds", for example, through gesture and language. The point is not that such actions are externalised translations of individual cognition, but that "thinking" (and science education practices like problem-solving, decision-making) develops in the interaction between these individuals.

Researchers adopting this perspective on embodiment tend to be rooted in the Vygotskian tradition of sociocultural theory (Vygotsky, 1962, 1978). As Anderson (2003) notes, such social interaction between bodies is not restricted to the cognitive or the physical but occurs in particular social and cultural contexts; that "actions themselves can have not just immediate environmental effects, but social or cultural ones" (p. 109). Analytically, this perspective emphasises attending to the social interaction of embodied actors and how meanings and abstract social and cultural structures develop.

Of course, there can be a role for social interaction in the previous three senses of embodiment. One can view embodied cognition through the lens of one's individual cognitive structures or lived experiences and still recognise the individual as being informed by social contexts. Similarly, in the *ecological* sense of embodiment above, the environment and even other social actors may function as part of the cognitive system. However, this *interactionist* sense of embodiment recognises embodied cognition as not merely grounded or informed by social contexts but as actually being constituted in social interaction. In the context of science education, interactionist views of embodiment invite us to design learning activities that require collaboration, coordination, and communication between students and their material and semiotic resources. To illustrate the analytical and practical implications of the *interactionist* sense of embodiment, we look at two collective embodied phenomena in physics education, the formation of matter and the transfer of energy, where students need to coordinate their actions to understand the physics concepts.

3.4.1 Analytical Example: Collective Embodied Phenomena and Group Cognition in Science Education

In an attempt to understand how the body can support cognition and learning in science education, Danish et al. (2020) combined frameworks of embodied cognition with a focus on the individual learner with frameworks for collective activity. Therefore, this analytical approach is a great example of how the *interactionist* sense of embodiment can inform science education research.

The Science through Technology Enhanced Play (STEP) project involved first- and second-grade students using an embodied, mixed-reality simulation to learn about the particulate nature of matter. The students acted as particles in different states of matter. Since this is a collective physics phenomenon where coordination between and across students is vital to their learning, Danish et al. argued that students' embodied actions served as a resource in understanding the embodied activity individually and collectively.

Danish et al. chose the collective activity as their unit of analysis to argue, first, that individuals move continually between an awareness of their own individual goals and actions and an awareness of their collective embodied activity system organised around a shared object. Second, the authors argued that the students' ongoing individual actions constructed the system as a collective unit. For example, one student in the study gestured if throwing a ball to another student who then started to walk more quickly. The two students had discussed this gesture previously, and it meant the gesturing student was giving energy to the second student, who would then move more quickly. The individual actions were shaped by the shared agreement that a throwing gesture implies the giving of energy.

In summary, the *interactionist* sense of embodiment implies that not all behaviour patterns in science education can be explored meaningfully at the individual level. When learning about complex scientific phenomena such as the movement of particles in different states of matter, students' coordinated embodied explorations play a crucial role in learning. Embodied cognition is both influenced by and helps shape the relationship between individuals and their social contexts. By acknowledging that the individual and the collective embodied dimensions operate separately while also being mutually constitutive, science educators can create resources and opportunities for group cognition to emerge in the classroom.

3.4.2 Practical Example: Students Choreograph their Actions in Energy Theatre

Rachael Scherr and colleagues have developed Energy Theatre as an instructional activity in which students express and develop their understanding of energy in collaborative, embodied interaction (Close & Scherr, 2015; Scherr et al., 2012). Through Energy Theatre, students enact energy transfers and transformations in different physical scenarios. Each participant represents a unit of energy of a unique energy form, shown by an agreed-upon gesture. Objects in the scenario correspond to areas on the floor, delimited by loops of rope. As energy is transferred and transformed, the students change location on the floor from object to object and change gestures between the energy forms.

Energy Theatre is a highly collaborative and communicative effort. The students negotiate and decide what sign to use to represent a particular energy form, which energy forms to involve, and how to transfer and transform energy. As opposed to other approaches of representing physical phenomena through dramatisation, where a teacher typically provides a script and acts as a director, students direct and choreograph themselves against the background of a few given rules of the game. When students have different interpretations of what energy form is involved in a phenomenon – for example, whether they should consider warm gas in a container as thermal energy or kinetic energy – the students have to resolve this conflict before performing the scenario together. Based on their analyses of teacher professional development courses, Scherr and Robertson consider learners' confrontation with their different interpretations of energy as a productive resource for reconciling their ideas (Scherr & Robertson, 2015).

The example of Energy Theatre provides another opportunity to unpack the same learning activity from different perspectives and examine how different senses offer valuable and complementary insights. On the one hand, the *interactionist* sense guides our attention to the different ways students negotiate their performance of a physical scenario. For the scenario to make sense, the students depend on all other students playing their part in an intended way. On the other hand, the *physical* sense provides a different and complementary perspective on science learning. When designing Energy Theatre, Scherr et al. (2013) drew explicitly on conceptual metaphor theory and the substance metaphor for energy. This metaphor represents energy as being conserved, located in objects, flowing among objects, and accumulating in objects, using the inferential structure of the container image schema. In particular, with the constraint that participants cannot be introduced or removed during a scenario, energy conservation is built into the rules of Energy Theatre. These features promote a model of energy transfer and transformation in real-world processes that students can enact in a performance of Energy Theatre.

4 Discussion

Although the human body is ubiquitous in doing and learning science, approaches to conceptualise the body in science education vary greatly. In the previous section, we have disentangled the various senses of embodiment with a view towards science education research and practice. By illustrating the *physical*, *phenomenological*, *ecological*, and *interactionist* sense of embodiment through recent examples from the science education literature, we have argued that the role of the body bears not only on practical educational problems but has a variety of theoretical implications in science education, as well. Table 1 summarises our presentation of the four senses and their relevance in science education research and practice.

This section discusses the usefulness and limitations of choosing four senses of embodiment as our organising principles to characterise different perspectives of embodied cognition. First, we recognise that different conceptual stances could be chosen to describe embodied cognition in science education in different terms. There is no

Table 1 Overview of the four different senses of embodiment

Sense of embodiment	Relevance in science education	Example of analytical approach	Considerations for instructional activities
The physical sense of embodiment views the body as a physical and biological structure. This sense describes embodiment as basis of cognitive structures.	Many concepts in science are abstract (i.e. not tangible) and far from our natural sensory capabilities. The *physical* sense of embodiment is relevant in science education because it tells us that understanding of abstract concepts is grounded in our bodies. The brain makes use of sensorimotor regions to build understanding of scientific concepts.	Conceptual metaphor theory is an analytic approach in science education that is informed by the *physical* sense of embodiment. The transfer of inferential structures from image schemas to abstract concepts is a crucial mechanism for learning science concepts. Conceptual metaphor analysis can identify features that make instructional metaphors and analogies fruitful in science education (Niebert et al., 2012).	The *physical* sense of embodiment can improve instructional practices by grounding instructional activities in embodied sources. Such grounding can take the form of letting students perform concrete kinaesthetic activities that link to scientific concepts (e.g. force and resistance in classical mechanics) (Bruun & Christiansen, 2016). The embodied grounding can also operate at the more abstract level of language use (e.g. choosing instructional metaphors with embodied sources) (Niebert & Gropengießer, 2014).
The phenomenological sense of embodiment views the body as lived experiential structure. This sense describes embodiment as lived experience.	Science is a practical discipline, and much scientific knowledge derives from experiments and observations of the natural world. The *phenomenological* sense of embodiment is relevant in science education because it tells us that students cannot fully understand science without experiencing science with and through their lived bodies to develop practical scientific knowledge.	The lived experience of students can serve as an analytical approach to shed light onto the role of the experiential body in science education. Such an approach conceptualises learning science content as learning to produce and observe science phenomena. In the lab, students' bodies are involved and intertwined with the production of physics phenomena, and knowledge becomes an integrated part of practice (Hardahl et al., 2019).	The *phenomenological* sense of embodiment has the potential to improve instructional practices by acknowledging the centrality of the first-person point of view and the importance of authentic bodily experiences in science education. Instructional activities can guide students towards sensory and phenomena-oriented experiences (e.g. in labs) or invite them to use their lived bodily experience to express scientific ideas (e.g. through dance or drama) (Nikolopoulos & Pardalaki, 2020; Ødegaard, 2003).

Table 1 (continued)

Sense of embodiment	Relevance in science education	Example of analytical approach	Considerations for instructional activities
The ecological sense of embodiment views the body as an integrated part of an extended environmental system. This sense describes embodiment as relational co-dependence between body, mind and world.	The systematic study of the natural world is a complex endeavour. Scientists routinely offload information (and use epistemic actions) to reduce the cognitive workload. The *ecological* sense of embodiment is relevant in science education because it allows reframing the learning of science in terms of affordances and actions. This new vocabulary brings processes of student-environment interactions into sharper focus. With the rise of new educational technology, the role of situated tools and digital affordances is likely to become even more relevant in the future.	The *ecological* sense of embodiment can inform an action-oriented view towards metaphors that put them to work in actual learning situations. Gallagher and Lindgren (2015) defined enactive metaphors as those that come into existence through students' embodied actions. Metaphorical performances can be embedded in the environmental structure of science activities such as students moving through an interactive and responsive mixed-reality environment. This approach allows conceptualising metaphors as the product of the student-environment-system.	The *ecological* sense of embodiment has the potential to improve instructional practices by encouraging students to use situated tools and the representational infrastructure of their environments. Conceptual labs are an example of lab activities in physics and engineering education that allows students to offload cognitive work onto probeware to link science concepts to objects and events in the environment (Bernhard, 2010).
The interactionist sense of embodiment views the body in coordinated (inter) actions with other bodies. This sense describes embodiment as sociocultural interaction.	Science is a sociocultural project and comprises collaborative activities in which scientists interact with each other. The *interactionist* sense of embodiment is relevant in science education because it emphasises the collaborative, communicative, and socially situated nature of embodied cognition. Importantly, the *interactionist* sense of embodiment recognises embodied cognition as not merely grounded or informed by social contexts but as actually being constituted in social interaction.	Analytical approaches that build on the *interactionist* sense of embodiment acknowledge that not all patterns of behaviour in science education can be explored meaningfully at the level of individual bodies. The Science through Technology Enhanced Play (STEP) project combined frameworks of embodied cognition with a focus on the individual learner with frameworks for collective activity to explore collective embodied phenomena in science education such as learning about different states of matter (Danish et al., 2020).	The *interactionist* sense of embodiment can improve instructional practices by inviting educators to design learning activities that require collaboration, coordination, and communication between students and their material and semiotic resources. By recognising that the individual and the collective embodied dimensions operate separately while also being mutually constitutive, science educators can create resources and opportunities for group cognition to emerge in the classroom.

obvious choice of a framework in a field with such rich historical roots and in which philosophy, psychology, cognitive science, and linguistics (among many other disciplines!) repeatedly have cross-fertilised educational theories and practices. Besides, embodied perspectives operate on multiple abstraction levels, from the nature of physical phenomena to more abstract concepts. Cognitive activities in science education may be actual, projected, or even imagined, as when we sit still with our eyes closed (Abrahamson & Bakker, 2016). Thus, we can expect a diverse range of analytical approaches that conceptualise embodied learning processes.

For example, it is worth noting that the embodiment assumed in conceptual metaphor analysis and many other approaches within the *physical* sense of embodiment is of an offline nature (Wilson, 2002). The development of image schemas from physical experiences typically happens at a very young age (Johnson, 1987). These schemas get recruited in formal education many years later but can still be regarded as necessary embodied resources in science education. In contrast, however, the other three senses of embodiment mostly depend on students' engagement of their bodies here and now in a more direct way.

Second, it is crucial to recognise that there can be overlap between the different senses of embodiment and that any particular science education activity can touch on multiple senses. Commenting on Merleau-Ponty's double sense of embodiment, Varela et al. (2016) observed that "these two sides of embodiment are obviously not opposed. Instead, we continuously circulate back and forth between them." We can find a similar circulation of all four senses around the common axis of embodied experience. As participants, students may focus on coordinating and communicating with each other (interactionist) in some moments, while at other times, representational tools and environmental infrastructure become more salient (ecological). As noted above, pedagogical designs like "Particle Dance" or "Energy Theatre" can productively support engagement across these different senses. As learning researchers, we may also analyse the same activity from multiple senses.

For example, the *physical* and the *phenomenological* senses of embodiment point towards and overlap with the *ecological* sense. While the *physical* sense of embodiment emphasises the body specifically as a basis of the cognitive mechanisms, the *ecological* sense extends this perspective from the mind and body out into the environment, for example, through the concept of distributed cognition (e.g. Hutchins, 1995). Likewise, the *phenomenological* sense foreshadows the *ecological* sense. The body's existence as "being-toward-the-world", as a projection towards lived goals, puts the *phenomenological* sense of embodiment into focus and points towards action and how cognition guides action. Again, we see that the different senses of embodiment are intertwined. The analytical distinction of the four senses allows researchers to move between multiple perspectives when studying embodied agents engaged in embodied (learning) activities.

As embodied agents, students act and interact in the rich environment of the science classroom. While there is probably one core sense that best describes an activity or analytical approach, researchers may wish to adopt a different sense as their analytical lens at different stages in the learning activity. Therefore, our senses serve as signposts that point us to specific views of embodiment and embodied cognition that inform a particular instructional activity. For example, while any science education activity might include social interaction or conversation, not every instructional activity is informed by an interactionist view of embodiment. Similarly, not every instructional activity that includes the production of scientific phenomena wishes to emphasise students' lived experience, which the *phenomenological* sense highlights. In our role as science education researchers or teachers, we need to decide if we want to foreground or background different senses of embodiment when designing, employing, or studying instructional tasks.

5 Conclusion

In conclusion, the contribution of this paper is, first, a clarification and contextualisation of the various perspectives on embodiment and embodied cognition and, second, an examination of the implications of these perspectives in science education. As illustrated by our examples, we have shown that researchers and educators may be referring to entirely different analytic and practice-oriented approaches within broader perspectives of embodiment. By disentangling and illustrating these differences with the help of our four senses of embodiment, we hope to provide a basis for applying embodied perspectives to advance science education research and improve learning in science classrooms.

As illustrated in Table 1, embodiment can refer to learning activities as diverse as language use, sensory and phenomena-oriented experiences, situated tool use and representational infrastructure, and social interaction. We must recognise that these are very different kinds of activities, and referring to each under the broader notion of embodiment loses quite a bit of nuance. It might be tempting for educators to reduce the findings from embodied cognition research to some version of "give students opportunities to use their bodies in science classrooms" or "students need to recognise conceptual metaphors". However, we hope to show the opposite – that there are very different ways of adapting such perspectives in research practices in the classroom.

We agree with Hayes and Kraemer (2017) that the domain of science learning provides an important proving ground for embodied theories of cognition. By proposing the *physical*, *phenomenological*, *ecological*, and *interactionist* senses of embodiment, we aim to contribute to a more productive discourse around embodied cognition in science education. The four senses of embodiment help us explicate the relative usefulness and potential integration of different perspectives of embodied cognition in science education. Notably, the different senses of embodiment are not mutually exclusive, and there are not necessarily clear boundaries between them.

Rather than aiming for an all-encompassing (and possibly elusive) framework of embodied cognition in science education, we shift our focus to the perspectives of researchers and educators. By asking how students can do their thinking and learning in embodied ways and how researchers can use these insights to understand science learning in new ways, we hope to establish the four senses as guiding principles that can inform science education research and practice. Greater awareness of the different embodiment perspectives and the vocabulary of the four senses allow us to sharpen our arguments and realise the full potential of embodiment and embodied cognition.

We hope that future work can recognise the different senses of embodiment and show how they might work together to inform science education research and practice. Specifically, we hope to see pedagogical designs in science education that are precise and intentional when applying these different senses of embodiment. We also believe that a reasonable next step would be to show how these different senses of embodiment can be applied analytically in new empirical contexts.

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Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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