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Expanding the Languages of Science and How They Are Learnt

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Abstract
While the multimodal nature of the languages of science is now broadly recognised, the role of affect and aesthetics in these languages, and the potential for this aesthetic focus to add to these languages, has tended to be ignored. Research into these languages has mainly focused on a codification of their functions, an approach to which aesthetics study would seem not broadly suited because of its ephemeral, complex, relatively unpredictable and affective nature. However, there is a growing awareness of its importance in learning. In this paper, we analyse a case study of art-science integration on the topic of optics to (a) put a case for the value of an explicit focus on aesthetics in science learning and (b) to clarify how teachers might integrate conceptual learning and aesthetic experiences into a broadened account of the languages of science. We argue that this focus on aesthetic responses needs to be included in accounts of productive science classroom discourse because such responses (a) enhance student motivation to learn, (b) enact generative sign-making in this discourse, (c) enrich student habits of perception in inquiry-based-learning and (d) licence more creative learning processes and outcomes. These effects are consistent with widespread policy advocacy of the need for students to find learning in science more meaningful.

Keywords Language in science · Aesthetics and learning in science · Affect · Science education · Student learning in science · Art-science links

Introduction

Early versions of learning science as learning a particular literacy (National Research Council 1996) had a strong linguistic emphasis. These have been supplemented more recently by

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accounts of science learning as entailing informed use of the multiple languages of this subject (Bezemer and Kress 2016; Jewitt et al. 2001; Lemke 2004; Tytler et al. 2018). Researchers have increasingly recognised that the material basis of scientific practices requires students to engage in multimodal reasoning and representation (Bezemer and Kress 2016; Hand and Choi 2010; Hubber et al. 2010; Tang and Moje 2010; Tytler et al. 2020; Yaman 2018). From this perspective, students learn through integrating and valuing linguistic, visual, embodied and mathematical signs in scientific meaning-making and communication.

The dominant linguistic mode is still foregrounded in science classroom discourse, with its focus on definitions, verbal explanations, translation across modes, re-descriptions and clarificatory classroom discussion, but researchers have also increasingly focused on other less formal meaning-making practices. These include physical manipulation of objects, embodied and gestural understandings, representation construction, visuo-spatial reasoning (Lehrer and Schauble 2006; Tang and Moje 2010; Tytler et al. 2013) and aesthetic and affective dimensions to this learning (Bloom 1990; Kress 2010; Lemke 2015; Wickman 2006, 2017). We acknowledge the importance of all these meaning-making practices but particularly focus in this paper on the aesthetic dimension. We do this because for us this dimension is (a) generally underrecognised and undervalued as part of science learning experiences; (b) central to understanding and incorporating affective and creative experiences into science learning and (c) an underutilised contributor to student engagement and learning. As noted by Kress (2010, p. 78), "the sensory, affective and aesthetic dimension is too often ignored and treated as ancillary (to communication)".

Research into the multimodal languages of science has mainly focused on a codification of their separate and integrative functions, an approach to which aesthetics study would seem not broadly suited because of its ephemeral, complex, relatively unpredictable and affective nature. However, despite these analytical and methodological challenges, we consider there is a need to clarify the place of aesthetics in science classroom discourse. We also seek to indicate how teachers might integrate conceptual learning and aesthetic experiences into a broadened account of the languages of science in this discourse. Within the constraints of space, this paper is intended to outline our reasoning.

Conceptualizing Aesthetics in Science Education

Aesthetics in science education has tended to draw on scientists' accounts, where aesthetics is understood as the appreciation of the beauty of the objects of study in science, as well as the elegance of scientific methods and accounts of these objects (Chandrasekhar 1987). However, as Daston and Galison (2007) noted, the long-standing tradition in scientific research of the pursuit of objective detachment (to minimise bias, subjectivity, distortion, ambiguity, inaccuracy and implausibility) has tended to lead to classroom practices that downplay or ignore an aesthetic affective focus. At the same time, a contrasting perspective has questioned this separation of reasoning, affect and aesthetics, and encouraged teachers and researchers to recognise inherent aesthetic dimensions to student engagement in all experiential inquiry, including scientific ones (Dewey 1897; Wickman 2006). For Wickman (2006), aesthetics has two meanings in relation to science. The first entails an appreciation of, and preferences in topics and approaches to inquiry in this subject, or what amounts to the particular aesthetic of doing science. The second meaning entails affective responses to these experiences of science. Such responses can include feelings of beauty, ugliness, intrigue, pleasure, displeasure,

irritation and surprise in practical inquiry (Anderhag et al. 2015). These responses influence whether students develop a taste for the aesthetic of this subject. In researching teacher practices where they elicited and acknowledged students' aesthetic responses in learning, Anderhag et al. (2015, p. 749) noted that:

> the teacher consistently followed up how the students acknowledged and enjoyed purposes, norms, and values of the science practice and so ensuing that they could participate successfully. During these instances, feelings and personal contributions of the students were also acknowledged and made continuous with the scientific practice.

For Wickman (2006), this richness of influences on what, how and why students learn should lead to researchers describing how students' habits of perception and action are transformed, rather than how aesthetic judgements (as internal mental states) enable or constrain conceptual learning. Wickman (2006) argued that aesthetic judgements have communicative immediacy, where feelings should be treated as contextual facts that shape student actions and intentions. He claimed that researchers should therefore aim to discern how aesthetic judgements promoted by teachers and activity become adopted as part of a transformed (and transforming) habit within the discursive practice of doing science. In this way, aesthetic judgements can contribute to the experience and process of inquiry, including feelings of anticipation, uncertainty, gain and learning success, and where negative aesthetic experiences (irritation, distaste, disappointment) are part of the struggle to learn. For example, in learning what constitutes a clean biological specimen or an adroitly orchestrated procedure, students learn about what counts as desirable, reliable practices in science, or what counts as an aesthetic of this subject. In this way, all classroom transactions contribute to how a student's taste for this aesthetic develops or is blocked.

In concurring with this line of reasoning, and drawing on socio-semiotic perspectives that view learning in classrooms occurring through culturally developed and agreed sign systems (Bezemer and Kress 2016; Lemke 2015; Tytler et al. 2013), we further claim that recognising this aesthetic and responding to it can expand what is understood as the languages (sign systems) of science. For Lemke (2015, p. 602), affect, or feelings, is always "functionally complementary, co-determined and co-determinative" in meaning-making and that this applies to both everyday feelings as well as elicited aesthetic feelings of wonder, anticipation, surprise or dismay in the science classroom. This is evident, for example, when a teacher elicits and acknowledges students' personal responses as they interact with the material objects and resources in an inquiry. This aesthetic dimension can also be elicited and acknowledged when students make, respond to, and value the semiotic systems (signs) that underpin and make communicable what they are learning and have learnt.

From this perspective, aesthetic considerations can enact new sense-making in science discourse, for instance as students learn to value and pursue scientific explanations. They can also influence other modes of sign-making (e.g. attending to clarity in drawing), as well as sense-making processes (e.g. driving inquiry into phenomenon). The potential of this focus is already evident in growing advocacy of, and emerging practices in, art-based approaches to science learning where students explore phenomena through the development of aesthetic products or pursue personally shaped design solutions that involve scientific exploration (Izadi 2017; Jakobson and Wickman 2015; Moerman 2016; Turka et al. 2016). Such approaches invite students to be open to varied methods in the design, enactment and communication of inquiry. Students are encouraged to make choices about what materials, images, design elements and principles they explore or use in their learning processes. Allowing time and

space for such learning (interdisciplinary makers spaces, project-based inquiries, art-science productions) provides opportunities for students to express and communicate creative personal responses to their experiences and their developing work (Hannigan 2018). Such aesthetic engagement can translate into interest in and appreciation of "what's going on?" with the science phenomena and an appropriate focus for science teachers to develop students' interest in and appreciation of conceptual exploration.

In this paper, we draw on one case study that is part of a wider research program exploring the outcomes of explicit links between the arts and science. In this case, we worked with a secondary science teacher to conduct material/representation construction activities aimed at developing an art-science display: the creation of photographs exploring visible light effects or infrared phenomena that promoted the artistic values of intrigue, surprise or beauty. This entailed students constructing and coordinating multimodal representations including visual, material, embodied and textual modes. We chose this topic as illustrative of potential integration of arts, science and aesthetics, but also because it has felicitous content overlap across the two school subjects. We use this indicative case to explore how aesthetic purposes and expression can be freshly understood as important and generative aspects of a widened view of science classroom discourse, involving both students and teacher. In this, we argue the importance of acknowledging aesthetics as offering a productive addition to our understanding of the wider languages of science.

Research Questions

In this study, we addressed the following research questions:

1. What possibilities for learning are opened up, and what are the challenges, in linking art with science in exploratory multimodal activities?
2. What are the implications for learning and the languages of science from such an approach?

Method

We utilised a case study methodology, entailing a whole class of students from a secondary girls' school (approximately aged 14) engaging in an intensive arts-based lesson, in a specially designed classroom, as part of a unit in optics. This "Science of Learning" classroom, at a local university, has 10 wall- and ceiling-mounted video cameras with zoom and tilt capacity, and radio microphones on each desk, controlled from a room with visual access to the classroom. The arrangement allows us to generate continuous high-quality visual and audio records for each of 10 pairs of students engaged in inquiry activities, with a separate video stream of their teacher circulating to provide support as needed.

The lesson plan (the framing of the task and the selection of equipment) was jointly constructed by the research team, all of whom had teaching experience, and intersecting expertise in science, language and art education. The lesson itself was conducted by one of the researchers and the teacher (Cathy; a pseudonym) who had a science degree and teacher training qualification but no specific experience of art-science integration. Cathy had expressed interest in the project as a way of engaging students' knowledge and interest. She and the researcher had previously discussed the intent of the lesson, including how it might fit within

the optics unit sequence. The students, sorted into small groups of 3 or pairs, were challenged to generate a photographic display as part of an exhibition "The art and science of the spectrum" that was artistic in the sense that it should bring out surprising or intriguing optical effects. As a stimulus, they were shown images of photographic work by photographers such as Man Ray and André Kertés, who focus on illusions and intriguing visual effects. They were asked to take photographs using iPads or infrared cameras, and organise these for the display using keynote software. They were to caption their work, explaining their intentions both in terms of art and science. They were given access to a variety of materials, including mirrors, water-filled beakers, marionette figures, bubble makers, lenses and prisms. As they carried out these investigations and photographic production, Cathy and the researcher circulated, helping with identifying equipment, questioning students' intentions and interpretations, and sometimes suggesting ideas. While the researcher presented the challenge, Cathy took the main responsibility for the pace of the lesson and keeping students on track.

Apart from the researcher who was in the room and helping, the other researchers viewed the lesson from the control room, occasionally intervening to ask the technicians to zoom in on particular groups or artefacts. The entire video record from the 10 cameras and microphones was then available for analysis. Our data included the student photographic artefacts including their captions, the video record of the lesson, informal discussion with Cathy during and immediately post-lesson and subsequent interviews with Cathy at the end of the unit several weeks later. The informal discussions with Cathy were captured in field notes. The interview was transcribed and analysed for key themes that emerged in her views about the art-science interactions.

For the video analysis, the research team viewed the recorded data multiple times, first individually and then together to identify key themes built around selected groups and episodes. Given that groups often made decisions in silence as they were constructing their artefacts and photographs, we focused particular attention on groups where there was a record of interactive talk in which they articulated their thinking about the phenomena they were exploring, sometimes in conversation with the teacher. Particular episodes that illustrated aesthetic responses to the phenomenon, or explicit aesthetic framing of their photographic decisions, and/or interpretive reasoning about the science of the phenomenon, were transcribed for further analysis. Some episodes of such aesthetic/scientific talk involved Cathy questioning or affirming their responses and ideas. The analysis and identification of themes focused on signs (mainly verbal expressions, object manipulation, the photographs themselves and writing) used in meaning-making by the students and by Cathy.

Results

Video Analysis

The video record showed that during the exploration of phenomena, there was not much explicit talk focused on the science concepts underpinning the phenomena that were constructed and experienced (e.g. reflection and refraction phenomena, colours in bubbles, infrared images). Most of the negotiation and implicit reasoning was evident in talk and action focused on changing camera angles or backgrounds, or mirror and container placement to maximise effects ("if you did this ..." as a student adjusted mirror angles). There are frequent expressions of aesthetic response (e.g. delight, interest, frustration,

disappointment), through extended material manipulation to achieve a quality image (e.g. satisfaction, enthusiasm for the framing), or in expressions of surprise ("wow", "that's cool", "oohh – weird").

Here we focus on two groups' activity. The groups were chosen because they presented an audio and visual record of their reasoning concerning the scientific or other constructs that guided their actions in creating the photographs, more so than many groups. They are not "representative" in that sense but represent "examples" that furnished us with insights into the possibilities of types of response, and language, that can attach to art-science integration. Ferguson et al. (2019) provide a description of the methodologies we utilised in the analysis of these rich video data sets, including the role of such examples. Kylie and Nerida (all names are pseudonyms) attended to spectra in bubbles caused by the room lighting and were explicit in crafting their science explanation at the end. The aesthetic language embedded in the teacher-student interactions is clear in the data for this group.

Spectra in Bubbles

Kylie and Nerida experimented with the light reflected and dispersed from bubbles. When Cathy (T) came by to ask what they are doing, Kylie explained:

K: On the table it actually bounces. The bigger the bubble the more it bounces and as it bounces it loses a little bit of it .. a little bit of the moisture from it and the little rainbow thing … it turns every time
N: We're taking a video so we can stop and then take photos (teacher asks what they are using …. . She seems to be pushing for a more complex investigation).
T: Just remember you are looking for something that's surprising.
K: I was surprised by … the jumps
T: Yeah … seeing all those, and I guess you can .. take those photos and try and see what else you can do to change it a little ...
Nerida then showed Cathy a bit of their video:
T: Let us have a look. Oh wow. So that's interesting …. in itself … isn't it.
They look intently at the video
N: See when it jumps, it stops and it gets caught …
T: Yeah and it was interesting … it had a number of …
N: Bounces …
T: Yeah yeah yeah yeah and a number of those (gestures with circulating finger) … spectrums on there.

Following this exchange, the pair played with mirror effects, carefully testing the angle of light shining on an object placed between two mirrors at a right angle. They then blow bubbles in between the mirrors (Fig. 1a). Both break into smiles:

K: That was so coo.. ool!
N: That was so good!

They then took a succession of photographs, carefully adjusting angle and lighting. Leading up to their selection of photographs and writing an account of their work, they discussed with the teacher the reason for the colour effects (Fig. 1 a and b). Their science interpretation for the

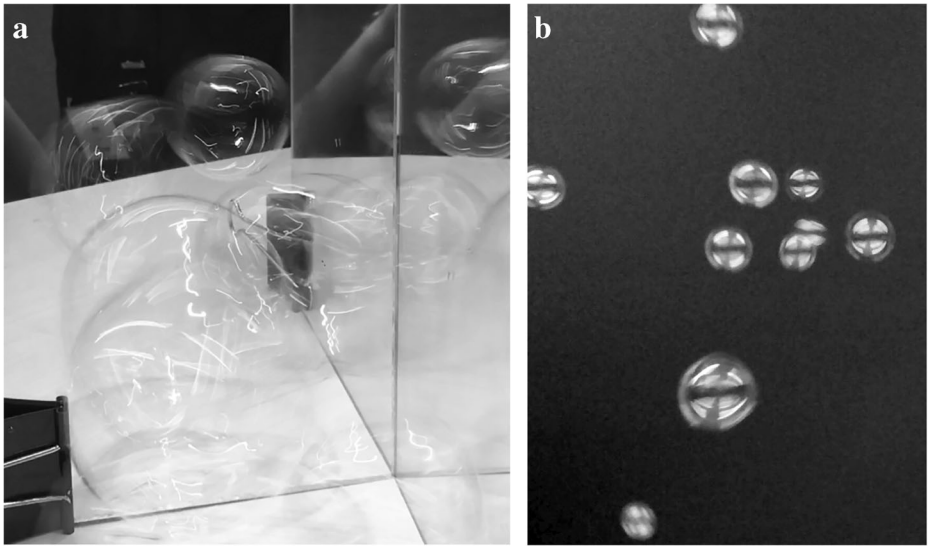

Fig. 1 **a** and **b** Monotone versions of Kylie and Nerida's photograph selections of light effects in bubbles

exhibition incorporating Fig. 1b reads: "We tried to capture the different colours in the bubbles as well as the different patterns. The white light bounces off the edges of the bubbles which separates the colours".

In this group's story, we can see a number of different generative features: the targeted exploration, using different settings, lighting conditions and backgrounds, of the dispersion phenomena in bubbles; the keen observation of the movement of bubbles, of dependence on the size of colour underpinning the crafting of their photographs; the interaction between the art and science as they use their photograph to interpret the science ("the light bounces off .. like it bends"); the aesthetics relating to surprise, intrigue and curiosity, in driving their investigation; the explicit aesthetic language of both the students and teacher in establishing interest in and reasoned attention to the phenomenon and the sense of joint exploration in the teacher-student exchanges. The aesthetics can be seen to be a core component of these students' multimodal language practices as they interpret the science and communicate both its coherence and its beauty through their very deliberate photographic construction.

Cathy's intervention illustrates a number of discursive moves that were common with her interactions with the groups generally:

- Affirming the aesthetic experience triggered by the phenomena and by the students' work;
- Encouraging further exploration of the phenomenon to enhance both the art and the science and
- Encouraging students to think about the science underpinning the effect.

Again, we see in these discursive moves the intimate linking of aesthetic and conceptual purposes around understanding and expressing the science ideas. In this particular instance, the science ideas, of interference in thin films, were not easily accessible to the students, so that the conceptual explanations were speculative.

A Constellation of Images

Cerise and Allie were two girls Cathy described in the post-session de-brief as not normally interested in science. In the session, Cathy remarked on the skills and abilities they displayed that she had not realised before. In working with a mannequin positioned in front of a mirror, the students were deliberate in their exploration of multiple and distorted images using angled mirrors and a beaker of water. Cerise suggested adding a second mirror at right angles and carefully arranged the mannequin in front of a glass of water. They subsequently introduced a third horizontal mirror, to create a constellation of images (Fig. 2).

A: Oooohh -weird
Cerise brings the mirrors in at a sharper angle. They collaborate in the placement.
C: Shall I put it like that?
A: Yes. Yes.

They carefully reposition, discussing as they go. Cerise brings a golf ball to put in the glass of water.

A: Oohh! Oohh!
C: It looks good

While they did not articulate their thinking as they explored mirror, mannequin and camera positions, their deliberate positioning and testing of effects indicated an active assessment and adjustment of image position and qualities. Again, we see their sign-making practices being driven by the combination of scientific curiosity and aesthetic sensibility. In their explanation, they wrote: “In this photo we utilized the mirrors to create a repeating effect with the mannequin. The golf ball was lit with a flashlight that gave the photo life”.

Fig. 2 Monotone version of Cerise and Allie’s photograph of visual effects

Subsequently, in an interview 1 month later, at the end of the optics unit, they explained: "The reflections in the mirror give a virtual image and it's hard to see where the mannequin ends and the virtual image begins because they're touching. The refraction in the cup of water makes the golf ball have an egg shape and you can see the virtual images in both the mirrors and it's pretty cool".

In this account, we can see the aesthetic expressions relating to surprise, delight, strangeness and satisfaction with the phenomena, as well as an artistic sensibility evidenced in the language ("gave the photo life") and in their careful adjustments of the mirrors, objects and camera.

Teacher Interview

Cathy was interviewed at the end of the optics unit back at her school, 2 weeks after the class, by the art education member of the research team. The interview focused on her experience of the session, her reflections on the art-science interactions and the extent to which the learnings from the session were taken up in the unit. She reflected that:

> Normally I would teach this in a more sciency way … (I) thought it was a very creative way to look at light and it is something I feel – the next time I teach light I will probably teach it to include this.

Summarizing her experience of the project as a whole, she communicated more than once an appreciation of the art and aesthetic dimension to learning in the "real world". She hoped that in the future "if they (students) see other images they'll think about what's going on". This led to a conversation between the researcher and the teacher about their own experiences of having learnt from the images the students created. This exchange throws an interesting light on the process of learning science and the role of aesthetics for teachers and students alike in responding to the world of scientific phenomena. Cathy responds with strong aesthetic language:

> R: well yeah that's another thing – you start to see the world a bit differently? because seeing those bubbles (in the photographs) – I mean I've never really stopped and looked at bubbles like that
> T: they were the most effective in many ways were not they? Particularly when they (students) had them in colour with maybe a filter, then just in black and white and you could see the shadows. Like that to me is amazing – that you still get shadows from something like a bubble that's quite transparent.
> R: Yeah I know – you can get whole images in them and I guess when you see bubbles you do not look so closely but when its captured in a photograph and blow it up a bit.
> T: They're BEAUTIFUL! Are not they?

Discussion

In this discussion, we respond to our two research questions, concerning (1) the possibilities for learning opened up, and the challenges, by linking art and science in exploratory multimodal activities and (2) drawing out the implications for expanding the languages of science to acknowledge aesthetic dimensions of learning more generally. We argue that the art-science

interaction can be generative of learning in science, and that an aesthetic framing offers a generative additional dimension to science classroom discursive practices, and should be seen as a necessary aspect of the language of science.

The aesthetic nature of the students' experience—their perceptions and their actions—is clear in these interactions from (a) their expressions of surprise, delight and intrigue as they discover the optical features of the bubbles, the dispersion, the refraction and multiple reflections; (b) their explicit recognition of this in conversation with the teacher; (c) the attention they pay to exploring and manipulating the phenomena, through the placement of mirrors, lights and cameras and (d) the attention to explanatory science that is evident both in their discussions with the teacher ("as it bounces it loses a little bit … of the moisture"), in their scientific captioning and later in the interview. This aesthetic aspect of the science exploration is also evident in the teachers' response, in the way she explicitly models and encourages a particular view of the intrigue and surprise in the phenomena, in her encouragement of further explorations of an aesthetic nature ("you're looking for something surprising") and in her own response ("They're BEAUTIFUL!"). We argue, with Dewey (1897, 1911) and Wickman (2006) that these aesthetic experiences are not simply a background motivational gloss on scientific learning but are a key feature of the discursive practices of these classroom science activities.

We claim that this recognition of aesthetic/affective dimensions to science learning experiences is a productive extension of current research into the variety of signs through which meanings and values are negotiated and established in the discourse of the science classroom. These elaborated accounts of the languages of science identify how the modes of "doing" science interact with linguistic contributions but tend to ignore what stimulates student inquiry at the point of interacting with phenomena and how students feel about this. In the photography activity, the students' immersion in "doing" both science and art offers an invitation to students that opens up new habits of perception and action (Wickman 2006), with the potential to enrich science classroom meaning-making through an enriched discourse. Perceptual engagement with optical effects here prompts both aesthetic responses ("it gave the photo life" and capturing "the different colours in the bubbles as well as the patterns"), and consideration of the science, for instance where Kylie observed and interpreted the bubbles bouncing and losing moisture, relating to changes in the spectral pattern. This aesthetic engagement is consistent with Wickman's (2006) analysis of the centrality of aesthetics to scientific practice and to accounts for the role of aesthetics and values in mono-disciplinary science classrooms distinct from art-science interdisciplinary settings. It is also consistent with Jakobson and Wickman's (2008) analysis of the way teachers elicit and support aesthetic language to establish interest in scientific phenomena and Bloom's (1990) analysis of primary school students' study of worms, showing a complex interaction of belief, emotions, values and aesthetics. We argue that these aesthetic responses of students and the teacher in this study cannot be viewed as simply motivational and peripheral to the cognitive work going on in their exploration of the science or the art, but rather are central features of their experience, of their reasoning and of the discursive practices of this art-science classroom. We argue that, despite the potential difficulty of encoding such aesthetic responses in grammar or meta-language, because of their power in shaping students' perceptions and actions pursuant to learning, they are important components of scientific disciplinary language practices.

With respect to the interdisciplinary art-science setting of the case, the literature suggests that students' aesthetic responses and the teacher's response to their work are characteristic of science classroom work more generally and not unique to this setting. The explicit arts perspective in this case appears to licence freer, more playful explorations, allowing students

to experiment with choices about what and how of creating aesthetic effects. Arguably this enhances their engagement in the learning, encouraging a deeper look at the phenomenon. This includes both the surprise and intrigue of optical effects and also the exploration of conditions under which these occur. These aesthetic positions are an inextricable aspect of a genuine interest in scientific knowledge and scientific activity (Wickman 2006) and similarly in technological innovations in STEM that incorporate science, aesthetics and robotics (Chandra 2018; Ginsberg et al. 2014).

In researching other art-science topics where students' aesthetic responses have been elicited and incorporated into the processes and products of their science learning, we note both the complexity of these responses and their overlap with affective engagement. Beyond an aesthetic focus on beauty, intrigue and surprise as noted in our optics case, other topics have elicited a wider range of aesthetic and affective responses to experiences in the science classroom and to their scientific representation. For example, in a topic where students constructed "trash puppets" to represent endangered species and to advocate for their survival to young children, we noted a range of aesthetic responses. These included a sense of care, responsibility, empathy and humour as the students constructed staged narratives of their assigned animal's plight (Hannigan et al. under review). In another school, students were invited to devise science-based practical ways to restore/enhance the urban environment in which the school is located, prompting aesthetic responses of shock, concern, distaste, entreaty, subversion and playfulness in their representations of possible actions and strategies.

In arguing for the importance of aesthetic responses in accounts of classroom discursive practices that lead to meaningful learning, we thus point out the potentially rich range of aesthetic/affective languages that may be brought into play. Our results show the ways in which these art-aesthetics challenges can motivate students to explore phenomena, and how this can potentially translate into interest in and appreciation of the underpinning science concepts. Arguably, such experiences can result in lasting links that underpin ongoing interest in and appreciation of the associated science ideas. A challenge in further developing the approach is the need to plan for productive alignment between science and artistic exploration and output. This involves developing languages and pedagogies that translate the experience into an aesthetic response to the science explanatory work itself. Students need to be led to appreciate/value the underpinning science ideas and representations, beyond the phenomena itself (see Anderhag et al. 2016 for a discussion of students' interest in science conceptual ideas, distinct from phenomena). A further challenge relates to the possibility of developing assessment approaches that acknowledge the profound links between affect and aesthetics, and conceptual learning. To date, assessment of attitudes to science has tended to focus on school science in general, and interest in topics (Tytler 2014), rather than aesthetic responses to the conceptual agenda of science as such. We argue that meaningful assessment of students' aesthetic/conceptual learning in science will inevitably best be achieved in the context of learning itself, rather than associated with previously learnt knowledge.

Conclusion

In this paper, we have argued that aesthetics needs to be seen as an important and generative dimension of the discursive practices of the science classroom. Our case study of the creative construction of art/science representations of optical phenomena demonstrates the close interplay between scientific exploration and aesthetic responses and purposes. We have argued

through this that the languages of science need to be taken to include more than formalised and codified linguistic modes, and informal and perceptually oriented visual and spatial modes. They should be conceived more widely in terms of the richer set of multimodal discursive practices occurring in science classrooms. In this, we have affirmed previous research on aesthetics as central to science and science classroom practices but have expanded these established ideas to introduce a wider set of aesthetic experiences and responses through interdisciplinary art-science activity and to argue the need to develop a recognised aesthetic language dimension that informs classroom discursive practices.

The case has demonstrated the aesthetically related sign-making practices involved as the students explore and respond to phenomena, as they manipulate material artefacts to construct the signs—the photographs and captions—through which they express their understandings of the science/art and in their talk in which the science and the aesthetic perceptions and responses are clearly intertwined. Similarly, the interventions of Cathy, the science teacher, demonstrate a sensitivity to the aesthetic and conceptual dimensions of the task in terms of her dealings with students and her personal responses to the scientific phenomena and the students' productions.

On these bases, we argue that the languages of science and of the science classroom need to incorporate aesthetic dimensions as a fundamental aspect of the sign-making, discursive practices of the discipline. We further argue that making this explicit for teachers, and embedding aesthetic experiences in approaches to teacher learning, opens up possibilities for teachers engaging students in sense-making processes that develop enriched habits of perception and action in doing science.

The limitations of the research reported in the paper relate to the specific nature of the case, and the lack of opportunity to work in depth with the teacher to rigorously investigate the range of science conceptual learning that might have resulted. The results are, we argue, compelling, but indicative. Further research is needed concerning the different ways in which generative links can be made between art and science and particularly the different ways in which the language of aesthetics can be nurtured to inform deeper engagement with conceptual learning in science. Part of this research needs to consider ways in which teachers, and systems, can include aesthetics as part of assessing science conceptual learning.

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References

Anderhag, P., Hamza, K. M., & Wickman, P. O. (2015). What can a teacher do to support students' interest in science? A study of the constitution of taste in a science classroom. *Research in Science Education, 45*(5), 749–784.

Anderhag, P., Wickman, P.-O., Bergqvist, K., Jakobson, B., Hamza, K. M., & Säljö, R. (2016). Why do secondary school students lose their interest in science? Or does it never emerge? A possible and overlooked explanation. *Science Education, 100*(5), 791–813.

Bezemer, J., & Kress, G. (2016). *Multimodality, learning and communication. A social-semiotic frame*. New York: Routledge.

Bloom, J. W. (1990). Contexts of meaning: Young children's understanding of biological phenomena. *International Journal of Science Education, 12*(5), 549–556.
Chandra, S. (2018). Introduction: Motorcycle and the semantics of design. *Aesthetics: Quantification and Deconstruction. Design Science and Innovation*. (pp. 1–7). Springer, Singapore.
Chandrasekhar, S. (1987). *Truth and beauty: Aesthetics and motivations in science*. Chicago: University of Chicago Press.
Daston, L., & Galison, P. (2007). *Objectivity*. New York: Zone Books.
Dewey, J. (1897), "The aesthetic element in education", reprinted in 1972, *John Dewey: The Early Work, 1882–1898*, vol. 5, (pp. 202–203). Carbondale: Southern Illinois University.
Dewey, J. (1911) "Art in education—and education in art". In P. Monroe (Ed.), *A cyclopedia of education*, (pp. 223–225). New York: The Macmillan Company. Reprinted in 1984 *John Dewey: The Later Works*, 1925–1953. vol. 2, In J. Boydston, (Ed.), (pp. 111–115). Carbondale: Southern Illinois University Press.
Ferguson, J., Aranda, G., Tytler, R., & Gorur, R. (2019). Video research – Purposeful selection from rich data sets. In L. Xu, G. Aranda, & D. Clarke (Eds.), *Video-based research in education – Cross-disciplinary perspectives* (pp. 124–139). Oxon: Routledge. https://doi.org/10.4324/9781315109213.
Ginsberg, A. D., Calvert, J., Elfick, A., Endy, A. D., & Schyfter, P. (2014). *Synthetic aesthetics: Investigating synthetic biology's designs on nature*. Cambridge: MIT Press.
Hand, B., & Choi, A. (2010). Examining the impact of student use of multiple modal representations in constructing arguments in organic chemistry laboratory classes. *Research in Science Education, 40*(1), 29–44.
Hannigan, S. (2018). A theoretical and practice-informed reflection on the value of failure in art. *Thinking Skills and Creativity, 30*, 171–179. https://www.sciencedirect.com/science/article/pii/S1871187117301694. Accessed July 2020.
Hannigan, S., Tytler, R., & Prain, V. (under review). Integrating science and art to enhance science learning.
Hubber, P., Tytler, R., & Haslam, F. (2010). Teaching and learning about force with a representational focus: Pedagogy and teacher change. *Research in Science Education, 40*(1), 5–28.
Izadi, D. (2017). Arts in science education. *Canadian Journal of Physics, 95*(7), xliii–xlvi. https://doi.org/10.1139/cjp-2016-0590.
Jakobson, B., & Wickman, P.-O. (2008). The roles of aesthetic experience in elementary school science. *Research in Science Education, 38*(1), 45–65.
Jakobson, B., & Wickman, P. O. (2015). What difference does art make in science? A comparative study of meaning-making at elementary school. *Interchange, 46*(4), 323–343.
Jewitt, C., Kress, G., Ogborn, J., & Tsatsarelis, C. (2001). Exploring learning through visual, actional and linguistic communication: The multimodal environment of a science classroom. *Educational Review, 53*(1), 5–18.
Kress, G. (2010). *Multimodality: A social semiotic approach to contemporary communication*. London: Routledge.
Lehrer, R., & Schauble, L. (2006). Scientific thinking and science literacy. In W. Damon & R. Lerner (Eds.), *Handbook of Child Psychology (6th Edition)* (Vol. 4, pp. 153–196). New York: Cambridge Publishers.
Lemke, J. (2004). The literacies of science. In E. W. Saul (Ed.), *Crossing borders in literacy and science instruction: Perspectives on theory and practice*. Newark: International Reading Association and National Science Teachers Association.
Lemke, J. (2015). Feeling and meaning: A unitary bio-semiotic account. In P. Trifonas (Ed.), *International handbook of semiotics* (pp. 589–616). Springer: Dordrecht.
Moerman, P. (2016). Dancing and learning natural sciences: Aesthetics, embodied knowledge and classroom interaction. *The international journal of science, mathematics and technology learning, 23*(3), 15–32.
National Research Council. (1996). *National science education standards*. Washington, DC: National Academy Press.
Tang, K. S., & Moje, E. B. (2010). Relating multimodal representations to the literacies of science. *Research in Science Education, 40*(1), 81–85.
Turka, J., Haatainen, O., & Aksela, M. (2016). Integrating art into science education: A survey of science teachers' practices. *International Journal of Science Education, 39*(10), 1403–1419. https://doi.org/10.1080/09500693.2017.1333656.
Tytler, R. (2014). Attitudes, identity, and aspirations toward science. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of science education, Volume II (82–103)*. New York: Routledge.
Tytler, R., Prain, V., Hubber, P., & Waldrip, B. (Eds.). (2013). *Constructing representations to learn in science*. Rotterdam: Sense Publishers.
Tytler, R., Prain, V., & Hubber, P. (2018). Representation construction as a core disciplinary literacy. In K.-S. Tang & K. Danielsson (Eds.), *Global developments in literacy research for science education* (pp. 301–317). Singapore: Springer.

Tytler, R., Prain, V., Aranda, G., Ferguson, J., & Gorur, R. (2020). Drawing to reason and learn in science. *Journal of Research in Science Teaching, 57*, 209–231. https://doi.org/10.1002/tea.21590.

Wickman, P.-O. (2006). *Aesthetic experience in science education: Learning and meaning-making as situated talk and action*. New Jersey: Lawrence Erlbaum Associates.

Wickman, P.-O. (2017). Back to the drawing board: Examining the philosophical foundations of educational research on aesthetics and emotions. In A. Bellocchi, C. Quigley, & K. Otrel-Cass (Eds.), *Exploring emotions, aesthetics and wellbeing in science education research*. Switzerland: Springer International Publishing.

Yaman, F. (2018). Pre-service science teachers' development and use of multiple levels of representation and written arguments in general chemistry laboratory courses. *Research in Science Education*, 1-32.