Cultural Studies of Science Education (2023) 18:1311–1341
https://doi.org/10.1007/s11422-023-10193-0

ORIGINAL PAPER

The role of teacher support in students' engagement with representational construction

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Received: 12 November 2020 / Accepted: 15 June 2023 / Published online: 1 November 2023

Abstract
In this article, we study the role of teacher support in a collaborative learning setting that involves students' constructions of visual representations in the environmental education context. Despite the consensus in the field of science education research that engagement with visual representations—such as diagrams, animations, and graphs—can support students' conceptual understanding, studies reveal that learning from engagement with visual representations can be challenging for students. Adopting a sociocultural approach, this study contributes to extant research by analytically scrutinizing the role of teacher support in learning activities that revolve around students' construction of visual representations. The empirical basis is a science project in which lower secondary school students drew and refined depictions of the effects of anthropogenic climate change. The analytical focus is on student–teacher interactions during group-based drawing activities in which students created representations of the carbon cycle and interacted with authorized representations. The analyses revealed how students found it challenging to compare, contrast, and integrate authorized representations and, additionally, to constructively use authorized representations in the process of designing their own representations. To support students in their efforts to construct scientific meaning, the teacher oriented the students' attention towards the salient features of representations, supported students in making sense of 'semiotic signs', and enabled them to link scientific concepts with detailed depictions. In addition to the different forms of support provided by the teacher, the analyses of the student–teacher interactions also reveal the teacher's use of specific 'talk moves' of elaboration and eliciting. The key implications include that teachers should select representations that are sufficiently different in terms of how concepts and phenomena are depicted, and that teachers should be prepared to support students in how to compare and contrast multiple representations. Further, strategies for supporting students' exploration of their own ideas and suggestions are essential in the dynamics between students' self-made representations and authorized representations.

Keywords Teacher support · Student-constructed representations · Student–teacher interaction · Collaborative learning · Sociocultural perspective

Lead editor: R. Gisewhite.

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Sammendrag
Denne artikkelen undersøker lærerens rolle i samarbeidsaktiviteter der elever lager visuelle representasjoner i naturfagundervisning om miljøspørsmål. Forskning på læring i naturfag om visuelle representasjoner som diagrammer, animasjoner og grafer har vist at slik ressurser utgjør viktig støtte for elevers utvikling av begrepsforståelse. Samtidig har en rekke studier vist at det er flere utfordringer knyttet til elevers læring med visuelle representasjoner. Med utgangspunkt i et sosiokulturelt og holistisk perspektiv, bidrar denne studien til eksisterende kunnskap ved å undersøke lærerens rolle i aktiviteter der elever skaper sine egne visuelle representasjoner. Det empiriske grunnlaget for studien er et naturfagprosjekt i en ungdomsskoleklasse der elevene arbeidet med å produsere og forbedre egne representasjoner om menneskeskapte klimaendringer. Det analytiske fokuset i studien er rettet mot elev-lærer-interaksjoner under gruppe-baserte tegneaktiviteter der elevene laget sine egne representasjoner av karbonkretsløpet. Analysene viser hvordan elevene strevde med å sammenligne, kontrastere og integrere autoriserte representasjoner, samt å kunne konstruktivt bruke autoriserte representasjoner i utformingen av egne representasjoner. For å støtte elevene i deres faglige meningsskaping, ledet læreren elevenes oppmerksomhet i retning av de fremtredende elementene i representasjonene, støttet elevene i å tolke 'semiotiske tegn' og i å skape sammenheng mellom faglige begreper og detaljer i representasjonene. Analysen av elev-lærer-interaksjonene viser også lærerens bruk av spesifikke strategier for utdyping og fremkalling av elevenes egne ideer i samtale med elevene. Sentrale implikasjoner inkluderer at lærere bør velge representasjoner som er tilstrekkelig forskjellige når det gjelder hvordan konsepter og fenomener beskrives, og at lærere bør være forberedt på å støtte elevene i hvordan de kan sammenligne og kontrastere flere representasjoner. Overordnet er konkrete grep for å støtte elevenes utforskning av egne ideer og forslag avgjørende i dynamikken mellom elevenes selvlagde representasjoner og autoriserte representasjoner.

The progress and exchange of scientific knowledge and ideas have always been dependent on scientific representations, such as texts, models, diagrams, graphs, animations, and simulations (Roth and McGinn 1998). Extensive digital and technological innovations in recent decades have led to the emergence of a variety of new visualization opportunities for presenting and engaging with complex scientific concepts. Today, encounters with visualizing scientific representations constitute central elements, both in our everyday and professional lives. Also in school science, visualizing representations have a long history as resources for introducing students to scientific concepts, processes, and ideas. In popular science and scientific articles, textbooks, news programmes, and Internet websites, (quasi) scientific explanations and arguments are commonly accompanied with visual representations. For instance in reports and articles on climate change, estimated effects of CO_2 emission are often depicted through visualizations of the melting of polar ice. Another example is the visualization of the spread of the coronavirus pandemic by graphical representations of exponential growth or flattening curves. Hence, being able to engage with and interpret various forms of scientific representations is not only crucial in the process of learning science in school settings but also for participating in scientific discourses in a societal and everyday context. Consequently, sustaining students' competency in interpreting, engaging with, and producing their own scientific representations is important for the development of their scientific literacy (Knain 2015).

Students' learning from scientific representations has been a central issue in science education research for decades (Disessa 2004). Research studies focusing on visualizing representations in the context of school science mainly fall into two research areas. The larger of the two encompasses studies focusing on students' engagement with 'canonical' representations (Lemke 1998), referring to representations that are 'authorized' as valid representations by scientific experts, researchers, or textbook authors and have been developed with the intention of making abstract scientific concepts more tangible. Such representations—either in paper-based or digital versions—are commonly found in school science settings, brought into the classroom by the teacher, textbooks, or the students. A second branch of studies, which aligns with the present study, includes studies focusing on students' engagement with student-constructed representations, that is, visual representations that students themselves create as part of classroom activities (Tytler, Prain, Hubber and Waldrip 2013).

Research in these two main areas has provided valuable insight into students' learning from engaging with authorized representations and from constructing and refining their own visual representations. In both areas, there appears to be a fair consensus that students need a considerable amount of support to engage productively with visual representations (Tippett 2016). However, while researchers have highlighted the role of the teacher in facilitating productive student engagement with both authorized (Furberg 2016) and student-constructed representations (Waldrip, Prain and Sellings 2013), only a few studies analytically scrutinize the support provided by teachers in settings in which students engage with representational construction. Further, while studies in both research areas have demonstrated the value of designing learning settings in which students engage with several types of representations when making sense of scientific concepts (Ainsworth, Tytler and Prain 2020), the literature on representational construction lacks studies that investigate the role of authorized representations as part of the representational ecology.

Departing from a sociocultural perspective (Wells 1999), an underlying premise in the current article is that students' conceptual sensemaking is closely linked with various forms of support provided by the teacher. This also implies the assumption that students' sensemaking in educational settings occurs in interactions among participants within the entire ecology of social and material resources that comprise the disciplinary and institutional practices of science education, including authorized representations. We argue that in order to understand the potential and challenges of visual representations as teaching and learning resources, we must analytically address the very process through which visual representations are employed by teachers and students in classroom activities as well as the meaning and functions that are realized interactionally as part of this process. The overall aim of the present study is twofold: to explore and provide insight into (1) the multifaceted task of supporting the development of students' conceptual understanding while engaging with representational construction and (2) how authorized and student-constructed representations emerge as conceptual sensemaking resources in student–teacher interactions.

The empirical setting for the present study is a science project on climate change, which involves a class of lower secondary school students and their teacher. This project involved instructional units designed to facilitate students' understanding of the greenhouse effect, ocean acidification, and the carbon cycle. Prior studies have demonstrated that students struggle to understand the carbon cycle on a global scale and as a system of key carbon-transforming processes (Zangori, Peel, Kinslow, Friedrichsen and Sadler 2017). The instructional design analysed here involved sequences of representational challenges that required collaborating students to create and refine their own drawings of the carbon cycle based on authorized representations. Employing the analytical procedures of interaction analysis (Jordan and Henderson 1995), we conducted detailed analyses of selected sequences of student–teacher interactions during group-based drawing activities in which students created representations of the carbon cycle. Directing analytical attention to student–teacher interactions during group-work activities revolving around visual representations enabled us to explore the support provided by the teacher in relation to typical issues and challenges encountered by students as well as how visual representations are employed by students and teachers in the context of student–teacher interactions. The following research questions guide our empirical analyses:

- What characterizes the support provided by the teacher in representation-oriented group-work settings?
- In what ways do authorized and student-constructed representations become sensemaking resources in student–teacher interactions?

Studies on students' engagement with visual representations in science learning

As the empirical setting in focus involves students' engagement with both authorized representations and construction of own representations, the following review focuses on findings from each of the two research domains. Each section focuses on findings from students' learning and those related to the role of teacher support.

Previous research on facilitation of students' engagement with authorized representations

Regarding research on authorized representations, most studies of students' engagement with authorized representations are designed as effect-studies that focus on how specific representation types, representation features, or combinations of representations impact students' conceptual learning or inquiry skills (Ainsworth 2008). Considering effect-studies that have explored students' engagement with diagrams, studies such as those conducted by Jennifer Cromley and colleagues (2013) and Peggy van Meter and colleagues (2017) have reported positive effects on students' conceptual understanding and diagram comprehension, in particular when the instructional design includes prompts that engage students in explaining or modifying authorized representations. With the growing prevalence of process-oriented studies of students' learning in science education, several authors have directed analytical attention towards the processes through which students engage with authorized representations in the course of instructional trajectories, demonstrating how authorized representations can serve as individual and social resources in collaborative learning settings. For example, in a study involving upper secondary school students' engagement with solar panel diagrams, Anniken Furberg and colleagues (2013) found that the diagrams became resources that enabled students to monitor and express their understanding and to explicate and explore elements in the solar panel function. Other process-oriented studies have demonstrated how authorized representations become deictic resources in students' collaborative dialogues, upon which additional modes of meaning making, such as gestures and bodily depictions, can contribute to the development of students' conceptual understandings. For example, Rolf Steier and colleagues (2019) investigated secondary school students' engagement with visual representations of flight paths in a physics unit on general relativity. Their analyses of student–student interactions during the unit showed that students' improvised representations served as crucial mediators in their collaborative efforts of making sense of the flight maps.

In addition to these promising findings reported in studies on authorized representations, researchers have also reported more challenging aspects, such as that students often struggle with identifying the relationship between representations depicting the same phenomena in different ways (van der Meij and de Jong 2006) as well as with identifying the relationship between the representations and their underlying scientific principles or corresponding real-world phenomena (Kozma 2003). Several studies have highlighted the role of the teacher in facilitating productive student interactions with authorized representations. Important support functions reported in process-oriented studies include directing the students' attention to relevant features of representations and distinguishing these from irrelevant features (Lindwall and Lymer 2008), supporting students in connecting authorized representations and underlying phenomena (Strømme and Furberg 2015), and engaging students in utilizing representational resources in their conceptual reasoning (Arnseth and Krange 2016). In their study of teacher support during students engagement with interpreting and contextualizing real-rime graphs from a laboratory experiment, Line Ingulfsen and colleagues (2018) demonstrated the significance of deploying both 1) an eliciting strategy in which the teacher elicits students' understanding of representational resources and real-world issues represented and 2) an elaboration strategy in which the teacher explicates challenging issues or provides information to support students' sensemaking process.

Previous research on facilitation of students' construction of representations

Studies focusing on settings where students construct their own representations are dominated by theory-informed intervention or design-based research studies aimed at enhancing students' development of conceptual understanding and representational proficiency. The impact of the intervention is usually measured by analysing students' self-constructed representations and their written explanations of scientific concepts, often in combination with interviews or various types of pre-and post-tests (e.g., Tippett 2016). Among the reported findings from these studies, one is that instructional designs comprising learning activities that systematically facilitate students' construction and re-construction of representations—such as drawings, graphs, and multimodal diagrams including text and visualizations—can support students' development of representational competence (Prain, Tytler and Peterson 2009), scientific reasoning skills (Waldrip, Prain and Sellings 2013), understanding of scientific concepts and phenomena (Zhang and Linn 2011), and scientific modelling skills (Schwarz and White 2005).

A second group of studies are explorative case studies that focus on how student-constructed representations become mediational means in classroom activities. For example, Margaret Brooks (2009) investigated primary school students' engagement in an inquiry-learning setting on light sources and light traps and found that student drawings served as a means for enabling the students to express, share, and elaborate their conceptual ideas to their peers and teacher. In another study focusing on middle school students' drawing processes related to topics such as energy, astronomy, and flower classifications, Russel Tytler and colleagues (2020) found that the student-constructed representations served two main functions. First, the act of drawing provided a material dimension in students' reasoning (drawing 'as' reasoning). Second, the drawings served as objects in students' reasoning processes that could be scrutinized, assessed, and revised (reasoning 'from' drawing).

Our review of studies on the facilitation of students' construction of representations reveals that there are few studies that analytically scrutinize the role of teacher support in such learning settings. The studies conducted by Noel Enyedy and Joshua Danish are important exceptions. In one study of primary school students' engagement with drawing maps of a wooden city, Enyedy (2005) explored teacher facilitation in whole-class sessions aimed at sharing and collaboratively reviewing students' drawings. Findings were that the teacher's efforts in clarifying and revoicing students' contributions served as significant means of building shared understandings of representational conventions. In another study that is of particular interest to the current study, Danish and Enyedy (2007) explored student–teacher interactions during group-work settings in a unit where primary school students created representations of pollination. A central finding in this study was that the teacher provided significant on-demand support, validating and elaborating students' ideas and eliciting students' prior knowledge regarding the represented scientific phenomena.

A review of previous studies reveals an apparent consensus in the literature that the potential value of both authorized and student-constructed representations depends on how they are used and integrated into the overall learning design. Moreover, there is consensus in acknowledging the importance of teacher support in facilitating productive interactions with social and material resources; several studies emphasize the significance of additional teacher support in guiding students' engagement with representations. However, the review also reveals that few studies have analytically scrutinized (a) *the challenges that students encounter* in learning activities where they construct their own representations and (b) the role of *teacher support*. Further, previous studies focusing on students' engagement with representations tend to have a *one-sided analytical focus* in that they focus on either authorized or self-constructed representations. This implies that only a few studies investigate the role of authorized representations as part of the representational ecology in settings where students construct their own representations. By adopting a holistic and sociocultural approach, the present study aims at providing deeper insights into students' learning processes and the role of teacher support in collaborative learning activities revolving around students' engagement with authorized and student-constructed science representations of the carbon cycle. To this end, we analyse student–teacher interactions that occur during two iterative drawing sessions.

In the following sections, we provide an account of our conceptualization of students' representational engagement from a sociocultural perspective and the methods that guide our analytical work.

Approaching students' representational engagement from a sociocultural perspective

From a sociocultural perspective, learning is conceptualized as a dynamic and dialogic process of meaning making between interlocutors (Linell 2009). Through their interactions in social practices, learners strive to interpret and make sense of situations, actions, materials, and concepts while making their own interpretations observable to other participants (Wertsch 1998). A central assumption in sociocultural perspectives is that all human interaction is mediated by cultural and semiotic tools (Vygotsky 1978). Language, particularly discourse, is considered the most important tool, providing a 'social mode of thinking' in social practices (Mercer 2004). In addition to discourse and other volatile modes of sensemaking, learning is contingent on material artefacts in which knowledge and social practices are inscribed (Furberg and Arnseth 2009). In the context of science education, visualizing representations play an important role as mediating artefacts in students' appropriation of scientific knowledge and practices (Roth and McGinn 1998). Whether authorized or student-constructed, these material representations can be acted upon and scrutinized as part of collaborative and goal-directed activities. However, the meanings and functions of representations and other semiotic tools are not inherent properties but arise in the context of their use (Wells 2008). As noted by Wolff-Michael Roth and Kenneth Tobin (1997), translating between different representations of one and the same phenomenon involves bridging an 'ontological gap', which requires experience with a particular representational practice. Consequently, the meaning potentials of visual representations and the relationship between visual representations and the corresponding phenomenon must be established, elaborated and made relevant to students in specific settings (Strømme and Furberg 2015).

From a sociocultural perspective, the teacher plays an important role in facilitating and guiding students' engagement with semiotic and cultural tools (Wells 1999). Lev Vygotsky's (1978) notion of the 'zone of proximal development' (ZPD) provides a conceptualization of the window in which support is required and is productive for students' learning processes. Following Gordon Wells (1999), we approach the ZPD as 'created in interaction between the students and the co-participants in an activity, including the available tools and the selected practices' (p. 318). From this perspective, the teacher's role in facilitating students' learning processes involves providing instructional support and orchestrating available resources to support students' sensemaking in relation to the issues and challenges that arise in the course of instructional trajectories.

In sum, a sociocultural perspective provides a lens through which to approach a teacher's work in supporting students' sensemaking with representations as a dialogic and situated process, constituted in the interaction among participants, purposes, and available resources. From this perspective, understanding the function of authorized and student-constructed representations implies scrutinizing how they are invoked, oriented towards, and adopted by participants in specific settings.

Research design

Empirical setting, participants, and instructional design

The science project in focus here was conducted as part of the larger intervention study entitled *Representation and Participation in School Science* (REDE). Based on a set of design principles (Collins, Joseph and Bielaczyc 2004), the researchers in the project—including the authors of this paper—collaborated with science teachers in three secondary schools to design instructional units related to the overall topic of climate change. The design principles guiding the development of the instructional units were informed by an adapted version of the representation construction approach (RCA) framework, developed by Russel Tytler and colleagues (2013). The RCA framework endorses instructional designs that facilitate students' engagement with both expert and student-constructed scientific representations; moreover, the framework promotes iterative learning activities wherein students generate, negotiate, and refine self-constructed representations in guided inquiry processes. In the planning phase, the teachers and researchers contributed to the overall instructional design. The teachers were responsible for selecting representations and designing specific learning activities. The teachers were not given any specific instructions regarding their roles during the project and were entirely responsible for implementing the instructional design without interference from the observing researchers. In keeping with the sociocultural approach to design-based research (Krange and Ludvigsen 2009), our aim was to observe and scrutinize interactions that unfolded in the specific classroom setting in which the instructional design was implemented. This implies that our analyses were guided by the concerns and orientations of the teachers and students who participated in the observed activities rather than the intentions and principles underpinning the instructional design.

The empirical data for this study were produced during a science project on climate change; the project was implemented in eight school lessons over the course of three weeks in October 2016. As mentioned earlier, the participants included a science teacher and his class of 25 lower secondary school students, aged 14–15 years. The science project comprised three instructional units: carbon cycle, ocean acidification, and greenhouse effect units. Here, we focused on the carbon cycle unit. The carbon cycle unit spanned over two lessons and included the classroom activities displayed in Table 1.

In the first lesson, the teacher briefly explained the carbon cycle, which was accompanied by authorized visual representations. The authorized visual representations are presented in Results section (Figs. 2 and 3). In Drawing Session 1, students worked in pairs or trios to compare and contrast the authorized representations before drawing their own version using paper and pen. During this activity, the teacher circulated among the groups and concluded the session by appointing a few student groups to present their drawings to the class. In Drawing Session 2, students were instructed to revise their first drawing in the light of a set of scientific concepts presented in a handout provided by the teacher. Drawing Session 2 concluded with a short presentation session in which selected student groups shared their drawings (see examples of students' drawings in Appendix 2). In the final task, the students uploaded their representations in their digital workbooks.

Data and analytical procedures

The main data comprised 75 min of transcribed video recordings of all student–teacher interactions during the carbon cycle unit. The teacher was followed around with a handheld camera, documenting all student–teacher interactions during whole-class and groupwork activities. Ethnographically inspired observation notes from classroom observations, teacher-produced materials, students' final drawings, and interview transcripts provided contextual data for the analyses of interactions (Derry, Pea, Barron, Engle, Erickson, Goldman and Sherin 2010). In the current study, we conducted detailed analyses of student–teacher interactions that occurred while the teacher was making rounds in the classroom during the drawing sessions. The student–teacher interactions during these group activities were initiated either by the students summoning the teacher for guidance or by the teacher checking on the students' progress. Most of the teacher's encounters with the student groups took the form of a dialogue that involved questions and concerns that the students had come across while working on the tasks. By selecting and analysing student–teacher interaction sequences that display typical student challenges during their

Table 1 Overview of activities in the carbon cycle unit

Lesson	Activity	Organization
1	*Introduction*	Whole class
	· Presentation by the teacher on the carbon cycle and authorized representations	
	· Introduction to drawing assignments	
	Drawing session 1	Dyads/trios
	· Students compare and contrast authorized representations and make their own drawings of the carbon cycle	
	Student presentations	Whole class
	· Nominated students' drawings are presented and reviewed by the teacher and students	
2	*Drawing session 2*	Dyads/trios
	· Students make an improved version of their drawings by including selected scientific concepts	
	Student presentations	Whole class
	· Nominated students present and explain their drawings	
	Consolidation and closing	Whole class/groups
	· Students upload their drawings to their digital workbooks	
	· Students sum up the activity in groups and whole class	

process of representing the carbon cycle, we examine how these challenges manifest and are addressed in student–teacher interactions across groups. Moreover, a focus on student–teacher interactions also enables us to scrutinize typical features of *how* authorized and student-constructed representations become mediational means in such interactions.

Thirty-six sequences of student–teacher interactions took place during the drawing activities. Of these, 20 instances took place during Drawing Session 1, while 16 took place during Drawing Session 2. The duration of the sequences of student–teacher interactions was typically between one and two minutes. We conducted the interaction analysis in two steps. The initial analysis involved an examination of all 36 student–teacher interaction sequences, which enabled us to identify general patterns and the challenges most frequently addressed by the teacher and students in each drawing session. In the second step, we selected five sequences for detailed interaction analysis to explore the issues and challenges encountered and to understand how the participants addressed these. Three of these sequences of student–teacher interactions were selected from Drawing Session 1 and two sequences from Drawing Session 2 (see Fig. 1). The detailed analysis was then conducted on transcribed excerpts of interaction from each of the five sequences, which enabled us to display the most essential aspects of each interaction sequence.

Three criteria guided the selection of the analysed sequences of student–teacher interactions. In accordance with our research questions, the selected sequences involved student–teacher interactions in which the participants' attention was directed towards the authorized and student-constructed representations. A second criterion concerned typicality, which implies that the issues and challenges addressed in the selected sequence represent the most typical issues addressed across all the student groups. The third criterion is concerned with interactional transparency in that the interlocutors' verbal and physical contributions are characterized by a certain degree of explicitness and enable a detailed analysis of their interaction (Linell 2009). Based on these criteria, the selected sequences were found to display typical patterns of student–teacher interactions during the drawing sessions.

The analytical procedure that was employed is interaction analysis, which involves sequential analysis of the interaction among interlocutors, including the artefacts in focus (i.e. representations or other instructional material) (Jordan and Henderson 1995). A sequential analysis implies that each utterance is considered in relation to the previous utterance in the ongoing interaction. Consequently, the focus is not on the meaning of single utterances but on how meaning is created through the exchange of utterances. To make sense of how the students and teacher addressed and used authorized and student-constructed representations, our analysis involved examining not only discourse but also non-verbal modes and the conjunction of modes in interaction. In addition, we used

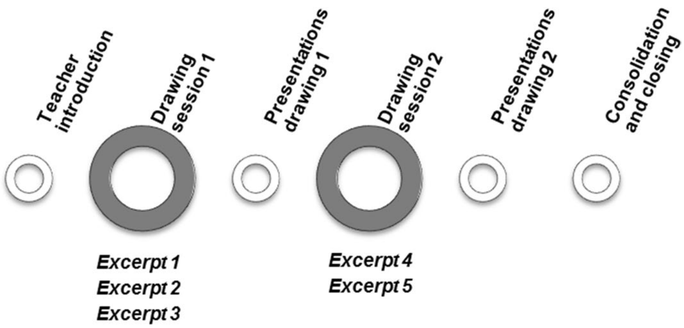


Fig. 1 Overview of learning activities in the sequences of interaction selected for detailed analysis

ethnographic information pertaining to the institutional setting as a background resource to understand what is going on. This procedural guideline for analysis ensures that it is the participants' concerns and activities that are examined rather than the researchers' intentions and predefined interests. The video recordings were transcribed according to an adaptation of Jeffersonian transcription notations (Jefferson 1984) (Appendix 1 provides the transcript notations). Further, we translated the Norwegian conversations into English and used pseudonyms for the participants in the excerpts.

Results

Here, we present and analyse five sequences of student–teacher interaction selected from the two iterative drawing sessions. Sequences 1, 2, and 3 took place during Drawing Session 1; Sequences 4 and 5 took place during Drawing Session 2. Before the analyses, we provide a brief description of the two authorized representations introduced by the teacher in the introductory lecture on the carbon cycle just before Drawing Session 1.

Drawing session 1: producing the first drawing

Two authorized representations of the carbon cycle served as material support during the drawing sessions. Both representations (see Figs. 2 and 3) fall within the broad category of science diagrams (Tippett 2016). The diagrams were presented by the teacher in a short introductory lecture about the carbon cycle, immediately before the teacher presented the first drawing assignment to the students. Diagram 1 (Fig. 2) includes pictures and written elements representing central examples of spheres, organisms, and human-made installations that are part of the carbon cycle.

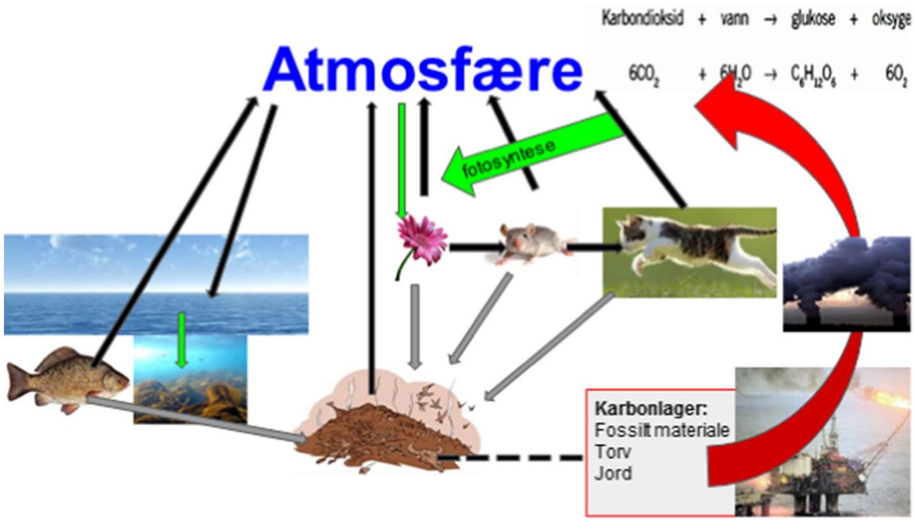


Fig. 2 Diagram 1. Translation of terms: Atmosfære: atmosphere; Karbondioksid: carbon dioxide; Vann: water; Glukose: glucose; Oksygen: oxygen; Karbonlager: carbon deposit; Fossilt materiale: fossil materials; Torv: peat; Jord: soil

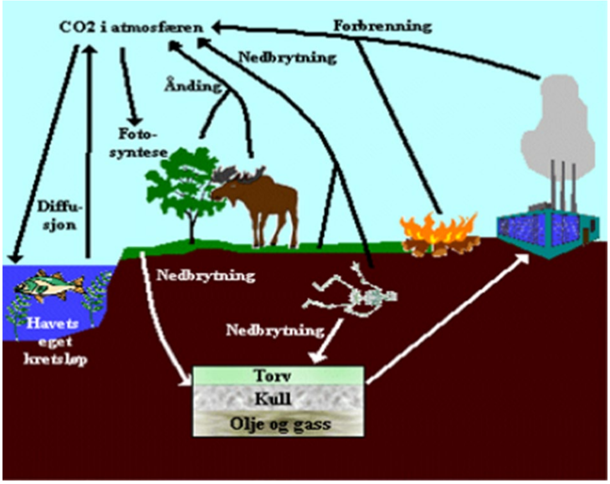


Fig. 3 Diagram 2. Translation of terms: CO_2 i atmosfæren: CO_2 in the atmosphere; Ånding: respiration; Forbrenning: burning/combustion; Havets eget kretsløp: carbon cycle in the ocean; Nedbryting: decomposition; Torv: peat; Kull: coal; Olje og gass: oil and gas

In Diagram 1, the elements that differ in terms of size, colour, and shape are connected by arrows. The arrows represent the scientific processes that relate all the elements in the diagram (photosynthesis, cell respiration, decomposition, combustion, diffusion). The colours of the arrows indicate different types of carbon exchanges, and the differences in arrow size and shape mark certain processes as more salient than others. In the teacher's presentation, Diagram 1 was presented as an animated PowerPoint diagram. In this version, all elements other than the arrows were displayed from the initial layer in the PowerPoint slide, while the arrows (with labels) were added in a stepwise manner.

Diagram 2 (Fig. 3) is a labelled diagram representing scientific processes similar to those displayed in Diagram 1. In this diagram, spheres, organisms, and objects are depicted iconically, with the sky, ground, and ocean forming the layout of the diagram. In addition to being displayed in a different mode, the diagram provides different examples of the referent categories as compared to those in Diagram 1. For example, the elements used to represent combustion are a building resembling a factory and a bonfire instead of an oil platform. Another notable difference between the diagrams is that the arrows in Diagram 2 are given written labels instead of colour coding to distinguish between types of scientific processes. Finally, as none of the arrows is foregrounded by size or colour, no particular scientific process is made more salient as compared to the other.

After the lecture, the teacher instructed the students to compare the two authorized representations of the carbon cycle (Diagrams 1 and 2) and then draw their own version. The teacher emphasized the importance of studying, comparing, and discussing the authorized representations and use these as resources for creating the best version of the carbon cycle. The students received printed handouts of the authorized representations and a list of the relevant scientific concepts, which they were encouraged to use when thinking about what to depict in their drawing. Below, we analyse three excerpts that illustrate the challenges encountered by students in creating their first drawing of the carbon cycle in Drawing Session 1.

Sequence 1: Making sense of the task. At the onset of the activity, the teacher went from group to group, dividing students into pairs and trios and handing out materials. It was evident that *comparing the two authorized representations* was not straightforward for the students, and most students needed additional support from the teacher in attending to the similarities and differences between Diagram 1 and Diagram 2. Another challenge experienced by several groups was regarding to *how to utilize the authorized representations as resources* in their own drawings. Excerpt 1 illustrates how these challenges are manifested and addressed by the students and teacher. In the interaction below, the teacher has just been summoned by Anna, Lisa, and Robert.

Excerpt 1

1 Anna: We didn't quite get it

2 Teacher: ((*leans over the table*))You are to make a drawing. ((*reaches for the handouts with the two diagrams*)) These are two models of the carbon cycle, ((*points at Diagram 2*)) and they describe it differently (.) But still it concerns how the carbon moves in different [cycles=

3 Anna: [Ah:: yes:: That's the natural, ((*points at the tree in Diagram 2*)) and that's the unnatural? ((*points at the text box representing the carbon deposit in Diagram 2; see picture a*))

4 Teacher: ((*moves his finger over the right side of Diagram 2; see picture b*)) Here we see the unnatural part (.) right? Where we use for instance oil and gas. ((*moves his finger from the carbon deposit to the factory in Diagram 2 a couple of times, see picture c, before removing his hand from the representation*)) That's the unnatural (.) You're supposed to make your own model of the carbon cycle, ((*looks at Robert*)) and you can use these images if you like, ((*points at Diagram 2*)) and make your own image

5 Robert: Shall we draw that one? ((*points at Diagram 2*))

6 Teacher: Yes, you can draw= You can select things from here if you like ((*points at Diagram 2*))

7 Robert: From the drawing? Shall we draw that? ((*points at Diagram 2*))

8 Teacher: I want you to make some choices right? But you can use that one as an inspiration ((*points at Diagram 2*))

9 Robert: Okay

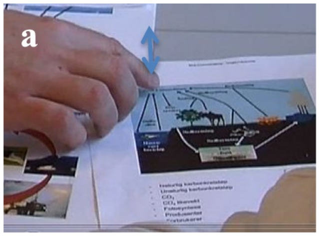
10 Teacher: And the aim is that you make a model that in a best possible way shows how the carbon moves in the cycle

Overall, Excerpt 1 demonstrates how task procedural matters and the role of the authorized representations were central issues in the student–teacher interactions in the initial phase of Drawing Session 1. Most importantly, the excerpt displays that the teacher provided support by invoking and interweaving available resources. Firstly, this support was provided by *reiterating instructions and framings* provided during the lesson introduction. In the opening of Excerpt 1 (lines 2, 4, and 10), the teacher rephrased the aim of the task along with his use of the metaphor of carbon trajectories when reiterating what must be displayed in the students' drawing. Secondly, the teacher provided support in *making connections between the two authorized representations* by explicating that both diagrams display the carbon cycle differently. As evident from Anna's response (line 3), this explanation served as a resource for the students to infer how aspects foregrounded in Diagram 1 are also present in Diagram 2. Thirdly, the teacher provided support in *utilizing student contributions* to align perspectives and develop shared understanding. For example, the teacher elaborated (line 4) on Anna's proposed distinction between the 'natural' and 'unnatural' (line 3), which was rather imprecisely construed, given that she included the carbon deposit as part of the unnatural carbon cycle. Examining the teacher's response (line 4), he first identified the unnatural part of the cycle before attending to the carbon deposit and explaining how it can also become a part of the unnatural cycle (picture c). Thus, he did not challenge Anna's imprecise construct of the unnatural carbon cycle but expanded her account by connecting the unnatural carbon cycle with associated elements in Diagram 2. A final and related point regarding teacher support relates to the teacher's use of *deictic movements* to direct the students' attention towards specific elements in the representation and merge verbal accounts with depicted elements. For example, he pointed and outlined to connect the term 'unnatural' and the elements in the right portion of Diagram 2 (line 4, pictures b and c).

Sequence 2: Using authorized representations as resources in conceptual sensemaking. As the students began creating their own versions of the carbon cycle, several students struggled to *utilize the authorized representations as resources in their sensemaking*. The authorized representations and the list of central concepts were the only material support in the drawing activity; thus, the students' prior knowledge of phenomena related to the carbon cycle became important resources when drawing. As demonstrated in the analysis below, the teacher played a crucial role in facilitating students' use of their prior knowledge and mediating between material and social resources to support students' understanding of what to draw and how to draw it. In Excerpt 2, students Haley and Steven wrote 'CO_2 in the atmosphere' on the upper edge of their drawing. In response, the teacher prompted the students to account for their choice of starting at this place in the cycle and their inclusion of 'CO_2' in the title. In replying to the teacher, Haley shifts attention to the authorized representations.

Excerpt 2

1 Haley: But I don't understand the rest



2 Teacher: Right but how=

3 Haley: I don't know what all that means ((*points at the concept list under Diagram 2*))

4 Teacher: But if you think about where the CO_2 in the atmosphere ((*Tapping at 'CO_2' in Diagram 2;* see picture a)) Where does it move? ((*looks from Haley to Steven*))

5 Haley: Everywhere?

6 Teacher: Yes (.) For instance to↑ (2)

7 Haley: ((*looks at Steven*)) Help me out here (2)

8 Teacher: What's photosynthesis? ((*looking from Steven to Haley*))

9 Steven: What?

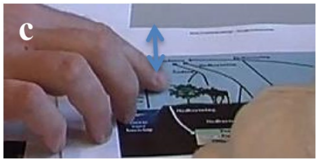
10 Teacher: What does photosynthesis do?

11 Haley: [It= it spins

12 Steven: [U::hm It makes plants grow

13 Teacher: ((*looks at Steven*)) Yes [or it=

14 Haley: [and makes animals die ((*laughs*))



15 Teacher: It= the photosynthesis= ((*taps at an arrow in Diagram 2;* see picture c)) It gets CO_2 and water in combination with sun energy and produces something called glucose

16 Haley: But glucose is in the body?

17 Teacher: Yes, and it does end up in our bodies eventually ((*nods*))

18 Haley: Because we eat (.) plants and animals↑

19 Teacher: That's right! Now you've started. ((*points at "Photosynthesis" in Diagram 2*)) So then I would've drawn an arrow from CO_2 in the atmosphere down towards a plant, for instance, ((*points along photosynthesis arrow in Diagram 2;* see picture d)) where it turns CO_2 into glucose

Excerpt 2 indicates several important aspects of teacher support. Firstly, it illustrates the support that the teacher provided in *guiding the focus of students' efforts* when students expressed difficulties making sense of the resources in the handouts. The teacher refrained from attending to the concept list when prompted by Haley (line 2) and directed the students' attention to their drawing while eliciting the students' understanding of the carbon transition from the atmosphere to producers (lines 1–4). Secondly, the teacher adjusted his strategy by *providing conceptual cues* when struggling to prompt adequate accounts using the metaphor of the carbon trajectory. In line 8, the teacher invoked the conceptual framing of photosynthesis to elicit student contributions after his unsuccessful attempts to prompt an adequate response in lines 4–7. This shift enabled the students to mobilize their existing knowledge, finally establishing the relevant connections. Thirdly, the teacher provided support by suggesting *how specific conceptual elements can be visualized* in the students' drawing. Specifically, he suggested that the transition between CO_2 in the atmosphere and the tree could be illustrated by drawing an arrow connecting these two elements (line 19).

Sequence 3: Using authorized representations as resources in drawing. As the students' first drawings developed, it became evident that they put a lot of effort into *personalizing their drawings*, rather than merely copying elements of the authorized representations. In particular, several students substituted specific elements of the authorized representations—such as drawing a sheep instead of a mouse (cf. Diagram 1) or an owl instead of a cat, as illustrated in Excerpt 3. Other students added elements that were not depicted in the authorized representations—such as the sun, a boat in the ocean, or a car emitting exhaust gas. These adaptions can be considered an uptake of the teacher's instructions on making choices regarding how and what to represent in order to make the best possible drawing. However, for certain students, putting extra effort into particular details of the drawings represented a potential distraction. The next excerpt demonstrates how the teacher balanced support in fostering the students to personalize the drawings and enabling students to progress in their work process. In Excerpt 3, the teacher approaches Thomas and Marcus and studies their drawing, while Marcus is drawing an owl.

Excerpt 3

1 Teacher: You draw nicely

2 Marcus: What kind of ears do owls have?

3 Teacher: U::hm (.) But listen= ((*points at the owl*))

4 Thomas: ((*Points at the owl*)) You don't have to draw the ears

5 Marcus: No?

6 Teacher: I understand that it's an owl. ((*points at the owl*)) It looks really good (2) and what will be the next step?

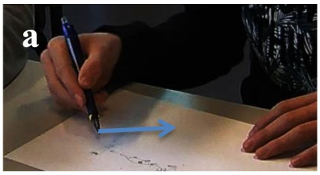
7 Marcus: Down to the ground ((*shows with the pen as making a line from the owl to the lower part of the paper;* see picture a)) and the consumers

8 Teacher: Uh:m yes (.) The decomposers.

9 Thomas: And you must draw better than that ((*points at the decomposers depicted in Diagram 1;* see picture b))

10 Marcus: Yes not only landfill (3)

11 Teacher: ((*Nods and leaves*))



Excerpt 3 illustrates several important aspects. Firstly, it demonstrates how *authorized and student-generated representations* were used interchangeably by students at this point in the drawing activity. Students engaged with specific elements in their own drawing (lines 2, 4, and 7) and elements in the authorized representations (line 9); they utilized both their own representation and Diagram 1 when accounting for elements not yet displayed in their drawing (lines 7 and 9). Secondly, the excerpt also demonstrates *the role of students' use of deictic movements* when creating verbal accounts. In lines 7 and 9, the students' accounts of elements not yet drawn were mediated by their outlining (picture a) and pointing (picture b) to convey the intended next move in their drawing. Thirdly, the excerpt demonstrates how the teacher provided support in *guiding students' attention towards salient aspects of drawing*. This is evident in his efforts to direct students' attention away from less significant aspects of drawing, like getting the details of the owl right. The teacher provided this support partially by providing positive feedback on the elements and partially by re-directing students' attention towards features not yet displayed (lines 3 and 6) by prompting student accounts of the next stage in their drawing.

In summary, the analyses of the three excerpts from Drawing Session 1 reveal that students struggled to make sense of the assigned task and the role of the authorized representations as drawing resources. The students required additional teacher support in making sense of the authorized representations as two different representations of the same phenomena to effectively use them as resources for their own representational work. Further, the teacher provided additional support in eliciting students' existing knowledge and guiding their efforts towards productive engagement with the authorized representations.

At the end of Drawing Session 1, the students photographed their completed drawings and uploaded the picture to their Padlet workbooks. Thereafter, the teacher nominated three student dyads to present their drawings to the class.

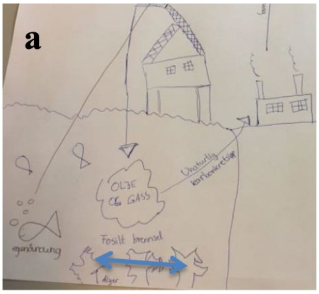
Drawing session 2: revising the first drawing in the light of scientific concepts

In Drawing Session 2, students were first instructed to draw an improved version of their carbon cycle representation and include concepts from the list of 11 scientific concepts in the handouts. The teacher emphasized that students must attempt to display as many concepts as possible in their drawings. He also encouraged students to utilize ideas from other students' representations when improving their drawings. Most student dyads made several changes in their second drawings. A few students began by making smaller changes (adding colours and written labels), while other groups made more extensive changes (adding elements and adjusting the structure and layout of their drawings). The classroom observations and initial analysis of the student–teacher interaction during the second round revealed that student-initiated issues largely comprised student requests for explanations of specific scientific concepts in the concept list. Apart from this, teacher support during this round of representational work oriented towards engaging students in conceptually oriented talk. Below, we analyse two excerpts illustrating how the student representations became mediational means in these conceptually oriented student–teacher dialogues.

Sequence 4: Accounting for the drawings. In his feedback to the dyads, the teacher commended the students' for making changes to personalize the drawings. Further, he also provided support by *holding the students accountable for their drawings* by indicating missing elements and prompting the students to account for the elements they had already included. In Excerpt 4, he checks in on Elizabeth and Andrew and commends them for adding various elements in their drawing. Then, he turns his attention towards the section in the lower left corner of their drawing (see picture a in Excerpt 4). Spotting that the three algae depicted at the bottom of the ocean are not connected to other elements, he requests an explanation.

Excerpt 4

1 Teacher: What about these algae then? ((*points at the algae on the drawing;* see picture a)) How do they become a part of the carbon cycle?



2 Eliza: U::hm

3 Andrew: Because u::hm the carbon goes down in the ocean and the algae take up the carbon. ((*pointing towards drawing*)) And the fish eats algae (.) And then when the fish dies= (.) no

4 Teacher: Yes

5 Andrew: Or does it have something to do with respiration? (2)

6 Teacher: Well it's got something to do with= These are green plants as well ((*points at the algae*))

7 Andrew: Yes

8 Eliza: ((*nods*))

9 Teacher: And they= Just like the produces here, ((*points at the flower in the drawing,* see picture b, *before pointing at the algae*)) the algae will also do photosynthesis

10 Andrew: Right

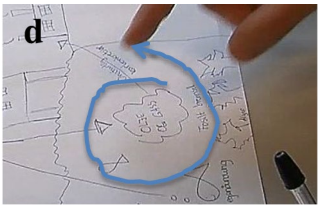
11 Teacher: But where do they get their CO$_2$ from? ((*moves his index finger in a circle around the algae*))

12 Andrew: Fro:::m fish?

13 Teacher: Fro::m ((*taps his finger on an empty space in "the ocean";* see picture c))

14 Andrew: The unnatural= or:: no

15 Teacher: What surroundings do they live in? ((*makes circular movements over the area depicting the ocean;* see picture d))



16 Andrew: The ocean

17 Teacher: Yes (.) So when the ocean takes up CO$_2$, then there is CO$_2$ in the ocean

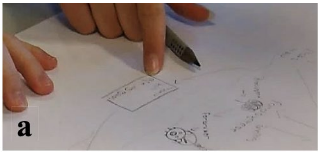
18 Andrew: Right

Excerpt 4 illustrates several important aspects of how the students' drawing became a mediational means in the conceptually oriented dialogue between the students and teacher. Firstly, the drawing served as an important resource for the teacher when *eliciting students' understandings* regarding the relationship between the depicted elements and the carbon cycle as a scientific process. At the beginning of the excerpt, the teacher utilized an 'unconnected' element in the drawing (the algae) to prompt student accounts of the element's relation to the carbon cycle as a whole. Another example is in lines 11–15, where the teacher invoked the depicted elements in the drawing as visual support when probing for an adequate response. Secondly, the excerpt also illustrates that the drawing served as *visual support in students' account making*, as evident in Andrew's attempt to elaborate on the algae's connections to the carbon cycle in lines 3–5, where he successfully explained the CO_2 exchanges prior to the algae. However, just as he was about to explain the relationship between the algae and fish, he hesitated and cut himself short, which might suggest that the lack of visual support (e.g. lines or arrows) became critical in his line of reasoning. Thirdly, the excerpt also illustrates the *difference in teacher and student orientations*. When utilizing the drawing as support for conceptual reasoning (from line 5 onwards), the teacher did not attend to Andrew's concern regarding the cell respiration. Instead, he returned to the CO_2 exchanges prior to carbon entering the algae. While the teacher oriented towards the exchanges between the ocean and algae, Andrew's orientation remained directed at the CO_2 exchanges between the algae and fish (line 12). Interestingly, although they aligned their perspectives by the end of the sequence, their exchanges regarding the relationship between CO_2 in the ocean and algae did not result in any concrete changes in the students' drawing.

Sequence 5: Aligning drawing features and scientific concepts. The endeavour to apply scientific concepts in their drawings challenged the students, as this process involved not only sensemaking of the various concepts but also decision-making regarding which of the 11 scientific concepts to include and ascertaining how the selected elements could be connected and integrated in the revised drawings. Certain concepts, like photosynthesis, could easily be integrated by labelling the arrow depicting CO_2 transmissions from the atmosphere to the producers, which all students included in their drawings. However, other scientific concepts required an *alignment of the meaning of the depicted elements and the scientific concepts*, which numerous students found challenging. Excerpt 5 provides an example of such an alignment process. In this sequence, Robert, Anna, and Lisa are occupied with labelling the elements depicted in their drawing. Anna suggests that they must indicate which part of their drawing displays the natural carbon cycle and which depicts the unnatural carbon cycle, both of which are on the concept list. However, such a conceptual distinction requires a specification of the meaning of each depicted element, which proves challenging.

Excerpt 5

1 Anna: But is that natural? ((*points at the lower part of the drawing*)) Those? ((*points at the text box illustrating the carbon deposit;* see picture a))

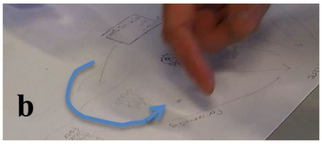


2 Teacher: They are what we call stored carbon

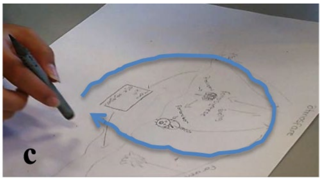
3 Anna Yes, but they are like= It happened naturally [that they

4 Robert: [Yes it happened naturally

5 Teacher: It happens naturally (.) But when we take= when we release it in the atmosphere((*points at 'Atmosphere' in the students' drawing*)) and make it part of the natural cycle, we say that this ((*points along the arrows in the right side of the drawing;* see picture b)) is the unnatural cycle

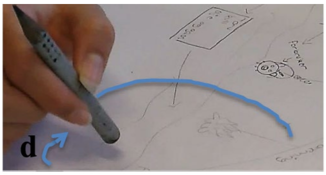


6 Anna: But is tha::t ((*making circular movements with the backside of her pen in the centre of the drawing, including the carbon deposit;* see picture c)) the natural (.) And tha::t ((*making circular movements with the backside of her pen in the centre of the drawing, including the carbon deposit;* see picture d)) the unnatural?



7 Teacher: Yes

8 Robert: Should we just make a circle around it then? ((*making circular movements with his index finger in the centre of the drawing just like Anna's circle in picture c*)) The natural



9 Teacher: Mark it in a manner that makes it distinct

10 Robert: But a fire can start (.) naturally? ((*points at the bonfire depicted in the drawing, which was included in the unnatural circle;* see picture d)) (3)

11 Anna: It's the factory that is unnatural

12 Robert: Yes

13 Lisa: Yes the factory is unnatural

14 Teacher: Yes that is unnatural

15 Lisa: But a bonfire is natural in a sense isn't it?

16 Robert: Not a bonfire

17 Anna: Humans make bonfires

18 Teacher: ((*Nods and moves on*))

Excerpt 5 displays several interesting aspects of the collaborative and multimodal process of developing conceptual distinctions in students' drawings. Firstly, it demonstrates how students *negotiate meanings of the elements displayed in their drawing* by playing off each other's and the teacher's accounts. For example, from line 10 onwards, Robert challenged the proposed distinction made by Anna (line 6) that the bonfire element is part of the unnatural cycle (see picture d). Robert's assertion that a fire can occur naturally was followed by a detailed mapping of both the bonfire and other elements in the unnatural category. This portion of the interaction also illustrates a second point—*the significance of the interplay between deictic movements and verbal accounts* when aligning meanings of depicted elements and conceptual terms. Lines 6 and 8 (see pictures c and d) illustrate this, where the circled outlining around specific elements provided a visual backdrop for the verbal accounts created by the students upon which Robert questioned the meaning of the bonfire. Thirdly, the excerpt demonstrates how the students developed and utilized *criteria for conceptual categorization* based on the contributions made by the teacher and students to the dialogue. In the first part of the excerpt, the students and teacher established the notion of 'naturally occurring' as the decisive criterion that placed the carbon deposit in the natural category (lines 3, 5, and 10). Later, the students utilized the same criterion when categorizing the bonfire element as unnatural (lines 15 and 17). A final aspect concerns *the role of the teacher in the dialogue* in the subsequent phases of the drawing activities. At the end of Drawing Session 2, most students worked more independently, fuelling their own inquiry and making representational inferences based on the points made in the dialogue. As illustrated in Excerpt 5, teacher support was mainly provided by confirming and elaborating on student accounts to verify and consolidate students' interpretations (lines 2, 5, 7, 9, and 14).

In summary, the analyses of Drawing Session 2 reveal that students' own representations served different functions in student–teacher interactions. For the teacher, it provided entry points to engage students in conceptually oriented talk, in terms of both displaying elements to prompt students and enabling the teacher to target connections between missing elements in the drawings. For the students, the drawings provided important visual support in creating verbal accounts and negotiating the meaning potential of their drawing elements in relation to the concepts and terms used in dialogue.

Towards the end of Drawing Session 2, the teacher again nominated student dyads to present their drawings in a short whole-class session. Shortly thereafter, students completed and uploaded a photocopy of their final drawings into their digital workbooks.

Discussion

Learning to interpret and construct representations that are appropriate for science is a fundamental aim of school science. Representations are integral to the epistemic practices of sensemaking and knowledge construction (Knain, Fredlund and Furberg 2021). These epistemic practices can be re-contextualized in school science, thereby creating an opening for students to experience representations as resources for conceptual sensemaking (Linell 2009). Previous studies have demonstrated how both authorized and student-constructed representations can constitute sensemaking resources in students' collaborative work (Steier, Kersting and Silseth 2019); moreover, in the context of teacher interventions, these representations can serve as shared resources in conceptually oriented dialogues (Ingulfsen, Furberg and Strømme 2018). For example, studies reveal that students' engagement with authorized visual representations can contribute to making abstract scientific concepts more tangible for students and provide individual and social resources in collaborative sensemaking (Furberg, Kluge and Ludvigsen 2013). With regard to student-constructed representations, studies have reported that students' drawings can become productive resources as they display the emerging conceptual understanding of students, which can be shared, challenged, and elaborated upon in the context of group work (Tytler, Prain, Aranda, Ferguson and Gorur 2020) and teacher-led discussions (Enyedy 2005).

However, along with the promising findings in existing research, certain studies also report challenging aspects. For example, students often struggle with connecting authorized representations that depict the same phenomena; their attention is often oriented towards the surface features of representations while neglecting the underlying principles and phenomena that are represented (Ainsworth 2006). In line with previous research, the present study displays a few challenging aspects of students' encounters with authorized representations in the process of constructing their own representations. For example, the analyses reveal that the students found it challenging to compare and contrast two different authorized representations of the carbon cycle (Excerpt 1). They also found it challenging to integrate the authorized representations in their sensemaking of the carbon cycle process (Excerpt 2) and to construct their own representations based on features and elements from both authorized representations. Finally, the students also grappled with aligning their accounts of specific features in their drawings and the underlying scientific principles that the features represented (Excerpts 4 and 5). These student challenges signify that despite a carefully designed teaching unit that included support resources in the form of teacher lectures on the carbon cycle, successive drawing activities, clear task descriptions, multiple authorized representations, and peer collaboration, students required additional support to realize the potential of their representational work.

With the students' representational and conceptual challenges as a backdrop, we now turn to the main issues of this article—the characteristics of the support provided by a teacher in settings in which students engage with representational work and how authorized and student-constructed representations become sensemaking resources in student–teacher interactions. In the following sections, we present and discuss what we consider our main empirical findings in relation to our research questions and findings from previous studies, and then present some possible implications for instruction.

The multifaceted ways of supporting students' conceptual sensemaking in representational work

With regard to the teacher's role, our findings coincide with previous research that emphasizes the significant role of the teacher and instructional design that facilitates productive interactions with visual representations and in guiding students' reasoning with representational resources (Enyedy 2005). The microanalyses of the student–teacher interactions in the current study enable us to distinguish between different types of teacher support and how the authorized and student-constructed representations emerged as sensemaking resources.

Task-oriented support. In line with previous studies on students' engagement in groupwork settings, we find that the teacher provided crucial support in the form of task-oriented support. This type of support was mainly provided during Drawing Session 1 and is evident in the teacher's efforts to reiterate instructions and elaborate on the role of the authorized representations in the assignment (Excerpt 1), thereby helping students to frame their activities into representation practices that align with science. Task-oriented support was important to guide students' explorations and create a dynamic between authorized representations and students' own verbal and visual sensemaking. Part of the dynamics occurred when interacting with single representations (e.g. when connecting verbal concepts and visual features by being challenged to explain items, being challenged to depict a verbal concept, or to verbally elaborate an item in an authorized representation). However, an important part of the dynamics was sensemaking across representations (compare and contrast authorized and/or self-created representations or challenging students to account for variation among representations).

Orienting students' attention towards salient features in representations. With regard to the students' sensemaking of representations, another type of support provided by the teacher was in the form of orienting the students' awareness towards salient features in representations. An example of this is in Excerpt 1, in which the teacher drew the students' attention towards the depictions of the unnatural carbon cycle. Another example is in Excerpt 2, in which the teacher helped the students attend to the process of photosynthesis and the specific elements depicting the phases in this process. Drawing the students' awareness towards the salient features of representations also included orienting them away from less salient features. An example of this is in Excerpt 3, in which the teacher implicitly toned down the significance of detailing the ears of an owl by assuring that the owl looked 'really good' and then prompted the student to think about the next drawing step. In this manner, the teacher supported students to perceive the significance of items ('owl') in the context of science practices as well as conceptual differentiation ('natural' and 'unnatural').

Making sense of 'semiotic signs'. Another form of support provided by the teacher was concerned with how to interpret and utilize semiotic signs in order to depict and make sense of phenomena appropriate to science—in this case, the procedural aspects of the carbon cycle, such as movement, causal connections, and course of events. This type of guidance was particularly evident when the students were to produce their own drawings based on what they considered salient features in the two authorized representations. An example of this is evident in Excerpt 2, in which Haley and her peers grappled with accounting for how the CO_2 ends up in the atmosphere. Here, the teacher made an iterative comparison of the use of arrows in the authorized representations, thereby drawing the students' attention towards a semiotic sign that can be used in their own drawings in order to depict the movement of CO_2 in the atmosphere. Another example is evident in Excerpt 4, in which the teacher oriented the students' attention towards how the absorption of CO_2 in seawater was depicted in one of the authorized representations.

Linking scientific concepts and detailed depictions. The analysis of the student–teacher interactions that took place in Drawing Session 2, in which the students revised their initial drawings in the light of a set of scientific concepts, indicates that the teacher provided support in the form of prompting students to provide explicit depictions that visually detail the particular concept or term in focus. This is displayed in Excerpt 4 in the discussion on how to depict the absorption of CO_2 in seawater. Another example is evident in Excerpt 5, in which Anna and her group discussed how to include a distinction between the natural and unnatural carbon cycle. This form of support invited further refinement of concepts as represented visually, again offering opportunities for sensemaking across verbal language and visual items.

Prompting students to provide explicit accounts for their representational choices. Closely related to making certain features of a representation salient and others less relevant is to establish verbal language connections to representation features. The analyses of the student–teacher interactions in settings in which the students produced their own drawings indicate that students occasionally tended to include unjustified visual or textual elements in their drawings. By holding the students accountable for the specific elements in their drawings, the teacher prompted the students to explain the inclusion of elements that appeared unclear to the teacher. For example, in Excerpt 4, the teacher asked Andrew and his peers to explain the relationship among the algae, the fish, and the sea depicted in their drawing, thereby prompting them to provide an account of the consequences of the absorption of CO_2 in seawater.

In addition to the different support forms provided by the teacher, the analyses of the student–teacher interactions also reveal the teacher's use of specific 'talk moves' defined by Catherine O'Connor and Sarah Michaels (1993, p. 334) as 'conversational moves intended to accomplish local goals'. Studies that focus on student–teacher interactions during representational work have identified talk moves in the form of eliciting and elaboration as essential in conceptually oriented classroom conversations (Ingulfsen, Furberg and Strømme 2018). Similarly, the analyses in the current study make it possible to identify that the teacher frequently deployed these two forms of talk moves in his interactions with students. The *eliciting talk move* became evident in the teacher's use of prompts and cued questions to elicit students' emerging understanding of specific elements in the representations or connection among elements. One example of this is evident in Excerpt 2, in which the teacher elicited students' ideas regarding photosynthesis to support their reasoning regarding how carbon moves from the atmosphere to the producers. Additionally, Excerpt 4 illustrates how the teacher targeted one element in the students' drawing that was not connected to the surrounding elements through arrows, thereby probing for student accounts of how the element fits into the carbon cycle as a whole. The *elaboration talk move* became evident in instances where the teacher reframed and elaborated on students' accounts of concepts or aspects of the representations. In certain instances, such elaborations were provided in response to students' requests. An example of this is evident in Excerpt 5, in which the students' wanted to know whether the carbon deposit is part of the natural carbon cycle. In other instances, the teacher's deployment of the *elaboration talk move* typically succeeded prior attempts to guide students' reasoning by employing an *eliciting talk move*. This is evident in Excerpt 4, in which the teacher finally provided an explanation of how algae is related to the carbon cycle as a whole. In addition to these talk moves, the detailed analyses of the student–teacher interactions indicate that *deictic movements* such as pointing and outlining constitute an intertwined and crucial aspect of teacher support in students' sensemaking with visual representations. The teacher's deictic movements served as a significant means of directing students' attention to specific features of the representations and contributed to framing and imposing meaning into representational resources. The identification of the instructional strategies contributes to demonstrate the multifaceted ways of supporting students' conceptual sensemaking in representational work. Helping students display and further develop their understanding of representational resources and concepts required the teacher to combine and balance discursive talk moves and deictic movements.

Overall, the findings in the current study demonstrate the pivotal role of teacher support in establishing visual representations as productive resources in students' conceptual reasoning. As evident in the analyses, the intended function of the authorized and student-constructed representations was not realized until it was invoked in and through the teacher's additional guidance. At the same time, the analyses also demonstrate the crucial role of the material resources in the teacher's effort to model and engage students' relevant ways of attending to, accounting for, and deploying the visual representations as conceptual resources. Seen together, these findings serve to illustrate how the support from visual representations and the support from the teacher were woven together in the teacher–student interactions and became interdependent means of establishing zones of proximal development in students' engagement with representational construction.

Implications for instruction

Based on our findings, a few possible implications for instruction can be made. First, the findings of the current study demonstrate the necessity of critically assessing material and instructional support when developing instructional designs and planning instruction. When selecting authorized representations that serve as material support in students' engagement with representational construction, it is important that teachers select representations that are sufficiently different in terms of how concepts and phenomena are depicted and that the teacher is prepared to support students in *how* to compare and contrast multiple representations. Second, it is important that teachers reflect critically upon what types of social and material support can benefit students' engagement during specific activities revolving around visual representations as well as consider ways in which instructional designs might fail to provide adequate support. Third, we argue that teachers might benefit from considering which challenges students are likely to encounter during their work and how different challenges should be addressed in situ. Fourth, students need space for exploration and sensemaking on their own terms. In the current study, the teacher addressed challenges mainly at the group level—that is, through dialogue with the student groups while making rounds in the classroom. A different approach would be to schedule time during whole-class sessions for targeting issues and challenges encountered across student groups. Either way, we would like to emphasize the significance of allocating sufficient time for activities in which students are provided with the opportunity to share and receive feedback on their emerging understanding of activities, representations, and scientific concepts in the presence of the teacher.

Concluding remarks

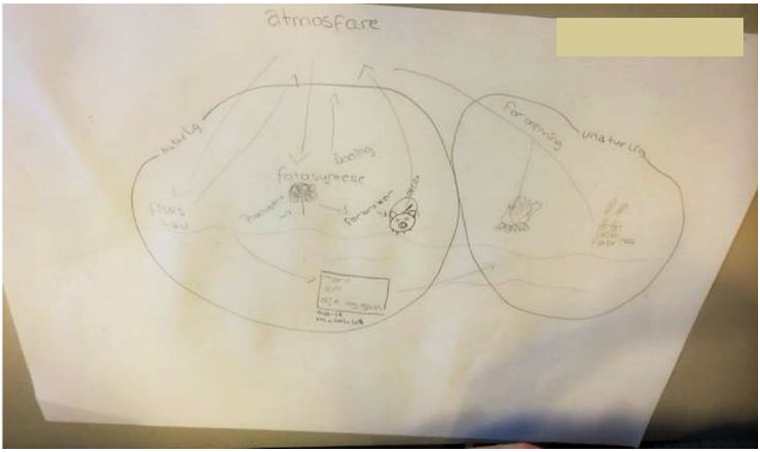
This study demonstrated how a sociocultural perspective of support provided by the teacher in settings in which students engage with representational work can enrich our understanding of how and why interacting with representations under specific conditions supports students' processes of conceptual understanding. From a sociocultural perspective, supporting students in their learning processes can be viewed in the light of Vygotsky's (1978) concept of the zone of proximal development, which refers to the difference between what a learner can do with or without guidance from a more experienced partner. The findings of our study reveal the considerable effort required for students to interpret, produce, and link scientific principles to authorized and self-produced representations, as well as the pivotal role of the teacher in providing support to students in this process. This study mapped and examined the zone of proximal development for this case. Furthermore, the study shows the potential of carefully designed educational settings in which authorized and students' self-constructed representations constitute an interactional space for students and their teachers.

With regard to further research, there is a need for additional studies that analytically scrutinize the role of the teacher in students' engagement with visual representations. Of particular interest are studies that aim to detail and explain the processes through which teachers facilitate students' representational construction in different knowledge domains and learning settings, which include authorized representations as a type of material support. Furthermore, in the wake of the various technological devices and digital resources designed for supporting students' learning in school science settings, there is a huge need for studies that focus on students' conceptual sensemaking with such representations, including how these resources become sensemaking resources in student–teacher interactions in whole-class and group-work settings. Such studies could improve our understanding of the potential of engaging students in learning activities that revolve around representational construction and the interrelationship among teacher support, instructional design, and peer collaboration. In addition, more research is needed to understand the type of strategies that benefit students' learning of different types of topics and learning objectives.

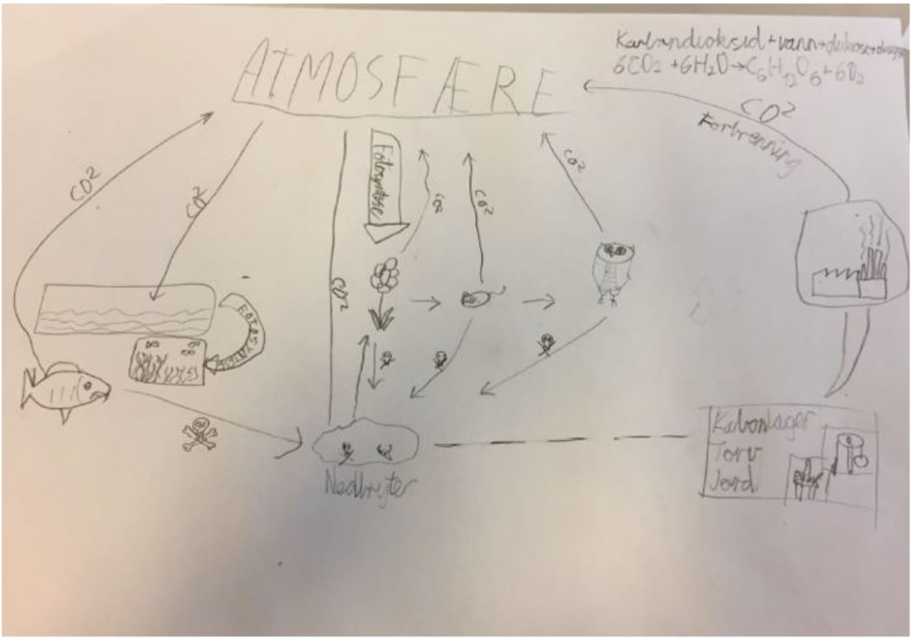
Appendix 1: Transcript conventions

=	A halt or interruption in utterance
(# of seconds)	A longer pause; duration indicated in seconds
(.)	A brief pause, usually under a second
? or ↑	Rising pitch or intonation
.	Falling pitch or intonation
,	Temporary rise or fall in intonation
Underline	Emphasized or stressed speech
:::	A prolonged utterance
((*italic text*))	Annotation of non-verbal activity
[text]	Overlapping speech

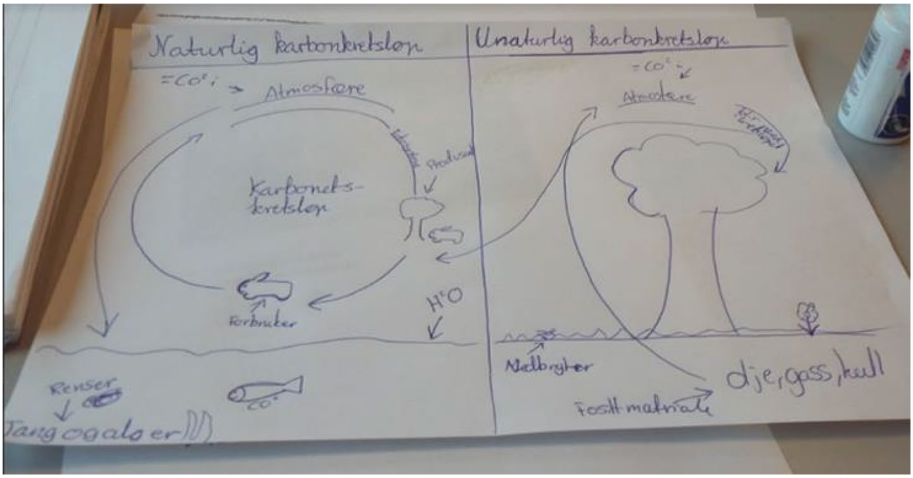
Appendix 2: Students' final drawings



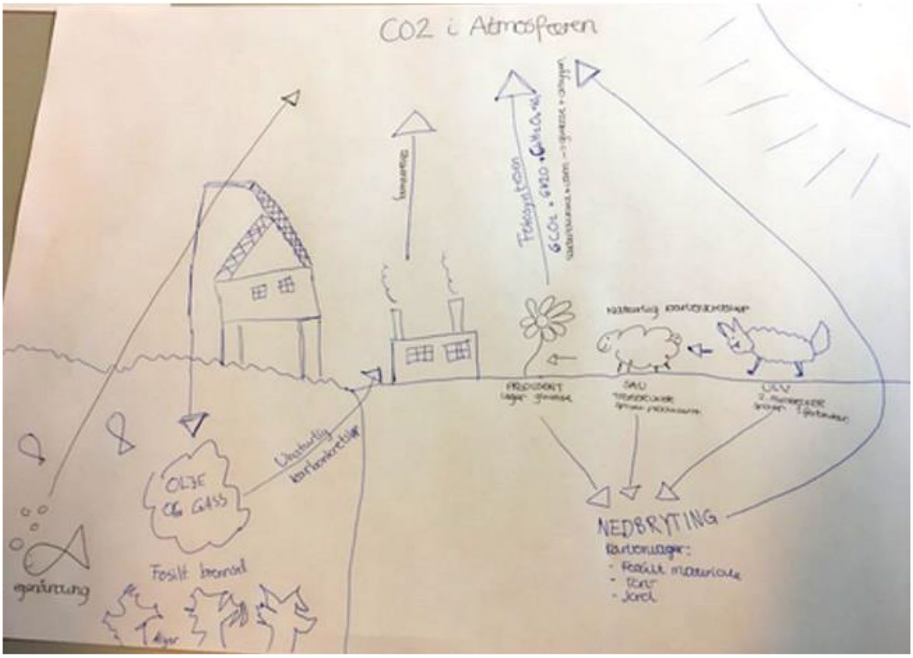
Picture (a) Anna, Lisa, and Robert's final drawing.



Picture (b) Thomas and Marcus' final drawing.



Picture (c) Haley and Steven's final drawing.



Picture (d) Elizabeth and Andrew's final drawing.

Acknowledgements We would like to thank our colleagues in the research project entitled *Representation and Participation in School Science* (REDE) for discussions and comments on earlier drafts of this article that have benefited the final version of this article. We would also like to thank our colleagues in the COSER, LIDA, and LinCS research groups for their constructive feedback on earlier drafts. We are also grateful to Andreas Lund and Kenneth Silseth for their valuable contributions. We extend special thanks to the teachers and students who participated in the REDE project. This research was supported by the Department of Teacher Education and School Research, University of Oslo, and the Research Council of Norway (the FINNUT programme, Grant No. 249872).

Funding Open access funding provided by University of Oslo (incl Oslo University Hospital).

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