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A pragmatist semiotic analysis of secondary students' embodied and material reasoning in astronomy

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ABSTRACT

Background: In learning astronomy, students need to shift between 3D and 2D representations involving complex interactions between the body and material environment. Little attention has been paid to the iconic nature of this astronomical diagramming.
Purpose: This research explored the value for students of diagramming to reveal the structural relationships of astronomical phenomena. The study aimed to 1) operationalise Charles Peirce's pragmatist semiotics to analyse students' bodily and material reasoning 2) identify the iconic nature of students' diagramming through Stjernfelt's activating of Peirce's iconicity.
Sample: Two students (a pair) from a class of 30 Year 7 students (12 years old) and their teacher (1) from a government secondary school in Melbourne, Australia.
Design and Methods: A micro-ethnographic approach to the analysis of video/audio records and student artefacts was utilised in the context of three moments from a 1 hr lesson on astronomy. This data was analysed using Peirce's sign types of icon, index and symbol to construct a triadic account of the bodily and material nature of students' reasoning as diagramming.
Results: The two students determined, by revealing structural relationships with their bodies as well as a mini-whiteboard and a torch and globe, that the Sun is higher in the sky in Summer than Winter due to the Earth's rotational axis with a tilt (of 23.5 degrees) and its elliptical orbit around the Sun.
Conclusion: For students to transduct between 3D and 2D astronomical representations, they need to coordinate space-based and Earth-based perspectives through bodily and material diagramming that makes apparent key structural relationships (i.e. iconicity).

KEYWORDS
astronomy; semiotics; pragmatism; material; embodied

Introduction

The entanglement of the body and materiality in student reasoning about scientific phenomena is of ongoing interest to science education researchers. There is a rich tradition of investigating student interactions with material objects in generating conceptual understandings in science (Hetherington et al. 2018). Recently, research has increasingly explored the experiential and embodied basis of students' understandings

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of science, pointing to the role of inquiry processes in learning (Tytler and Ferguson, 2023). The role of embodiment and materiality has received renewed attention through emerging research on multimodal and multiple representations, with the body and materiality conceptualised as constituent modes/media in the construction, evaluation and refinement of representations (Tang et al. 2022). While extensive research exists on the integral role of hands-on experience and direct observations to student understanding of scientific phenomena, limited research has investigated the role of the body and materiality in topics such as astronomy for which direct observation of phenomena is difficult and modeling is central to learning.

The particular context of astronomy necessitates shifts between 3D and 2D representations involving complex interactions between the body and material environment (Vosniadou, Skopeliti, and Ikospentaki, 2005) that often includes the construction and refinement of diagrams in various forms. In our recent research (Prain and Tytler 2022, Tytler and Prain, 2022), we have explored the ways in which students undertake 'transduction' (Kress and van Leeuwen 2006, 39) as they work across and with various representational forms in science. This is a process which, as framed by the socio-semiotics of Lemke (1998) grounded in Charles Peirce's pragmatist semiotics, constitutes 'correspondence between explanatory features and key features of the phenomena' as well as 'internal coherence as an explanatory account' (Prain and Tytler, 2022, 3). We propose that productive scientific reasoning for students involves creatively 'relating and orchestrating' material and embodied sign systems (Xu, Ferguson and Tytler, 2021, 1184) as part of their induction into the epistemic practices of science. In the case of astronomy, students are required to undertake processes of diagramming that involve the coordination of material and embodied sign systems which are iconic in nature (Stjernfelt, 2007). This paper draws on and activates in new ways Peirce's pragmatist semiotics to understand the bodily and material nature of students' reasoning about astronomical phenomena as they collaboratively construct diagrams. We utilise Stjernfelt (2007) explication of Peirce's iconicity to do so. Our research question is:

> How can Stjernfelt's focus on iconicity in Peirce's pragmatist semiotics provide fresh insights into the role of embodiment and materiality in secondary students' diagrammatic reasoning in astronomy?

Background

Bodily reasoning in the material world of science

Research studies that emphasise bodily and material interactions usually draw on distributed/embodied or social semiotic perspectives to explore student reasoning in science. The basic premise of the embodied and distributed perspectives is that all cognitive activities are fundamentally grounded in sensorimotor experiences of the learner. The ideas of 'grounding' (Glenberg 2010), 'conceptual mapping' (Lakoff and Johnson 1999) and 'conceptual blending' (Fauconnier and Turner 2008) are central to recent explorations of embodied and distributed learning in mathematics and science education, as evident in a special issue of the *International Journal of Science Education* (Amin, Jeppsson, and Haglund 2015) and more recent studies on mechanistic reasoning

(Andrade et al. 2022, Weinberg and Sorensen-Weinberg 2022). This *IJSE* special issue draws on two assumptions from embodied cognition: 'the grounding of mental processes in body-based knowledge structures and the offloading and simplification of cognitive processes onto external objects and symbols (including both language and gesture)' (Amin, Jeppsson, and Haglund 2015, 749). More recently, Furtak and Penuel (2019) and Tang (2022) argue that the material aspect of teaching and learning science involves students and teachers working together to create and utilise a variety of semiotic tools, including bodily and material sign systems, to enact scientific reasoning.

All these studies point to the epistemic potential of embodied experiences and bodily interactions within semiotic systems as students undertake inquiry tasks in science. However, this research is yet to fully account for the specific roles of the body as a semiotic resource in these meaningful conceptual mapping processes. We have started to explore such micro-level phenomena in classrooms, focusing on students' creative orchestration of embodied and material sign systems in astronomy and physics (Prain and Tytler, 2022, Xu, Ferguson and Tytler, 2021). We extend this research in this paper as we explore the role of the body and materiality in student reasoning in astronomy. Learning astronomy involves working with very specific visual spatio-temporal relations through the construction and interpretation of 2D drawings (e.g. pencil on paper inscription of the Earth rotating on its axis) coordinated with 3D models (e.g. torch as the Sun and its light) that represent relations between astronomical objects (Tytler et al., 2020). As such, the topic offers rich opportunities for exploring novel perspectives on the role of materiality and embodiment in student reasoning in science.

Spatio-temporal reasoning in the astronomy classroom

Students often enter the science classroom with deeply entrenched alternative conceptions about astronomical phenomena (Vosniadou and Brewer 1992). Trumper (2001) showed that while some astronomical phenomena such as day-night and seasonal cycles are accessible to secondary students, many details such as variation in the Sun's overhead position pose difficulties. It is by developing astronomy-specific practices of the body and materiality that students can convert their entrenched ideas into canonical understandings (Trumper 2006).

Problem solving in astronomy involves reasoning with/about specific visual, spatial and temporal relations between astronomical objects (Tytler et al., 2020) across two frames of reference for any particular astronomical phenomenon: an Earth-based perspective and a space-based perspective (Plummer, Kocareli, and Slagle 2014). For example, the scientific explanation for seasonal changes involves shifting between: 1) Earth-based perspective in terms of the Sun's altitude and path in the sky leading to temperature changes, and 2) space-based perspective in terms of the Earth's tilt with respect to the orbital plane of the Earth around the Sun, resulting in varied exposure to sunlight. In explaining astronomical phenomena, students are often challenged to shift between 2D representations and their 3D imaginations and modeling of the astronomical system.

Spatio-temporal reasoning as a visual process helps to explain student differences in understandings of astronomical phenomena (Kikas 2006, Padalkar and Ramadas, 2008). Baxter and Preece (2010) proposed that the value of astronomical tools such as dome and computer planetaria is to afford spatial reasoning as they make possible the visualisation of the spatiality of astronomical phenomena as distributed in time. Often, this astronomical reasoning plays out as students construct and evaluate astronomical diagrams as semiotic meaning makers (Padalkar and Ramadas, 2008, Uchinokura and Koba 2022).

However, this spatio-temporal reasoning, in particular perspective taking, is not just visual but also bodily and material in nature. Researchers have collaborated with teachers to implement interventions to support student development of perspective taking, so they can connect complex sequences of motion across astronomical reference frames (Plummer, Bower, and Liben 2016, Plummer et al. 2022). Student observation of visual simulations as well as undertaking hands-on activities and executing gestures can help to improve their development of explanations for celestial motion (Plummer, Kocareli, and Slagle 2014, Plummer et al. 2022). Similarly, teachers' intentional pedagogical gestures and student spontaneous gestures can facilitate student understanding of the dynamic (spatial/temporal) properties of astronomical systems, such as Sun-Earth-Moon (Padalkar and Ramadas, 2008). Morrow (2000, 252) calls this 'kinaesthetic astronomy' to refer to the bodily/material experience of astronomy; bodily and material elements exist semi-independently and interlace to afford meaning making as mutually constitutive processes. In this way, the abstract nature of astronomical phenomena can be productively encountered by students through a process of concretisation of spatio-temporal phenomena (i.e. individuation in material and bodily forms, from 2D to 3D and vice versa), drawing upon the meaning making potential of digital modelling resources such as image processing software (Danaia, McKinnon, and Fitzgerald 2017) or hands-on models that enable manipulation and observation of the movements of the Sun-Earth-Moon (Türk and Kalkin, 2018).

A Peircean lacuna: clarifying the meaning of 'body' and 'material' in science education

While there is widespread consensus among the science education community that bodily and material processes form an essential part of students' inquiry practices in science, there is ambiguity as to what is precisely meant by 'body' and 'material' and what roles they play in this context. As Kersting, Haglund, and Steier (2021) argued, 'researchers and educators often blur … and use various claims of embodiment [and materiality] interchangeably' (1183). They highlighted the need to develop greater conceptual clarity about the roles of the body and materiality in science education research. We take their position as the provocation that drives our paper.

Kersting, Haglund, and Steier (2021) propose 'four senses of embodiment that conceptualise the body in physical, phenomenological, ecological, and interactionist terms' (1183). They suggest that a pragmatist perspective can add to these accounts of these intertwined processes, but such an approach has yet to be properly realised. We propose in this paper that Peirce's pragmatist semiotics can cohere many of the key aspects of the four senses, as well as adding new perspectives that are crucial to realising more refined terminology and practices when it comes to the body and materiality in science education. In particular, we argue that Stjernfelt (2007) highlighting of the centrality of iconicity in Peirce's account of meaning making can clarify the role of diagramming in astronomy.

Enacting astronomy as diagrammatic reasoning: a Peircean approach

Signifying the body/materiality

In this paper, we draw on Stjernfelt (2007, 2014) 'biosemiotic' reading of Peirce's philosophy. We focus on the way that Stjernfelt makes apparent Peirce's conceptualisation of the body and materiality as fundamentally semiotic processes of a pragmatic nature. Here, Stjernfelt means 'semiotic' as reasoning as/through signs of a triadic nature: we make meaning by moving iteratively and continuously around a triad of *representamen* (the thing that is signifying), *object* (the thing that is signified) and *interpretant* (the effect of the interrelation of the representamen and the object on the interpreter), with each triad indefinitely interlinking with subsequent triads. Stjernfelt invokes 'pragmatic' in a specifically Peircean way as reasoning to understand and take actions with a practical bearing on our habitual actions in the world.

Stjernfelt (2007) talks of the 'signifying body' as a 'semiotic concept of embodiment' (257), such that 'Peirce's doctrine of signs to minds dispenses with the subject-object dichotomy' (194). Nakassis (2013) makes clear that for Peirce there is 'no semiosis without materiality, and no (experienceable or intelligible) materiality without semiosis' (401). Thus, for Peirce, the body and materiality are delineated but mutually constituted as bodily/material semiosis. To understand and maximise reasoning, Peirce argues that the focus ought to be on the semiotic composition of the meaning-making milieu, rather than trying to localise particular meaning-making products to specific parts of the bodily and material environments.

The body and materiality, from this perspective, can be framed according to Peirce's *second division of signs*, which focuses on the object-representamen relationship (Jappy 2013). There are three different but complimentary sign types according to this division: icon, index and symbol (Table 1). Legg (2017) emphasises that any representation will have iconic, indexical and symbolic elements, but often one type will dominate the functioning of the sign.

This division of signs is primary to the division between the body and materiality when it comes to reasoning and brings them closer together by making evident the semiotic (i.e. sign type) differences and similarities as they pertain to the problem at hand (i.e. pragmatism). We argue that understanding students' reasoning as bodily and material processes should not only focus on the forms of signs as 'multi-modes' (e.g. visual, tactile, etc.) but also consider the functions of signs in context as 'multi-signs' (icon, index, symbol). To investigate this with regard to student reasoning in astronomy, in which

Table 1. The object-representamen relationship. Adapted from Legg (2017) and Jappy (2013).

	Icon	Index	Symbol
Definition	Signify objects by resembling them structurally. Parts are related in the same way that the objects represented by those parts are themselves related.	Signify their object by being in some way directly connected with them.	Signify their objects by some convention or habit that is arbitrary.
Affordance	Enable us to exercise our imagination, and think about what is possible because their objects may or may not exist.	Connect us with particular objects in the world because of their direct pointing function.	Give us general concepts because their defining conventions are repeatable.
Example	Map.	Wind vane.	The word 'star'.

diagrams play a central role, we turn our attention via Stjernfelt (2007) to the sign type with the power for revealing structural relationships, the icon.

Iconic power of diagramming

Peirce was explicit in stating that the unique generative power of an icon lies in the fact that 'by the direct observation of it other truths concerning its object can be discovered than those which suffice to determine its construction' (CP 2.279).[1] In pursuing analyses of student reasoning in astronomy through diagrams, we focus on a subcomponent of Stjernfelt (2007) biosemiotics that he calls 'diagrammatology' (xv). Stjernfelt argues that this Peircean lens makes apparent the iconic power of diagrams to afford new understandings of the structural relationships that constitute natural phenomena. 'Many diagrams', Peirce states, 'resemble their objects not at all in looks; it is only in respect to the relations of their parts that their likeness consists' (CP 2.281). We follow Stjernfelt in positioning diagrams as a particular type of icon which is structured in the sense that it represents the relationships, mainly dyadic, of the parts of one thing by analogous relations in their own parts (Jappy 2013, Merrell 1997). Stjernfelt explicates Peirce's notion of the diagram as such:

> Diagrams are skeletal icons, representing their object as analyzed into parts among which 'rational relations' hold, be they explicit or implicit … as soon as the icon consists of parts whose relations mirror the relations between the corresponding parts of the object, and the sign is used to gain information about those parts and their interrelations, a diagram is at stake (Stjernfelt 2014, 207)

Stjernfelt makes evident here that diagrams for Peirce are not restricted to purely visual forms but can manifest in any way so long as they fulfill his pragmatic and semiotic definition (see above). As such, we propose that it is more appropriate to speak of 'diagramming' (a dynamic process) than 'diagrams' (a static product) in invoking Peirce's semiotic pragmatism to reveal the bodily and material nature of students' spatio-temporal reasoning in astronomy. According to Peirce (CP 3.363), it is because of their distinctive iconic nature that diagrams afford discoveries and new understandings, but this creative reasoning potential can only be realised if the meaning maker 'goes to work' on the diagram through manipulation and observation as a form of bodily/material transduction (Stjernfelt, 2007). Our primary intent in this paper is to explore the ways in which students diagrammed structural relationships of astronomical phenomena through bodily and material means of enacting iconicity.

Method

Participants

A class of 30 Year 7 students (12 years old) and their teacher from a government secondary school in Melbourne, Australia, undertook with informed consent a 1-hour lesson on astronomy that was consistent with the school's Year 7 curriculum. This lesson was developed in collaboration with the participating teacher to reflect a representation construction (guided inquiry) approach. While the session was carefully scripted, it was designed to afford opportunities for student creative reasoning through collaboration with peers and the teacher, with a focus on student joint construction and critique of astronomical diagrams. We aimed to investigate how collaborating pairs of students coordinated experimental exploration and multiple representations to develop explanations of astronomical phenomena. The teacher first introduced basic ideas about the Earth in space, emphasising the need to coordinate Earth-based and space-based perspectives in generating explanations of astronomical phenomena. Student pairs were then tasked with representing on paper an account of how the time differed in London compared to Melbourne, with a globe and torch available as modelling materials. Student pairs were then assigned a second astronomy task to which they responded by using a mini-whiteboard with markers and an iPad. The research was approved by human research ethics committee at the Authors' institution.

Data collection

The astronomy lesson was conducted in a classroom specially designed for video and audio capture, with multiple wall- and ceiling-mounted video cameras with tilt and zoom capability and desk-mounted radio microphones. This set-up meant that 10 video tracks of about 50 minutes were generated for the lesson, with a camera focused on each of six tables able to separately capture a video and audio record of two pairs of students. One camera tracked the teacher, who had a separate radio microphone. Two ceiling-mounted cameras were also employed to provide a separate view of students' collaborative reasoning from above, which enabled the capturing of their use of modelling materials as they talked and gestured to each other to construct astronomical diagrams. Student artefacts were also collected in the form of photographs of their final mini-whiteboard drawings and digital copies of their iPad creations.

Data analysis

A micro-ethnographic (Erickson 2006) approach to the analysis of video/audio records and student artefacts was adopted to identify and explore students' reasoning as they engaged with the tasks and activated modelling materials with their bodies. As in our previous work (Tytler et al., 2020, Tytler and Prain, 2022), we focused our analysis on a pair of students who were verbally explicit in transducting across 2D and 3D representational forms, making their reasoning 'accessible' to us, as they switched between Earth-based and space-based perspectives. The task for this student pair was as follows:

> Lisa lives in Melbourne. She notices two big differences between Summer and Winter. First, the Sun is much higher in the sky at midday in Summer, than in Winter. . . . Construct a presentation on the iPad that will explain as simply as possible why the Sun is higher in the sky in Summer . . . Use models or role plays or drawings or written text, as you like.

We iteratively and dialogically explored the video/audio data, generating transcriptions when necessary, and student artefacts for this pair to determine 'examples' (Ferguson et al., 2019) that would afford answering of our research question. These were moments affording fresh, often unexpected, insights concerning the interconnected role of the body and the material in the process of diagrammatic, spatio-temporal reasoning in astronomy. We determined three such interconnected moments of reasoning in which the two students generated new understandings of astronomical phenomena.

We undertook a nested analysis of each of these moments: 1) descriptive narration of the whole task as undertaken by the students; 2) conceptual unpacking of the students' insights as afforded by bodily and material processes; and 3) semiotic deconstruction of the iconicity of this reasoning. We present the first layer of analysis on its own followed by the second and third layers of analysis presented together. This nested analysis was grounded in a detailed semiotic analysis of the final drawing (identifying icons, indices, symbols), only partially presented here as part of the first layer of analysis.

Results/Findings

Narrative of diagramming

Figure 1 shows the final drawing with five clusters of representations which we numbered (1–5) to indicate the approximate order in which they were constructed. The students tended to move flexibly between the different representational clusters, such that the construction process was not linear but rather iterative in nature.

Each cluster consists of a set of interconnected signs that we deconstructed in terms of iconicity, indexicality and symbolicity. We analysed the semiotic relationships *between* as well as *within* these clusters. We highlight here the iconic relationship between the five clusters, as shown in Table 2. The narrative that defines the engagement of the two students with the astronomy task is made evident as a constellation of interconnected icons full of structuring potential. Through tracing this narrative, the drawing is positioned as part of the distributed diagramming consisting of the students' bodies and their encounters with the modelling materials.

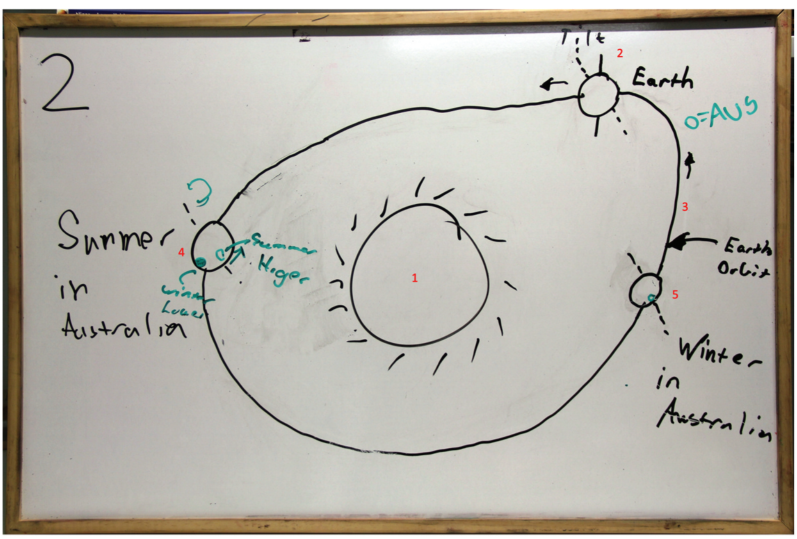

Figure 1. Final drawing consisting of five clusters of representations.

Table 2. Iconic relationships between and within the five clusters of representations.

Cluster	Iconic relationship
1–3	This depicts the structural relationship between the Sun (1) and the Earth's elliptical orbit (3) around the Sun (1).
1/3–2	This depicts the structural relationship between the Earth on its rotational axis with a tilt of 23.5 degrees (2) and its elliptical orbit (3) around the Sun (1). Note: students did not actually indicate 23.5 degrees as the precise axial tilt.
1/3–4	This depicts the structural relationship between the Earth on its tilted rotational axis during Summer in Australia when the Sun is higher in the sky (but also Winter in Australia when the Sun is lower in the sky) (4) and its elliptical orbit (3) around the Sun (1).
1/3–5	This depicts the structural relationship between the Earth on its tilted rotational axis during Winter in Australia (5) and the Earth's elliptical orbit (3) around the Sun (1).
1/3–4/5	This depicts the structural relationship between the Earth on its tilted rotational axis during Winter (5) and Summer in Australia (4) and the Earth's elliptical orbit (3) around the Sun (1).

Moment 1

The two students (Student 1 = S1 on the left, Student 2 = S2 on the right) started by exploring the Earth's rotation on its axis and its orbit of the Sun. S1 drew the Sun in the middle of the Solar System and then drew an Earth with an axial tilt. By visually examining the drawing and the globe, S1 raised the question, *'Did I put the tilt the wrong way?'* He then rubbed out the Earth and redrew it without the axial tilt, but conscripted the globe to explore how the axis is arranged by holding the globe (left hand) and spinning it in an anticlockwise direction (right hand) (Figure 2) while saying, *'So it would be like this'*.

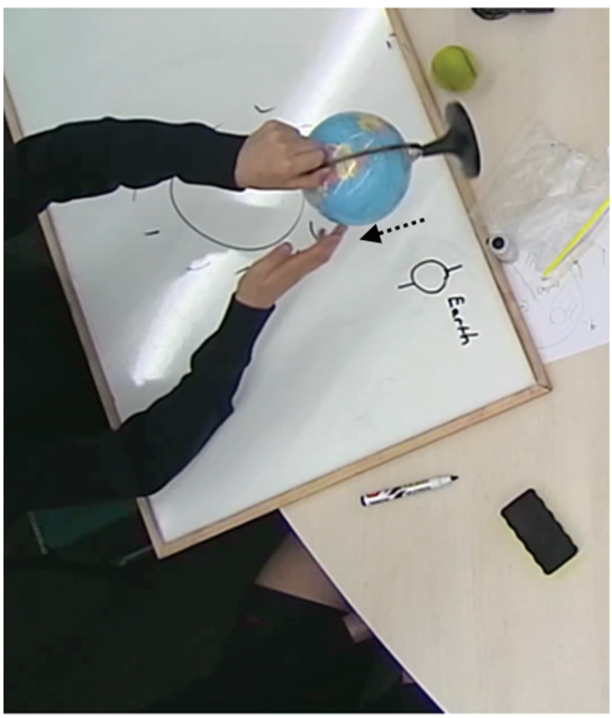

Figure 2. S1 spins the globe in an anticlockwise direction (as indicated by our dashed arrow).

This is an iconic enactment by the body (left hand and right hand) and modelling materials (globe) as it resembles the structure of the Earth rotating on its axis at 23.5 degrees to the orbital plane. At this point, the globe is held 90 degrees off its actual orbital axis, which is not structurally accurate. The students are thus harnessing the iconic potential of this bodily/material diagramming process to adopt a space-based perspective that structurally linked the Earth's rotational axis and its orbit.

S1 then held the globe (both hands), looked at it and placed it down (Figure 3) and said, *'Yeah, yeah, so, it's this way, okay'*, referring to the axial tilt. S1 then represented the rotational axis on the Earth, with the agreed knowledge that it in fact is oriented out of the plane of the drawing, including a 'Tilt' label. This process enabled them to establish that the rotational axis is more or less vertical (23.5 degrees) to the plane of the Earth's orbit, with S1 saying, *'I get it'*.

In the diagrammatic reasoning during this exchange, we note that the problem of representing the tilt in the drawing is performatively resolved, at least partially, using the material manipulation of the 3D globe to cross-reference and align the Earth rotation and axial direction with the students' drawing. In this case, **the body becomes the medium by which the diagrammed, iconic nature of the Earth's rotation is performed by the students. The embodied performance is also used to draw out the structural relationship between the Earth's rotation and the orbital plane**, crystalised through agreed meaning between the two students in the 2D signs in the drawing.

The students then consider the Earth's orbit. S1 drew the orbit around the Sun, labelled it as 'Earth orbit' and then drew two arrows on this orbit to indicate the direction of the Earth's orbit (Figure 4). **This drawing of Earth's orbit is iconic as it resembles the structure of the Earth orbiting the Sun on an elliptical path**.

The students seemed to be aware that the tilt of the Earth is responsible for the seasons, which probably triggered their understanding that this is the key determinant of the different height of the Sun in the sky in Summer and Winter. They then drew (Figure 5) an Earth at opposite sides of the orbit, first for Summer in Australia, correctly

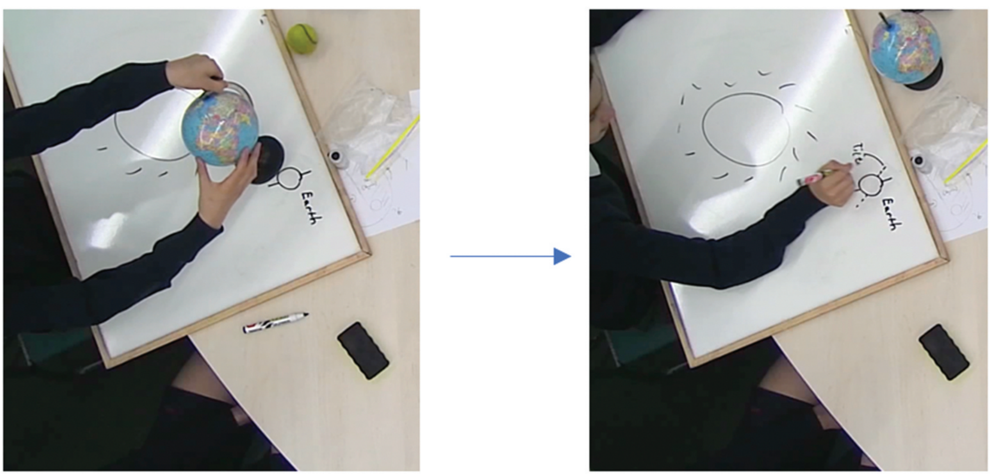

Figure 3. S1 holds the globe, looks at it and places it down and then draws the tilt (rotational axis of the Earth) and labels it.

Figure 4. S1 draws arrows to indicate the anticlockwise direction of the Earth's elliptical orbit of the Sun.

angling the tilt to 'expose' the Southern Hemisphere to maximum energy from the Sun, and then for Winter in Australia, correctly angling the tilt to 'expose' the Southern Hemisphere to minimum energy from the Sun. **These iconic drawings resemble the structural relationship of the Earth relative to the Sun in Summer and in Winter in Australia**.

S2 then visually inspected the two drawings by S1, and then said to S1, *'Wait, no but put like . . . '*, as he then drew a small green circle on the 'Winter in Australia' Earth to indicate the location of Australia and then drew a small green circle on the 'Summer in Australia' Earth to indicate the location of Australia (including, '0 = Australia' as a key) (Figure 6). **These markings are iconic as they resemble the structural relationship of Australia on Earth relative to the Sun in Summer and Winter**. They then explored the dependence of Summer and Winter on the Earth's tilt by manipulating the globe-torch modelling arrangement.

Moment 2

The two students attempted to explain why the Sun is higher in Summer in Australia compared to Winter. S1 started by rotating the globe (left hand) so Australia was fully exposed to the torch light (right hand) as he said, *'Here, it would be Summer, because it is pointing directly at the Sun'*. As he did so, he repeatedly gestured (left

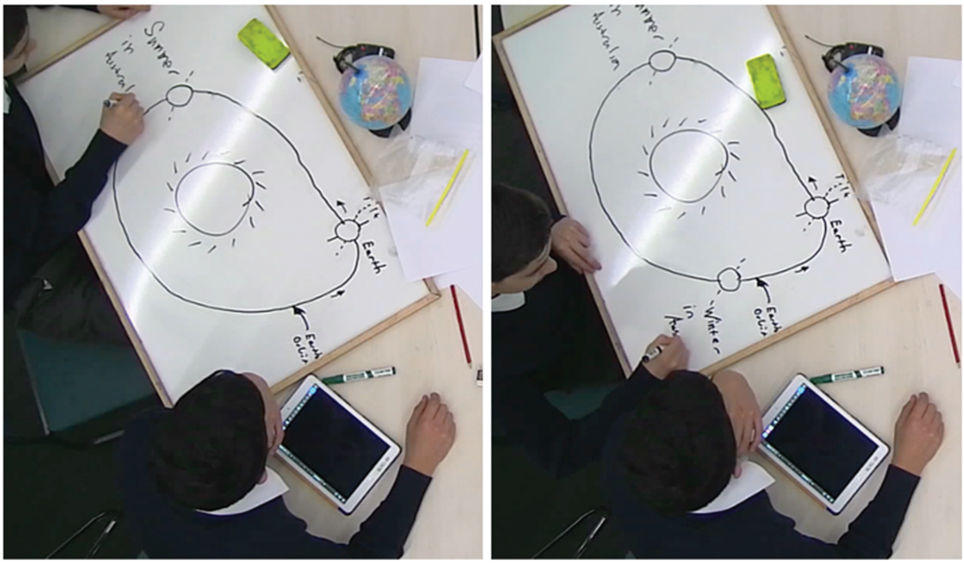

Figure 5. S1 draws the astronomical position of Earth in Summer in Australia (exclaiming *'And here, it's Summer in Australia'*) and the astronomical position of Earth in Winter in Australia (labelling *'Winter in Australia'*).

hand) a straight line from the Australian location on the globe to the torch (Figure 7). **This iconic enactment by the body (left hand and right hand) and modelling materials (globe and torch) highlights the structural relationship of the Earth relative to the Sun when it is Summer in Australia as traced by the Sun's light rays (i.e. torch light). The hand gesture represents the angle at which the Sun's light rays hit the Earth *('pointing directly')* when it is Summer in Australia**. We call this embodied-material diagramming process that S1 used repeatedly as 'light rays'.

S2 then said, *'No, it's talking about why the Sun is higher, in Summer'*, as he used the torch (right hand) to shine light at the Australian location on the globe at a higher angle (Figure 8). **Here, the body was used to iconically show the structural meaning of *'higher'* in terms of the angle of the Sun's rays (i.e. torch light) hitting the Earth (i.e. globe)**.

S1 then repeated the 'light rays' diagramming process as he said, *'Yeah, yeah, no, no, I am saying this because here . . . it's pointing right at it . . . it sees the Sun more it than it does in Winter . . . '* S2 responded, *'Oh, yeah, yeah, yeah'*, as S1 again executed the 'light rays' diagramming process as he said, *'Because it's looking at it'*. S1 thus made use of **the torch-globe arrangement to realise the iconic potential of the 'light rays' diagramming process to adopt an Earth-based perspective that structurally linked the Australian location on the Earth to the Sun.**

S1 then tilted the globe down (left hand) from its orbital axis (so part of the base of the model was off the table) (Figure 9) and said, *'But down in Winter . . . '*, while shining the light (right hand) from the torch (i.e. Sun) at Australia on the globe (i.e. Earth). **By tilting the globe down from its orbital axis, they iconically highlighted the angle at which the Sun's light rays hit Australia in winter**.

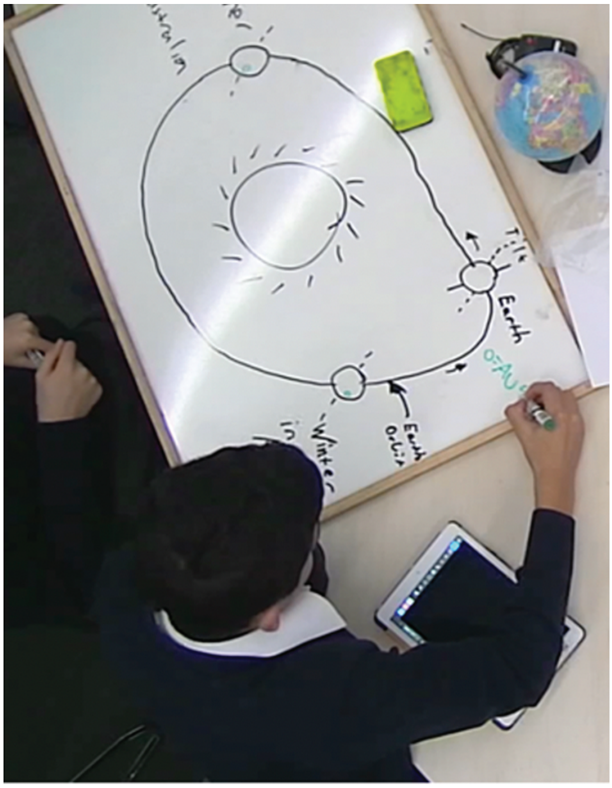

Figure 6. S2 draws circles on the 'Summer in Australia' and 'Winter in Australia' Earths to mark Australia's location relative to the Sun's incoming energy.

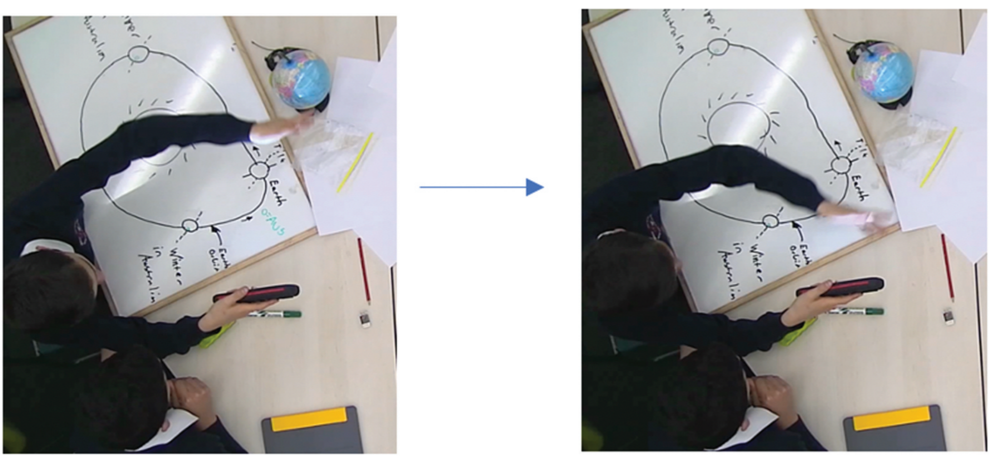

Figure 7. S1 using the globe and torch to gesture the exposure of Australia to the Sun's light rays in Summer. We call this material-embodied diagramming process 'light rays'.

Figure 8. S2 using the globe and torch to show the ‘higher’ angle of the Sun’s light rays hitting Australia in Summer.

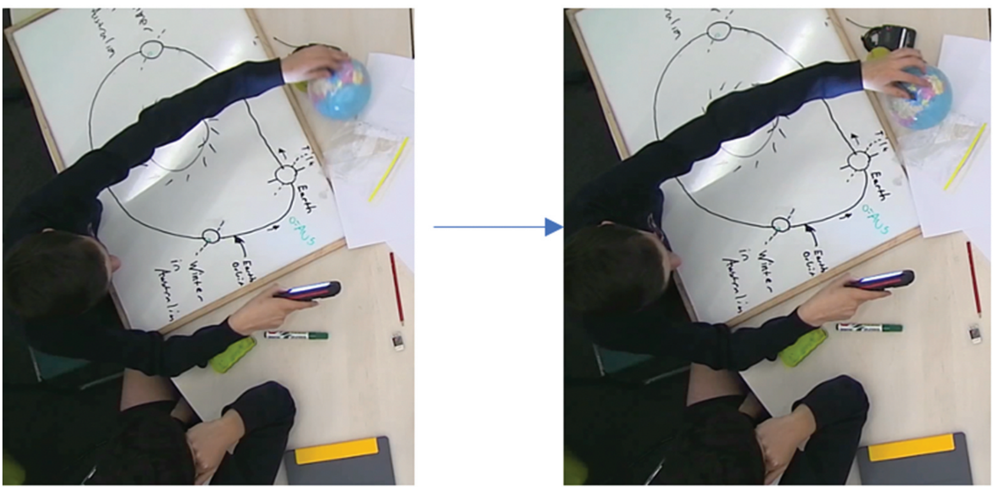

Figure 9. S1 tilting the globe from its orbital axis to emphasise the angle at which the Sun’s light rays hit Australia in Winter.

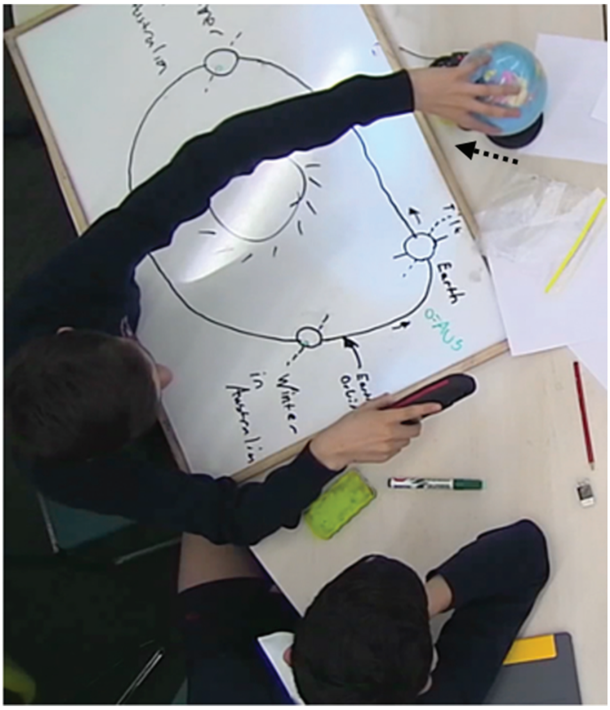

Figure 10. S1 rotating the whole globe not on its axis but from its base (as indicated by our dashed arrow) while shining the torch at Australia.

The two students then further explored the Winter scenario, but used the tilted model globe more deliberately as S1 rotated (left hand) (Figure 10) the whole globe not on its axis but from its base to effect the opposite tilt (thus representing the Earth at the opposite orbital point) and shone the torch light (right hand) on the Australian location on the globe, which in combination with the previous manipulation (Figure 9) meant that the Australian location was at a lower angle (relative to the torch, i.e. Sun) than it was before. **It is through such embodied/ material enactment that the students were able to establish key structurally grounded relations: the Sun's light rays hit Australia in Winter at a lower angle than in Summer**. This iconic-embodied diagramming enabled them to adopt an Earth-based perspective (*'see it'*) that was essential for productively engaging with the task.

In this second moment, the students' bodily actions were used to perform the meanings of the signs and their relationships as represented in their diagram to allow alignment between the 2D drawings and 3D modelling. The students have established the effect of the Sun angle in a general sense, but have yet to construct a formal link to the 'height' of the Sun as seen from Melbourne. For this, they needed to go back to the drawing to embed their insights from the 3D model.

Moment 3

The two students proceeded to embed in a convincing way the spatio-temporal insights they now had from the 3D model into the 2D drawing. S2 pointed (right hand) to the rotational axis of ‘Summer in Australia’, **resembling the structure of the Earth’s rotational axis**, as he said, *‘So, here, the axis is here’*. S2 then explained, *‘So, it rotates . . . that way, okay?’* as he then inscribed (right hand) a curved arrow next to the rotational axis of ‘Summer in Australia’ (Figure 11) to indicate the Earth rotating on its axis. This inscription is almost incidental to S2’s gesture that he used to indicate this rotation, such that the curved arrow is a trace of his gesture in spinning the 3D globe. **Both the inscription and gesture structurally resemble the rotation of the Earth on its axis**. The students are here again adopting a space-based perspective.

S2 then said, *‘It’s, it’s day here, when, when it’s here . . . ’* as he indicated a hollow green circle, and continued with,’ . . . *it has more of an angle up* . . . ’, as he inscribed (right hand) an arrow below the hollow green circle (‘Summer in Australia’) which points up and perpendicular to the dotted line that indicates the Earth’s rotational axis (Figure 12). **Both the inscription and gesture depict the angle between Australia and the Sun in Summer**. We consider that their 3D material/embodied and verbal exchanges (*‘light rays’* and *‘looking directly at’*) were translated in the drawing into an abstract form (an arrow pointing towards the Sun) representing the direction of the Sun as seen from Australia in Summer. In their diagramming, the students are coordinating Earth-based and space-based perspectives.

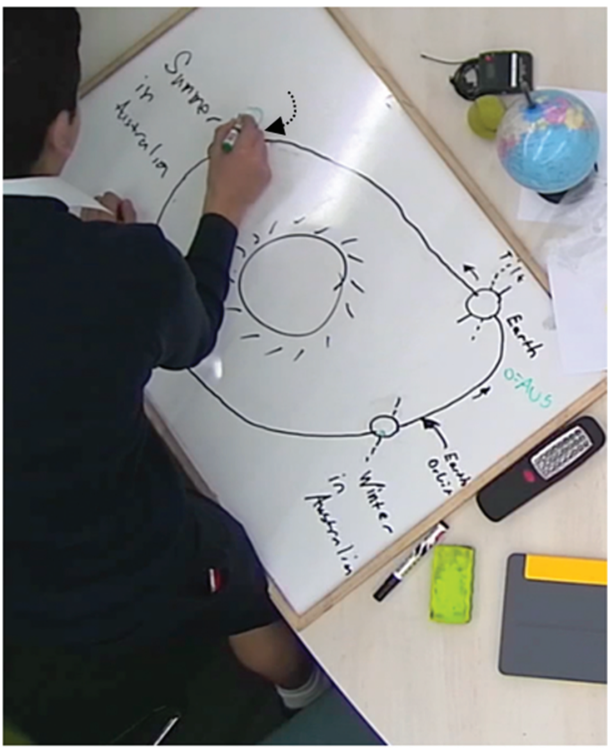

Figure 11. S2 gesturing and drawing the rotation of the Earth on its axis (as indicated by our dashed arrow).

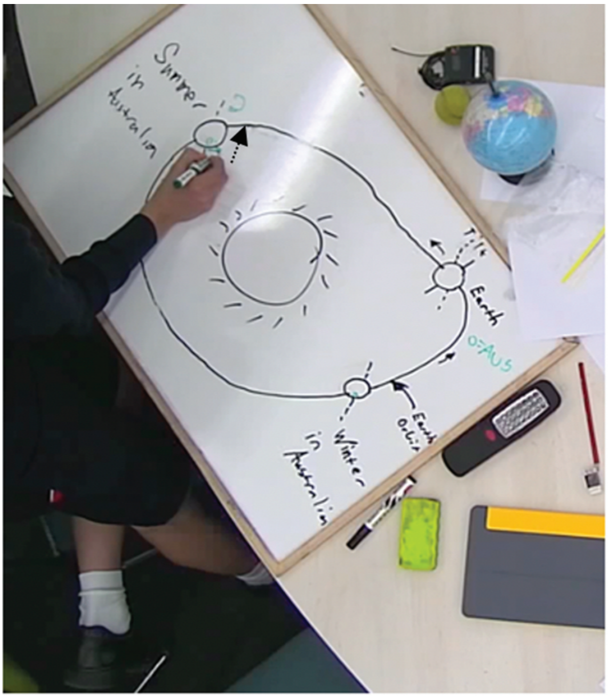

Figure 12. S2 gesturing and drawing the 'upward' angle of Australia on Earth relative to the Sun in Summer (as indicated by our dashed arrow).

S2 then completed his explanation, ' . . . *than over here . . . when it's night*', as he drew (right hand) a filled green circle that then seemed to be confused with an iconic indication of the position of Australia during Winter (Figure 13).

From this point, the students continued their collaborative reasoning through investment in the 2D/3D diagramming process to **refine (albeit incompletely) the iconicity of the drawing to depict the structural relationship between Australia and the Earth's tilt at opposite points in its orbit, and the direction of the Sun as seen from Australia at these times.**

We can determine from this narrative, however, that this complex iconicity is not restricted to the 2D drawing, but its meaning has been constructed in relation to the students' experience of the 3D modelling involving both body and material forms. Throughout this performative process, we observe the material and embodied nature of the diagram construction, with an agreed meaning established through this iterative process accompanied by talk.

Discussion

Bodily/Material nature of diagramming as iconicity

Our analysis reveals the way in which the structural relationships between key components of the astronomical system that was the focus of the task were performed by the students as collaborative diagramming. We suggest that icons, for this case of astronomy,

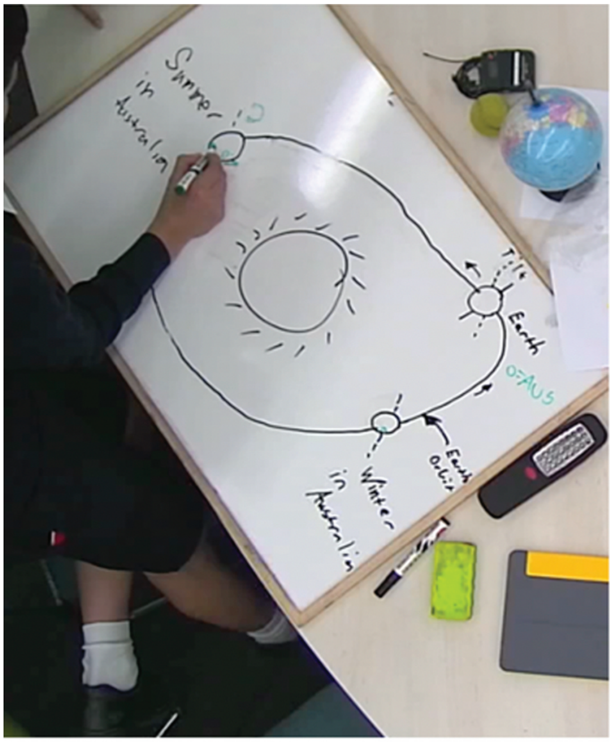

Figure 13. S2 drawing the position of Australia (green circle) during the Winter.

only have meaning through this material-embodied mutuality exhibited by these two students. We propose that student diagramming in science is a material-embodied process, such that the epistemic power of the body and material environment for learning ought to be understood as iconic potential. This material-embodied diagrammatic meaning making of astronomy is not only evident as students manipulated the globe and torch as the positions of the Earth and Sun but also as they summoned embodied Earth-based and space-based perspectives – structural relationships – and 'projected' these onto the globe, torch and mini-whiteboard. We argue that this investment of material/embodied meanings in astronomy and possibly all diagramming in science is precisely the origin of disciplinary discernment (Eriksson 2019)

By unpacking the semiotic constitution of the two students' bodily and material encounters in detail, we demonstrate that iconicity is partial in that diagramming necessarily involves highlighting certain structural relationships and not others. The structural relationships between Earth and space as represented by the drawing are a partial/reductive snapshot of the system. In student diagramming, the representamen (i.e. representation) does not always accurately stand for its denoted object. As such, astronomical diagramming by students is a material-embodied process of approximations, realised through the complex transductive process between 2D and 3D representations, such that the iconic relations in the drawing are understood by them through this performative diagramming process. However, while we focus in this paper on icons, we stress that in most cases the students could only unlock the epistemic potential of the iconicity of their bodies and their material environment as interlaced with the indexes and symbols.

The creative diagramming exhibited by the two students is, according to Peirce (CP 3.363), deductive in nature as they activate their bodies and the material environment to reveal structural relationships. We argue that the two students exhibited what Peirce calls 'corollarial deduction' (CP 2.267), as they first assembled all the necessary astronomical components required for the task into a system, which crystallised in the drawing but which emerged from the whole body/material system, and then interpreted (i.e. read) the meaning of these relationships in terms of their structural manifestations. We therefore endorse Ferguson's (2019, 2022) and Ferguson and Prain's (2020) recent Peircean account of creative scientific reasoning in the classroom, according to which students are creative not only in their abductions and inductions but also in enacting deduction as inquiry through bodily/material diagramming.

By adopting this Peircean perspective, novel insights about the body and materiality in learning astronomy are made possible; the boundary between the two is eroded (in a productive way) if we reframe a focus on modes in terms of icon, index and symbol. While it is useful to consider the different bodily and material aspects involved in astronomical reasoning in themselves, by exploring the semiotic nature of these processes, as a milieu of icon-index-symbol, we can reveal the primal role that they play in student understanding of astronomy. The distinctive yet intertwined and complimentary nature of the bodily and material environments in astronomical reasoning is more fully determined by considering them as iconic processes that reveal particular structural relationships through diagramming.

Perspective taking as realising structural relationships through 2D/3D transductions

In our analysis, we have shown that the key to the two students making meaning was adopting both Earth-based and space-based perspectives, and shifting between and aligning these different views. While this finding is entirely expected based on long-standing understandings from science education research (Hubber and Tytler, 2017, Plummer, 2014), we provide fresh insights into the semiotic nature of students' spatio-temporal reasoning as diagramming in astronomy. These students adopted a space-based perspective to realise the way in which the Earth orbits the Sun with a tilted rotational axis. They adopted an Earth-based perspective through their bodily-material exploration of Australia 'seeing' the Sun more directly in Summer than Winter, and transducting this insight into an abstracted arrow in the 2D drawing representing the structural relationships of the Sun's direction in relation to the Earth's surface. In doing so, the students were able to strategically realise the iconicity of their diagramming, coordinating these two perspectives, to deduce that the Earth's tilt as it orbits in relation to the Sun's position was the reason for the changing height of the Sun in the Earth's sky. We propose that perspective taking is so valuable for student understanding of astronomy because it is rich in iconic potential; *perspective taking in astronomy is deducing structural relationships*. Those moments when the two students confused the relevance of the Earth rotating on its axis and revolving around the Sun were moments when there was a breakdown in their perspective taking to understand and complete the task.

The two students were able to progress their inquiry because they were committed to determining both the *temporal* and *spatial* structural relationships of astronomical phenomena, which manifested in bodily/material forms as evident in the way they oriented their bodies to adopt different astronomical perspectives. The students needed to understand that the reason for the seasons is due to the movement of astronomical bodies in space that is also necessarily a matter of time as this spatial movement is tied to particular temporal points and patterns. As such, the reasoning that is essential for students to understand the temporal and spatial dimensions of astronomy is not just visual in nature, but also necessarily bodily and material. If students are to fully realise Earth-based and space-based perspectives, they need to enact structural relationships with their bodies and their material environment.

Thus, the real challenge for these students was to align the structural elements across the 2D and 3D representational forms. This is a form of creativity that is commensurate with the creativity of corollarial deduction mentioned earlier. No single representation in this diagramming process made sense on its own. Transduction across these 2D and 3D forms should be considered as an iterative process whereby the 2D drawing is invested with meaning that is inherently 3D and embodied/material in nature, while these bodily and material actions of the students with the models in 3D are overlaid with abstract understandings rooted in the 2D form of the drawing. This is a process of unlimited 2D/3D semiosis in bodily/material forms that constitutes a milieu of meaning making in which students are immersed in a landscape of signs that they both create and interpret to change their immediate learning environment in epistemically useful ways. The disciplinary meanings of each sign need to be interpreted through importing material and embodied correspondences from other, related signs. The iconic power of diagramming for student understanding of astronomical phenomena is dependent on this transduction process involving 2D/3D and material/body systems. By tracking students' transductive moves across signs (in particular icons) through the diagramming sequence, we can identify how they stitch together a variety of modes (gestures, drawing, speech, manipulation) for meaning making.

Conclusion

The two focus students were able to achieve, with limited teacher intervention, a reasonable but not full account of the Sun's height in the Earth's sky depending on the seasons. We argue that the epistemic success of these students relates to their attempts at deduction as creative reasoning through diagramming. While the teacher can set up opportunities for students to enact diagramming in astronomy using different signs, ultimately students need to be able to creatively reason across 2D and 3D representational forms to realise the iconic potential of diagramming as central to their learning. Students are required to activate their bodies and their material environment in ways that maximise meaning making through iconicity. The teacher's role should be to focus on supporting this process of student transductive reasoning across sign systems (2D to 3D and vice versa). Student diagrammatic learning is only made possible by diagrammatic teaching. As such, we endorse what we call *iconic guided inquiry* for astronomy. Teachers need to be sensitive to the ways in which students activate their bodies and material environments to adopt the space-based and Earth-based perspectives that reveal the key structural relationships of astronomical phenomena.

Our detailed pragmatist semiotic analysis has shown the potential value of this Peircean perspective to enrich accounts of students' embodied and material reasoning in science. These bodily and material processes ought to be understood as diagramming in action, as the epistemic power of icons is realised to lay bare structural relationships that underpin scientific phenomena. It is the semiotic constitution of the bodily and material environments for pragmatist ends – the milieu – that counts for teaching and learning in science, particularly in the realm of icon-infused astronomy. We encourage others interested in demystifying the role of the body and the material in student meaning making in science to join us in exploring and operationalising Peirce's ideas on the iconic power of diagramming.

Note

1. CP x.y = *Collected Papers of Charles Sanders Peirce*, volume *x*, paragraph *y*.

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