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Qualitatively different ways of unpacking visual representations when teaching intermolecular forces in upper secondary school

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Abstract

Since visual representations play a particularly important role in the teaching and learning of chemistry, the exploration described in this article focuses on them. This is an explorative study of the qualitatively different ways that visual representations can be unpacked by Swedish upper secondary school chemistry teachers dealing with intermolecular forces. *Unpacking* is characterized as the ways that visual representations get used to open up the possibility of having the critical aspects and features of an intended object of learning being brought into focal awareness, initially on their own and then simultaneously. The analysis, which combines a phenomenographic and a social semiotic approach, leads to the characterizations of five qualitatively different ways that visual representations may be unpacked. These outcome categories are presented in terms of a conceptual hierarchy, where two of these ways of unpacking are characterized as being teacher-centered and the other three as student-centered. This leads to a case being made that if teachers use student-centered ways of unpacking visual representations, then their students will be more likely to gain greater access to critical aspects and features of the enacted object of learning. We argue that in terms of making theoretical and practical contributions to the phenomenographic perspective on learning, the results can be used as a tool for researchers wishing to explore how visual representations can be used effectively in science education and also provide a useful basis for discussion in teacher education and in teacher professional development programs.

KEYWORDS
chemistry teaching, phenomenography, social semiotics, unpacking, visual representations

1 | INTRODUCTION

All phenomena in chemistry are concerned with matter, its structure, and properties. However, with many of the processes involved in chemistry being invisible to the naked eye, it is often experienced as a difficult subject both to teach and to learn (e.g., see Cokelez et al., 2008; Jaber & BouJaoude, 2012). A particular aspect of chemistry that has attracted attention in recent years, is its use of visual representations, such as molecular models, chemical equations, formulas, chemical structures, and chemical symbols, all of which have been developed by the discipline and its pedagogical equivalent to describe the phenomena being studied (for research in the area of representations in science and chemistry education, see Ainsworth & Newton, 2014; Eilam & Gilbert, 2014a; Gilbert et al., 2000; Justi & Gilbert, 2003; Kozma, 2003; Prain & Waldrip, 2006; Rau, 2018; Treagust et al., 2003; Uttal & O'Doherty, 2008; Wu & Shah, 2004).

In this article, we seek to contribute to the understanding of the qualitatively different ways in which visual representations may be unpacked using the teaching of intermolecular forces, as an illustrative case study. This aim makes up our specific research question.

This article also contributes to the broader field of science education. It does this in four distinct ways. First, while a great deal of research has emerged from teaching and learning with different kinds of representations, little has been reported on how visual representations get "unpacked" by teachers. Here the term unpacking is used to refer to the ways that visual representations get used to open up the possibility of having the critical aspects and features of an intended object of learning being brought into focal awareness, initially on their own and then simultaneously (an expanded discussion of what we refer to as unpacking is given later). Knowing these possibilities and relating them to the discernment of educationally critical aspects and their features presents a new thread of educational awareness that could be fruitfully and effectively used in both teacher education and professional development. Second, it contributes to educational theory and practice that is built on the phenomenographic modeling of "an anatomy of awareness" and how that awareness can be optimally achieved (see Marton, 2014). Third, it provides a more refined way of looking at the teaching practice that is often referred to as *unpacking* by the science education community (e.g., see Cahapay, 2020). Fourth, it provides science education researchers and practitioners with a new set of tools to study individual teacher's unpacking of visual representations and link their practices to learning outcomes for comparative purposes.

Our analytical framing and its epistemological assumption draw on two perspectives —phenomenography and social semiotics. After introducing the parts of phenomenography and social semiotics, relevant for this article, an expanded discussion of what we refer to as *unpacking* is presented.

1.1 | The intended, enacted, and lived object of learning

Phenomenography is both an educational perspective and a research approach that originated in Sweden during the late 1970s. As a research approach, it is constituted on a number of points of departure (discussed later). Epistemologically it drew on gestalt psychology and ontologically on nondualism. As an educational perspective it capitalized on these to present a view of classroom learning with the following basic attribute: the structural and referential (meaning) aspects of awareness in relation to learning to discern new things and learning to discern things in new ways (Marton & Booth, 1997; Marton & Säljö, 1976a, 1976b; Marton et al., 1977, 1984; Marton, 1981, 1986). The content of the learning task is referred to as the "object of learning" and it is the way that the *object of learning* is "handled" that determines the possibility of learning. This handling of the *object of learning* has three distinct parts that can be separated analytically; *the intended*, *enacted*, *and lived objects of learning* (Marton & Tsui, 2004). The *intended object of learning* are those aspects of curriculum content and their features that a teacher considers critical for students to discern in order for them to constitute the intended learning. In this regard, we take aspects and their features to be inseparable, for as Lo (2012) reminds us:When children can discern 'redness'

> (the critical feature), they must also have discerned 'color' (the relevant critical aspect). It is impossible for someone to discern a critical feature without knowing which critical aspects that feature belongs to. Critical features and critical aspects are inseparable. (Lo, 2012, p. 30)

For example, a critical aspect of intermolecular forces would be polarity. This is because the degree of polarity in a molecule provides important information about the strength of a particular intermolecular force — which in turn, manifests as particular physical properties, for example, boiling points. The actual distribution of charges in a specific molecule is taken then to be a critical feature of the critical aspect polarity and this feature is visually represented more often by $\delta+$ and $\delta-$ signs, signifying partial charges.

At this point it is important to note that the *enacted object of learning* refers to how the teaching of the critical aspects and features from the *intended object of learning* gets played out in the classroom — what critical aspects and features the teacher aims to bring to the fore for their students' discernment. The *lived object of learning* is what gets constituted as meaning by the students; what they experience, what comes to the fore for them (Marton & Morris, 2002; Marton & Tsui, 2004).

It is the *enacted object of learning* that determines the parameters of what is made possible to learn and it is this aspect that is the focus of this article. Here we build on an earlier study published in this journal (Patron et al., 2017), that looked at upper secondary school chemistry teachers' descriptions of their *intended object of learning* as it related to their use of visual representations when introducing chemical bonding to their students. The motivation for this study lies in the fact that intermolecular forces are an aspect of chemical bonding that students typically find particularly challenging to make sense of (e.g., see Özmen, 2004). Furthermore, chemical bonding plays a central role in chemistry reasoning (Hilton & Nichols, 2011), and thus, it is important that students gain a thorough understanding of bonding to make sense of other chemical phenomena (e.g., see Yayon et al., 2012). This is therefore a very distinct area, where teachers need to help students to make coherent conceptual links between the visual representations that are used to present the critical aspects of an intended object of learning. Furthermore, this is an area where little research of this type has taken place as a function of the ways that teachers attempt to help students discern the parts that make up the intended object of learning.

1.1.1 | The idea of focal awareness

To create a coherent "whole" of disciplinary meaning, various aspects of the intended object of learning have to be simultaneously brought into focal awareness (Marton, 2014). In phenomenography, what is in focal awareness for a given learning situation is an integral part of understanding the experience of learning new things and learning things in new ways, as Marton and Booth (1997, p. 100, emphasis added) describe it: "qualitatively different ways of experiencing something can be understood in terms of differences in the structure or *organization of awareness at a particular moment*."

The critical aspects of an intended object of learning "and the relationships between them that are discerned and simultaneously present in the individual's focal awareness define the individual's way of experiencing the phenomenon" (Marton & Booth, 1997, p. 101). Collectively what is in focal awareness and what is in the background make up a person's "structure of awareness" at a particular time for a particular context (see Marton & Booth, 1997, p. 101). What is directly relevant in terms of an enacted object of learning is how the enactment can be analytically dealt with as a function of efforts to make learning possible — how visual representations can be unpacked in a way that gives students access to educationally critical aspects, and how such an analysis can be effectively achieved through the use of a social semiotic lens.

1.2 | Social semiotics

The definition of social semiotics that we are drawing on for this article is: "the study of the development and reproduction of specialized systems of meaning making in particular sections of society" (Airey & Linder, 2017, p. 95). In our article, the "section of society" refers to the upper secondary-school chemistry classroom. From a social semiotic perspective, learning can be seen as "coming to appropriately interpret and use the disciplinary-specific meaning potential of semiotic resources" (Airey & Linder, 2017, p. 99). Examples of semiotic systems that are used to share meaning in chemistry are diagrams, drawings, mathematics, and spoken and written language. Such semiotic systems are collectively utilized in particularly distinct ways within the discipline in the form of representations of, for example, molecular, empirical, structural, and condensed formulas and chemical equations. Adopting a social semiotic perspective for analytic purposes in chemistry education brings into sharp focus the particular meanings that students need to acquire to constitute disciplinary relevant knowledge meanings from these various representations. A social semiotic approach has been used in science education research previously (e.g., see Airey & Linder, 2017; Danielsson, 2016; M. Eriksson et al., 2020; U. Eriksson, 2014; Euler et al., 2019; Fredlund, 2015; A. Linder et al., 2014; Moro et al., 2020; K. Svensson et al., 2020; Tang et al., 2019; Volkwyn et al., 2017; Weliweriya et al., 2019). Furthermore, social semiotics have been combined with methodological approaches in a fruitful way. In a recent article, Knain et al. (2021) explored how social semiotics, in combination with interaction analysis, could provide new insights into students' meaning making when engaging with self-produced representations in science. Furthermore, the concepts used in social semiotics are under constant development. For example, K. Svensson and Eriksson (2020) recently expanded the social semiotic concept of transduction and made a theoretical claim that transductive links, which they define as semiotic systems that "supports the transduction process between two different semiotic systems" (p. 4), can be used as a tool to describe and understand the learning challenges that students encounter in science, and also be used in ways that increase students learning experience. Furthermore, Volkwyn et al. (2020) introduced a new way of looking at students' representational competence in science from a social semiotic point of view. They argue that students can increase their representational competence by learning how to link different discrete semiotic modes to real world phenomena and scientific concepts, and then, with help from the teacher, make transductions between the semiotic resources in different modes.

1.2.1 | Visual representations vis-a-vis disciplinary and pedagogical affordances

In this article, we define visual representations as being semiotic resources that are directly visual to the naked eye, excluding written language that is not part of a sketch or a diagram. Examples of visual representations used in chemistry education include ball and stick models, Lewis structures and structural formulas. To communicate and make sense of chemical bonding and other aspects of chemistry, visual representations are essential (Eilam & Gilbert, 2014b; Rau, 2017).

Visual representations used in chemistry can be characterized as having high *disciplinary affordance*, i.e. "the agreed meaning making functions that a semiotic resource fulfill for the disciplinary community" (Airey & Linder, 2017, p. 99). Visual representations with high disciplinary affordance have come to enhance, through design and reformulations over many years of usage, certain aspects of some phenomenon, while other important aspects will not be directly visible. In other words, some aspects will be present in the representation, making them directly visible, and thus available for discernment, while those other aspects that are not directly visible will need to become *appresent* in the "seeing" experience (i.e., being aware of them without being directly visible). If such appresentation do not emerge in the learning experience, then there will be little realistic possibility for the full intended meaning to be constituted (Ingerman et al., 2009; C. Linder, 2013).

Chemistry teachers and school textbooks often use so-called "simplified" versions of the disciplinary representations used by the broader chemistry community (Gilbert et al., 2000). These simplified representations have been characterized by Airey and Linder (2017, p. 105) as having high pedagogical affordance, which they define as "the aptness of a semiotic resource for the teaching and learning of some particular educational content." In other words, pedagogical affordance is a construct that reflects how useful a representation may be in a particular educational setting to use as an unpacking tool. Airey and Linder (2017) argue that a representation that is utilized in an educational context will possess both pedagogical and disciplinary affordances. However, they also argue that the relationship between pedagogical and disciplinary affordance typically has an inverse aspect in that a gain in pedagogical affordance may lead to a loss of disciplinary affordance. At the same time, it needs to be recognized that ultimately students will still need to be able to effectively work with the disciplinary-specific representations of chemistry. In other words, the "unpacked" disciplinary representation will still need to be "re-packed" in the students' learning experience (e.g., see Volkwyn, 2020).

1.2.2 | Semiotic modes, and moving within and between modalities

Earlier we introduced the idea of chemistry semiotic systems using these examples: diagrams, drawings, mathematics, and spoken and written language. However, in a general sense, these kinds of semiotic systems are also commonly referred to as semiotic "modes" in the literature (see, e.g., Kress, 2010). For this reason, the term mode will be used from this point onwards. In the broader multimodal literature, the idea of what a mode is, is somewhat diffuse (see examples in Kress, 2016, pp. 60–75). For what is to be taken to be a mode depends on the specific communicative requirements in a particular context (Bezemer & Cowan, 2020; Bezemer & Kress, 2008; Kress, 2016). For our research, we gave particular attention to the visual modes used for teaching intermolecular forces, such as drawings, static illustrations, animations, and physical objects. Representations that are made up of different collections of modes are said to have different intrinsic affordances and constraints (Bezemer & Kress, 2008; Kress, 2016). This is because each of the modes used is only able to give partial direct visual access to what is important. In other words, each mode used can potentially bring different aspects of a phenomenon into an observer's focal awareness. Hence, it has been proposed that a "critical constellation" of modes needs to be used in order for students to be able to constitute a holistic and appropriate sense-making of a phenomenon (see Airey & Linder, 2009). For example, an animation of water molecules can make it possible to show the movement of the molecules and how hydrogen bonds may be formed and broken (something which is hard to show with the use of, say, a static illustration). However, students may find it challenging to move between different representations of the same phenomenon. Either, between different representations that are made up in the same mode, for example, from one type of graph to another; which is referred to as transformation in the literature. Or, between representations that are made up of different modes, for example, from a graph to an animation; which is referred to as transduction (in both instances, see Bezemer & Kress, 2008). This necessitates teachers' facilitation of students' meaning making with multiple representations and their connections and synesthesia: the "constant transition, translation and transduction between different modes" as Kress (1997, p. 36) puts it.

1.3 | Unpacking

Two models have influenced how we constituted the meaning of unpacking for this article. These were the Doll (1992) model of "curriculum unpacking" and the phenomenographic highlighting of the role that discernment (awareness) plays in classroom learning (as summarized in Marton & Booth, 1997; Marton, 2014) and its modeling of the "space of learning" (Marton & Tsui, 2004). Both models contain the distinction between what is intended and how that intention gets played out in practice. Our use of the term in this article refers to the process of interpreting an object of learning (a curriculum item), formulating an intended object of learning, and enacting that intention in classroom practice. In our case, this process of unpacking gets characterized through the ways that visual representations (i.e., semiotic resources) get used to open up the possibility of having the critical aspects and features of an intended object of learning being brought into focal awareness, initially on their own and then simultaneously. The artistry of such unpacking of a visual representation should arguably, by default, be about extending the pedagogical affordance in ways that facilitates the critical aspects in the representation becoming potentially more perceptible for students (Airey & Eriksson, 2019). Furthermore, we argue, in line with Fredlund et al. (2014) that the unpacking of disciplinary representations constitutes an important aspect of (experientially) coming to appreciate the disciplinary affordances of representations, in ways that can decrease the learning challenges students face when trying to make meaning with disciplinary representations.

2 | RESEARCH DESIGN

2.1 | The research approach phenomenography; an overview

When phenomenography started to develop as a research approach in the latter 1970s under the leadership of Ference Marton and his colleagues at Gothenburg University in Sweden it presented "a reaction against, and an alternative to, the then dominant tradition of positivistic, behavioristic and quantitative research" (L. Svensson, 1997, p. 171). As such, it became widely renowned for its distinct point of departure. As an analytical approach, Marton and his colleagues built phenomenography by drawing on Gurwitsch (1964) model of awareness to craft out a distinction between the referential (meaning) and structural (parts and the whole, and how these related to each other – often referred to as internal and external horizons) in the phenomenographic characterization of experience. In phenomenography this is referred to as an "anatomy of awareness" which, in turn, also reflects a "non-dualistic" view of human cognition (Marton, 2014). From this perspective, the content of our thinking is taken to be made up of the internal relationships that are established between ourselves and the phenomena we experience (i.e., as a function of our understanding, perceiving, handling or articulation of a phenomenon). Phenomenography was essentially conceptualized to answer certain questions about thinking and learning and about common-sense considerations about learning and teaching (Marton, 1986). As such, it is an approach that is particularly relevant for research on teaching and learning.

During the 1990s, particularly following the seminal publications of *Learning and Awareness* (Marton & Booth, 1997) and *The University of Learning* (Bowden & Marton, 1998), phenomenography unequivocally became the stalwart backbone of what is now widely referred to as "the student learning literature" (C. Linder & Fraser, 2009). Overviews of this student learning literature may be found in Marton (2014), Marton and Tsui (2004), and Entwistle (2018). Marton and Booth (1997) provide an in-depth and extensive discussion of all aspects of this point of departure. Hence, only a very brief summary of the most pertinent parts of the point of departure for our study is provided here. This point-of-departure summary is constituted from four sources, the two seminal publications mentioned above, Booth (1997), and L. Svensson's (1997) presentation of the "theoretical foundations of phenomenography".

1. As a research approach, phenomenography presents a particular framework to empirically study what is axiomatically taken to be the limited number of qualitatively different ways that people experience phenomena. In phenomenography, the term experience is taken to conceptualize, understand, perceive, apprehend, and so on. These terms are used interchangeably by the phenomenographic community. The point we are making here is not to deny that there are differences in what these terms refer to, but to suggest that the limited number of ways in which a certain phenomenon appears to us can be found, for instance, regardless of whether they are embedded in immediate experience of the phenomenon or in reflected thought about the same phenomenon. For our study, this gets brought to the fore through the ways visual representation are handled (presented) for a particular intended object of learning in a chemistry classroom. The ways of handling visual representation of a particular intended object of learning we are referring to, is how teachers in a chemistry classroom unpack visual representations to help students make educationally critical meanings of intended objects of learning. Following the theme of phenomenographic work that linked the referential to the "what" aspect and the structural to the "how" aspect (Booth, 1997; Ellis, 2004; Marton, 1988; Reid & Petocz, 2006), the analytic link for our article is grounded in the assumption that the "how" and "what" of what is conveyed is directly related to how teachers' have experientially constituted "what matters'' when it comes to using and unpacking a particular visual representation. These two aspects are taken to be "dialectically intertwined" that is "neither can exist apart from the other." (Lybeck et al., 1988, p. 5). Such "how" and "what" aspects are further explained by Booth (1997, pp. 135-136) as follows:

   > If we limit our attention to educational settings, we can say that in general "learning" means coming to an understanding of curricular content as a result of tackling various learning activities. As a result of the task, a new way of experiencing the content is reached. Thus, there are two aspects to any learning situation which, while being inextricably intertwined and probably unconsidered for the learner, are important analytical aspects for the researcher. They are referred to as the "what" of learning and the "how" of learning; the "what" concerns the quality of the understanding arrived at, or the perspective taken on, or the conception held of the content of the learning task, as a result of the learning activity; and the "how" concerns more the nature of the act of tackling the learning task.

2. Phenomenography is ontologically non-dualistic. In phenomenography, the term "non-dualist" is used to signify that a person and phenomenon are not seen as separate entities. In contrast, reality, ways of knowing this reality, and the communicative representations of how this reality is known are relational. In this way, phenomenography can be seen to have an ontology that rests on the idea that people communicate about the phenomenon in terms of how they are experienced.
3. The focus of the research is on qualitative difference in a "second order" perspective. This means that our study was not focused on an object of learning, but on the variation in the communicative handling of the intended objects of learning. In other words, phenomenography is about studying ways of experiencing phenomena in contest to studying the phenomena themselves.
4. Phenomenographic analysis focuses on capturing qualitative differences in relation to experiencing some phenomenon. Thus, the analysis cannot be done at an individual level but has to be done at a collective level to capture the variation, that is, across all the individuals that participate in the study. This means that:

… the empirical results lie at a level above the individual but can inform the researcher and the teaching practitioner of the learning practices even at individual level. More precisely, empirical data is collected from a selection of persons, chosen to cover the range of persons for whom the research questions are relevant, and are pooled for analysis; thus the results lie across the whole source of data, a collective level. (Booth, 2008, p. 451)

This has two important consequences. First, it is important to choose a group of participants that are likely to include a range of experience (ideally this range should maximize the possible variation under study). Second, no claims get made about individuals, just about qualitative differences in experience (which a later study could use to sort individuals by). In our case, the possible ways of using visual representations to bring critical aspects and their features to the fore through unpacking of the visual representations used.

5. The analytic outcome presents the key aspects of this variation found in terms of a limited number of internally related hierarchical categories. Collectively these categories make up what is known as the *outcome space*. This outcome space, because it is constituted from the variation found at the collective level, can only provide a partial description—a characterization of the whole.
6. The outcome space that arises from a phenomenographic analysis of variation is constituted by descriptions of the internal relations between the qualitatively different ways of experiencing various aspects of the world. This means the outcome space is never made up of just "lists" of categories, which are often unrelated when arising from other methodologies, for example, content analysis. Marton and Booth (1997) describes the criteria of the development of categories and their hierarchical order in the outcome space as follows:

There are certain criteria for the quality of a set of descriptive categories, that can be seen as methodologically grounded or grounded in the anatomy of awareness as expounded earlier. The first criterion that can be stated is that the individual categories should each stand in clear relation to the phenomenon of the investigation so that each category tells us something distinct about a particular way of experiencing the phenomenon. The second is that the categories have to stand in a logical relationship with one another, a relationship that is frequently hierarchical. Finally, the third criterion is that the system should be parsimonious, which is to say that as few categories should be explicated as is feasible and reasonable for capturing the critical variation in the data (Marton & Booth, 1997, p. 125).

For our study we drew on the phenomenographic approach to constitute qualitative differences in terms of experience, which in this case refers to the ways of handling or articulation of a phenomenon. Using this approach for our study, it is what the research team discerned as telling us something distinct about how the given object of learning was experienced in terms of how it was handled that shaped our outcome space. Hence, what was taken to be qualitatively different is what distinguished one category from another.

2.2 | The study participants

The data for the study was derived from observations of classroom teaching practices in Swedish upper secondary schools. Three chemistry teachers participated in the study. The three teachers were all teaching the same chemistry course and were employed at different upper secondary schools in the same geographical location in southern Sweden. All three had more than 10 years experience of teaching chemistry at this level. The three schools were similarly resourced with regard to equipment and computer access and were located in a middle-class socioeconomic environment. These specific teachers were purposefully selected because they offered us a wide potential variation with regard to their practical use of visual representations for unpacking. We knew this because they had participated in an earlier study reported on in a previous edition of this journal (see Patron et al., 2017).

Video recordings were made of teaching sequences dealing with intermolecular forces. During these teaching sequences, field notes were taken for potential cross-reference use when analyzing the recordings. From our previous study (Patron et al., 2017), we had obtained insights into the amount of visual representations that teachers were likely to use. As anticipated, the data set was both rich and extensive and was thus considered to be sufficiently comprehensive for the aim of this article.

This study was conducted in accordance with the Swedish Research Council's ethical principles (Swedish Research Council, 2017). This included the participating teachers receiving information about the purpose of the study and how the data would be used and presented when the study was reported on. This was done in both written and oral form before the classroom observations. The teachers were also informed that their participation was voluntary, that they could end their participation at any time, and that the data would not be used for other purposes than those stated in the information material. All teachers gave a written consent to participate in the study.

2.3 | Data collection

The teachers' lessons on intermolecular forces were observed and "action" video-recorded. This means that the video-camera was continually focused on the teacher's activities and thus able to capture all of their communicative actions, including the visual representations that they employed. During the observed lessons on intermolecular forces, the three teachers used a total number of 37 different visual representations. The lessons were given in Swedish and the analysis took place in Swedish. The illustrative extracts from the lesson transcriptions presented in this article were translated by the third author into English. These translations were then independently verified. In this process, the few and small translation ambiguities that were identified, were solved through mutual discussion.

2.4 | Data analysis

The analytic steps involved making constant comparisons between similarities and differences of aspects of data content in terms of the referential meaning aspect and the structural aspects of what had been presented by the teachers. It is important to stress, not in terms of differences between individuals, but in terms of differences in ways of handling the unpacking of visual representations. Iterative steps in the analytic process included looking for distinct qualitative differences, which grounded the emergence of our different categories. While working with one theme in the data at a time, we also were simultaneously looking for overall patterns and how these were related to one another. Furthermore, an empathetic understanding of what was involved in the unpacking, which derived from observations of how the unpacking was handled and the authors own experiences of teaching about molecular forces, underpinned the entire process (as such, the phenomenographic approach is hermeneutical in nature). The iteration process described continued until the category system was stabilized, that is, saturation was reached. How these steps were implemented by the authors both individually and collectively is described below.

To familiarize ourselves with the data, all authors independently viewed the video recordings repeatedly. The joint analysis began with the transcription of all the teaching sequences that occurred around the 37 communicative actions that involved visual representations. For all the communicative actions that involved teaching sequences, working matrices were constructed. The matrices contained descriptions of what the teacher did, what they said, what visual representation they were dealing with at the time, and our observations of how the intended object of learning was handled in terms of actions aimed at helping students extend their focal awareness (i.e.,

TABLE 1 Example of unpacking by transduction and corresponding analytic parts

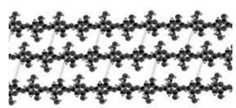
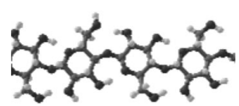
Unpacking by transduction				
Transcript of spoken language	**Transcription of teaching action**	**Description of visual representation(s) used**	**Intention**	**Handling of the intention**
Then the question is, the special sound, what kind of sound is it?	Placing the log on the floor and holding the axe over their (own) head.	Visual representations: an axe, a log of wood and a static illustration of cellulose chains represented by molecular structures	The teacher aims to bring the students focal awareness toward the hydrogen bonds between the cellulose chains	Using an axe and a log of wood to bring the students focal awareness toward the hydrogen bonds between the cellulose chains in the static illustration
When I chop now, what bonds will I be breaking? Thus, I will chop in this way, I will chop in this way now.	Using the axe to show the "chopping" direction in the representation of cellulose on the whiteboard, that is, the axe is moved in parallel with the direction of the polymer chain.	(See Figure 5d for molecular structure in color).  Affordances: Axe: pedagogical; Molecu lar structures: mainly disciplinary		

TABLE 2 Examples of unpacking by verbal explanation and corresponding analytic parts

Unpacking by verbal explanation				
Transcript of spoken language	**Transcription of teaching action**	**Description of visual representation used**	**Intention**	**Handling of the intention**
Here we have many [beta-glucose units] that are bound together, now it's beginning to look like a fiber of cellulose. Can you see that we still have hydrogen directly bound to oxygen?	Shows a diagram of cellulose with several glucose molecules bound together. Points with one hand at hydrogen atoms that have covalent bonds to oxygen atoms in several of the glucose units	Visual representation: Static illustration of four beta-glucose units bound together with glycosidic bonds, represented by a molecular structure (see Figure 5c for figure in color).  Affordance: disciplinary	The teacher aims to bring the students focal awareness toward one critical feature (hydrogen is directly bound to oxygen)	Verbally highlighting the bond between those atoms and at the same time pointing at those features in the visual representation

discern aspects that were originally not directly visible and some visible aspects in new ways). For examples of these working matrices, see Tables 1 and 2.

The working matrices were independently reviewed in detail in relation to the relevant teaching sequences. This review process continued for about 10 weeks with the authors meeting weekly until all issues had been resolved with respect to both differences and similarities in how the representations were unpacked. Then, our initial categories were independently developed using the iterative process described earlier. After this, the authors again met weekly for approximately 5 weeks to establish the final outcome space. During these meetings we discussed what modifications and adjustments should be made by constantly referring back to our working matrices and the video data. This joint iteration continued until the system was stabilized and no more adjustments were deemed necessary by any of the authors (i.e., saturation was reached). The result of this analytic pathway was a set of categories that made up our outcome space results (see Table 3).

2.5 | Limitations of the study

In this section, we discuss what we see as the most important aspects concerning study limitations in phenomenography as they relate to our study.

The intent of our phenomenographic study was not only to explore the different ways in which unpacking is undertaken by teachers in an introductory level chemistry classroom but also to examine how the qualitative differences found and characterized in categories are structurally related to one another. When originally formulated, phenomenography axiomatically took it as a given that there are a limited number of ways that people get to experience the world. This axiom has since been well confirmed empirically — between five and seven ways would be typical. Hence, the fundamental limitation of any phenomenographic study rests with the richness obtained in the data set (and not the number of people involved). If this richness is sufficient to create a credible and useful set of categories, then the limitations of the study are deemed to be small. This credibility has two main aspects. First, there is experiential recognition by others familiar with classroom unpacking in introductory chemistry, second, it lies in the ways that relations between them are illustrated in the data analysis description. Our article provides the basis for both of these. In this way, any limitations will be established by readers with the relevant realm of experience. As regards replicability as a limitation; would another set of researchers constitute the identical categories? Marton (1986, p. 35) has argued that: “The original finding of the categories of description is a form of discovery, and discoveries do not have to be replicable. On the other hand, once the categories have been found, it must be possible to reach a high degree of intersubjective agreement concerning their presence or absence if other researchers are to be able to use them.” In our study we adopted a team approach described earlier, which is arguably a valuable way to include interjudge agreement into the analytic process. At the same time, for our study, it provides a sense of analytic replicability (for more discussion on how to minimize limitations in phenomenographic studies, see Johansson et al., 1985; Marton & Booth, 1997; Marton, 1986, 1988; Säljö, 1988).

Our analysis included consideration of how we perceived how the unpacking could facilitate students' getting to see things in new ways and see new things. Thereupon, the categories were arranged hierarchically based on how we saw the way of unpacking facilitating the possibility of achieving this. Table 3 gives a summative overview of our phenomenographic analysis. The context could be seen as presenting a limitation in capturing qualitative difference in that a different context could have teachers who have different teaching experience and/or different depth of chemistry knowledge. Such differences could then manifest in seeing different features as being educationally critical. Arguably this kind of new context would only limit the number of categories in the outcome space.

Since phenomenography is a second-order approach (see earlier), a phenomenographic analysis considers the researcher's experience of the collective researched experiences, vis-a-vis how the variation in the researcher's experience gets captured and characterized in terms of qualitative differences. Thus, the analytic outcomes are

TABLE 3 An overview of the phenomenographic analysis of the qualitatively different ways of teacher-handling of intermolecular forces, with respect to the unpacking of visual representation being used in the act of teaching

	Structural aspect (the "how") of the unpacking of visual representations as the handling of an object of learning (i.e., intermolecular forces)		**Referential aspect (the "what") of the unpacking of visual representations as the handling of the object of learning (i.e., the intended affordance through what is made visual)**	
Category of description	**Communication directed at constituting additional pedagogical affordance**	**The essential parts that make up that communication**	**Nature of the knowledge made possible through the unpacking**	**Intended affordance**
Unpacking by assumption	None	None	None, make sense of intermolecular forces using critical aspects as presented in the visual representation	Assumption is that full disciplinary affordance is available from the transmission of the visual representation as is. No additional pedagogical affordance is being constituted.
Unpacking by verbal explanation	Verbal	Verbal description of critical aspects in the visual representation, often combined with gestures	Make sense of intermolecular forces by a verbal foregrounding of critical aspects presented in the visual representation	Assumption is that most of the disciplinary affordance is available from the transmission of the visual representation as is. No additional pedagogical affordance being visually presented. The attempt to increase the pedagogical affordance is also in transmission style; through verbal explanation only.
Unpacking by adding features	Additional visual presentation	Stepwise adding initially appresent critical features to the original visual representation	Make sense of intermolecular forces by a visual foregrounding of critical features, previously appresent in the representation	Assumption is that the disciplinary affordance is partially available from the transmission of the original visual representation. Starting to open up the constitution of meaning-making by increasing the pedagogical affordance of the visual representation.
Unpacking by translation	Additional visual representation in the same mode	New visual representation(s) being presented, that draws on the original visual representation,	Make sense of intermolecular forces by foregrounding critical aspects in new way(s) and visualizing critical aspects	Assumption is that the disciplinary affordance is barley available from the transmission of the original visual

(Continues)

TABLE 3 (Continued)

Category of description	Structural aspect (the "how") of the unpacking of visual representations as the handling of an object of learning (i.e., intermolecular forces)		Referential aspect (the "what") of the unpacking of visual representations as the handling of the object of learning (i.e., the intended affordance through what is made visual)	
	Communication directed at constituting additional pedagogical affordance	**The essential parts that make up that communication**	**Nature of the knowledge made possible through the unpacking**	**Intended affordance**
		using the existing mode of presentation	appresent in the original representation	representation. Constituting new meaning making opportunities through the addition of a new visual representation in the same mode but with higher pedagogical affordance.
Unpacking by transduction	Additional representation in a new visual mode	New visual representation(s) being presented that draws on the original visual representation, using new visual mode(s) of presentation	Make sense of intermolecular forces by foregrounding critical aspects in new way(s) and make them distinctly visible for the first time, offering new perspectives (i.e. presenting appresent visual aspects not possible to make visible in the first mode used)	Assumption is that the disciplinary affordance is not available from the transmission of the original visual representation. Increased pedagogical affordance and a more holistic meaning is provided by the addition of a representation in a new visual mode with other intrinsic affordances.

direct functions of the researcher's analysis of what differences are critically significant. In other words, they are "the researcher's ways of experiencing how other people's ways of experiencing something vary" (Marton & Booth, 1997, p. 136). The researchers in this study have varying experiences in regard to chemistry knowledge and experience of teaching and research. We argue that this is a strength since we were all able to provide new perspectives during the analysis.

Finally, the hierarchy in which we order the variation represents the researchers' value judgments about what counts as a good, or a better, way of unpacking a visual representation. "Value judgements cannot be empirically grounded, but they can be argued" (Marton & Booth, 1997, p. 107). The better experience or handling of a phenomenon is thus defined in terms of the researchers' analysis of the qualitatively different ways of experiencing or handling the phenomenon, and "less advanced ways of experiencing it are partial in relation to more advanced ways of experiencing it. They reflect a simultaneous awareness of some aspects of the phenomenon reflected by a more advanced way of experiencing it." (Marton & Booth, 1997, p. 107).

3 | RESULTS

Our analysis of the teachers' ways of using visual representations in their teaching led us to formulate categories of unpacking the educationally critical aspects of intermolecular forces in terms of verbal explanation, adding feature (s), transformation, transduction and assumption. These characterizations are now expanded upon and illustrated further below.

3.1 | Unpacking of visual representation by verbal explanation

Critical aspects in a visual representation were brought to the fore by highlighting certain features in the representation, mainly by way of spoken language. Concurrently, the teachers also employed gestures, for instance by pointing to the specific feature they wanted the students to focus on. However, no new visual representations or additional features were added to the representation by the teacher.

An example of where a verbal explanation was observed, was during a lesson in which dipole–dipole interactions were presented (for the visual representation, see Figure 1). The teacher had drawn the visual representation before the lesson and showed it for the students on a screen. The representation had high disciplinary affordance, similar to those typically used in a formal chemistry discourse. The teacher used chemical symbols to represent different atoms and lines to represent the intramolecular bond between the atoms. In the representation dashed lines were included to illustrate the attraction between the molecules, and arrows emanating at the words "attractional force" annotated the dashed lines. The teacher verbally unpacked some of the critical features in the representation — for instance, the intended signification of the symbols δ+ and δ–, and the lines representing the

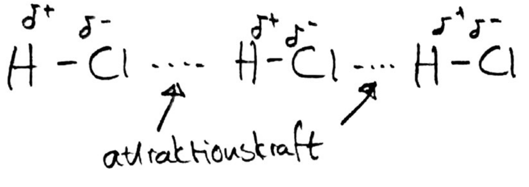


FIGURE 1 A predrawn drawing of structural formulas representing the dipole–dipole interactions between hydrochloride molecules. The word "attraktionskraft" written under the arrows is Swedish for "attractional force." See Table 4 for further details of the verbal unpacking of this representation

TABLE 4 A teaching transcription that illustrates how critical features in a representation of dipole–dipole interaction is pointed out using gesture and spoken language

Transcript	Teaching action (all pointing refers to the representation given in Figure 1)
Chlorine has a higher electronegativity than hydrogen, therefore we'll write a little delta-sign here just to show that we get a small minus charge there…	Points at δ− symbol over Cl
… and here we get a small plus charge.	Points at δ + symbol over H
If we do this with several hydrogen chloride molecules here…	Points at the three H–Cl
…then we will come to realize that well, in this molecule…	Moves a finger in a circle around the first molecule
…then we get a plus-minus charge, we'll get it in this one too…	Points at the next molecule
… and in that one and so on and so forth.	Points at the third molecule
Then we see that, then actually the negative charge in a molecule…	Points at the Cl-atom
…or charge and charge, but we can call it the negative end, attracts the positive end of the other molecule.	Points at the H-atom in the next molecule
It sounds quite logical, right? And the attraction I've drawn with little dots here, then…	Points at the dotted lines drawn between the molecules
…is what we call a dipole-dipole bond.	Points at the dotted lines again
So, the attractive force that develops there between them, we call a dipole-dipole-bond.	

dipole–dipole interactions. The teacher did this by pointing at those parts in the representation while at the same time verbally explaining what these features represented and what chemical signification they had. Thus, it can be inferred that the teacher intended to direct the students' focal awareness toward those parts of the representations (see Table 4 for a verbal explanation of Figure 1).

3.2 | Unpacking of visual representations by adding feature(s)

Another way of unpacking a visual representation with high disciplinary affordance was to add critical features to the high disciplinary version of the representation. An example of this is when one of the teachers explained dispersion forces to the students. The teacher began the lesson by drawing the structural formulas of chlorine

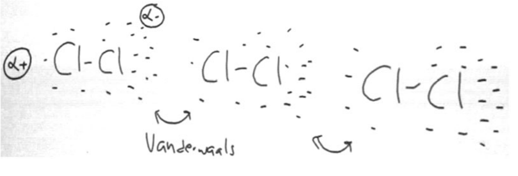


FIGURE 2 The final drawing of dispersion forces between chlorine molecules. The red lines symbolizing electrons, the δ + and δ− symbols and the double headed arrows were added stepwise during the presentation. Under the double-headed arrow the words "van der Waals" was written, which is an alternative term for dispersion forces

molecules as Cl–Cl. Structural formulas are representations with high disciplinary affordance since they have a high degree of appresent information.

While explaining the concept of dispersion forces, the teacher added more information to the representation (see Figure 2). For example, red lines representing electrons were added to the structural formulas to illustrate a temporary delocalization of electrons. After drawing the red lines, the teacher added the symbols δ+ and δ– representing partial charges, and double-headed arrows between the structural formulas to represent the attractive forces between them. In this way, the teacher made some of the critical features that were appresent in the first version of the representation visible to the students, thereby unpacking the representation and increasing the pedagogical affordance.

3.3 | Unpacking of visual representations by transformation

Yet another way of unpacking visual representations with high disciplinary affordance was by adding representations with high pedagogical affordance in the same semiotic mode—that is, implementing a transformation.

An example of this was when one of the teachers discussed dipole–dipole interactions. The teacher began by drawing a scientifically accepted visual representation — a structural formula of hydrogen chloride (see Figure 3a) and then added a simplified, visual representation of a dipole (Figure 3b), which had a high degree of pedagogical affordance that was rather different from generally accepted scientific ways of representing the concept. In the representation with high pedagogical affordance, both the chemical symbols and the lines representing intramolecular bonds were eliminated. This allowed a focus on one critical aspect — namely, that the molecule is a dipole and therefore able to form dipole–dipole interactions with other dipoles, an aspect that was appresent in the representation with high disciplinary affordance (Figure 3a).

3.4 | Unpacking of visual representations by transduction

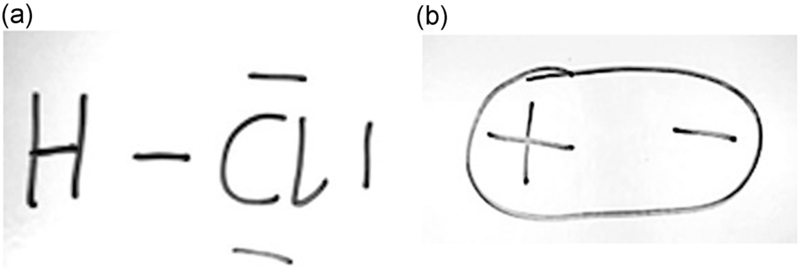


FIGURE 3 These snapshots from the lesson show the teacher's way of illustrating dipole–dipole interaction. (a) A hydrochloric acid molecule, drawn with a structural formula. (b) A drawing illustrating that the molecule is a dipole

Unpacking by *transduction* takes place when a representation in a different visual mode is used to unpack a visual representation. Figure 4 illustrates an example of where this was used in the teacher's explanation of dipole–dipole interactions. Here the teacher employs a magnetic whiteboard eraser, which is a transduced version of the drawn representation, to illustrate how one dipole attracts another dipole. First, the teacher moved the eraser on the whiteboard toward the drawn dipole in the wrong direction (i.e., with the minus sign on the eraser pointing toward

FIGURE 4 A snapshot from the lesson showing a way of illustrating how an attractive force arises between two molecules that are dipoles by using a drawing and an eraser to represent the polarity and consequent interaction of two molecules

the minus sign in the drawn dipole). At this point, many of the students reacted and pointed out that the eraser should be turned around, so that the side with the plus drawn on it was closest to the drawn dipole's minus-side. In this way, the teacher aimed the students' focal awareness toward how dipole–dipole interactions can be orientated relative to each other.

Another example of unpacking visual representations by *transduction* is when the students were shown pictures of glucose and cellulose-fibers (Figure 5). The teacher then introduced a log of wood and made chopping movements with an axe horizontally and vertically, respectively, to make a comparison between the strengths of intramolecular forces and hydrogen bonds (see Table 5).

The teacher started by showing the structural formula of two glucose molecules on the projector (Figure 5a). The teacher then moved on to show a representation of two glucose molecules bound to each other (see Figure 5b). The teacher quickly moved on to show a representation of several glucose molecules bound to each other. In this representation, the molecules were represented as ball and stick models, rather than structural formulas (Figure 5c). In the last representation that was shown to the students, several cellulose fibers were connected to each other via hydrogen bonds, which are illustrated as blue lines in Figure 5d.

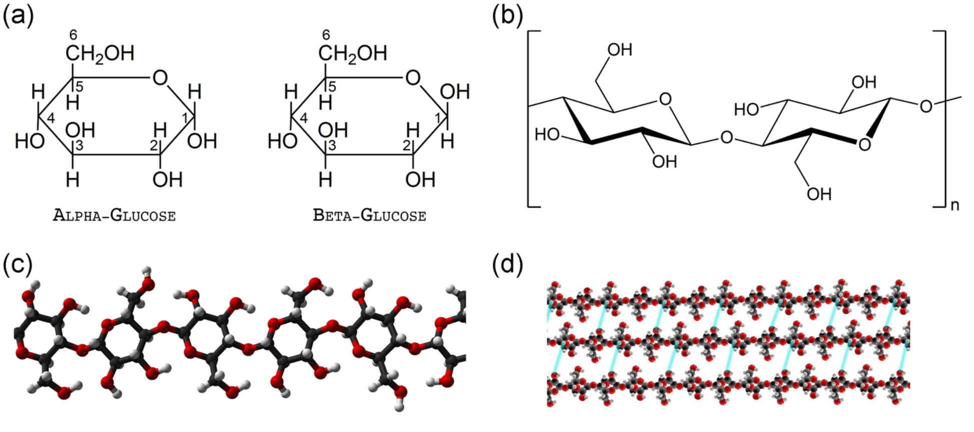


FIGURE 5 Four different visual representations used when discussing the hydrogen bonds between cellulose molecules.(a) The structural formula of two glucose molecules are displayed, while (b) shows the structural formulae of two glucose molecules bound together through a covalent bond. (c) A ball and stick model is used to illustrate several glucose molecules bound together through covalent bonds, forming a cellulose molecule. Finally, in (d), several cellulose molecules are shown to be bundled together with hydrogen bonds, in this representation illustrated as blue lines. *Sources*: a,b: drawn by author based on the images displayed by the teacher; c,d: https://en.wikipedia.org/wiki/Cellulose

TABLE 5 An excerpt from a dialogue where the teacher and two students discuss which type of bond there is between cellulose fibers

Source	Transcript	Teaching action (all pointing refers to the representation given in Figure 5d)
Teaching	Here we then have cellulose fibers that are directed in that way…	Shows the image with three fibers of cellulose, points using the hand
Teaching	…and what kind of strange bond will we have between the different fibers? Jennie? Sorry, Sandra?	Points at the hydrogen bonds using the hand
Student 1	Dipole–dipole bond…	
Student 2	van der Waals…	
Teaching	Hydrogen directly bound to oxygen…	Points at a fiber
Teaching	…hydrogen directly bound to oxygen	Points at the fiber above
Student 1	van der Waals bond	
Teaching	Van der Waals, we have that one too, we have that one always	
Student 1	Hydrogen…	
Teaching	Hydrogen bonds, hydrogen bonds between there.	Points on hydrogen bonds between fiber 1 and 2
	And hydrogen bonds in between here.	Points between fiber 2 and 3
	Polar covalent and covalent in that direction	Draws a hand along the representation of a fiber

After all four representations had been verbally presented to the students, they were asked if they understood, at which point many of them said no. The teacher then went back over their explanation, after which the following discussion (Table 5) transpired.

This discussion clearly illustrates that at least these two individual students had not been able to access the critical aspect that the teacher sought to illustrate with the representations, even when the teacher attempted to bring their focal awareness toward the molecules' ability to form hydrogen bonds.

With the representation of cellulose fibers (Figure 5d) still up on the screen, the teacher picked up an axe and a log of wood. Holding the log in front of the image of cellulose fibers on the screen, the teacher then asked the students what kind of bonds would be chopped off if the log is cut in the "wrong" direction. The ensuing discussion is reproduced in Table 6.

In this instance, the teacher added a visual representation in another visual mode to unpack the critical aspect — the difference in strength between intramolecular forces and hydrogen bonds in the representation with high disciplinary affordance projected onto the screen.

3.5 | Unpacking of visual representations by assumption

During the observed lessons, not all representations used by the teachers were unpacked. We define this lack of unpacking as *unpacking by assumption*, to indicate that the teacher assumed that students were able to make meaning with the visual representation without their support.

An example of where this took place was during the final minutes of one of the lessons, when the teacher showed the students two animations (see Figure 6) from a website associated with their textbook. When the

TABLE 6 An excerpt from a dialogue where one of the teachers and two students discuss which intermolecular bonds one chops of when chopping wood

Source	Transcript	Teaching action (all pointing refers to the representation given in Figure 5d)
Teacher	So, that means if I use the axe to chop in that direction…	Makes a chopping movement (using an axe) toward the log. The movement is aimed perpendicularly to the growth direction of the wood.
Teacher	…when I chop like this, yeah?	
Teacher	What bonds do I chop off then?	Makes a chopping movement toward the image. The movement is aimed perpendicularly to the direction of the representation of the polymer chain.
Student 1	Polar covalent bonds.	
Teacher	Then I would chop off covalent bonds between carbon and carbon, ya know…	Points at a line representing a covalent bond between two carbon atoms on the illustration shown at the projector screen.
Teacher	…and polar covalent bonds between carbon and oxygen…	Points at lines between a carbon atom and an oxygen atom in the same molecule
Teacher	…and what do we say about these bonds?	
Student 1	They are strong.	
Teacher	They are strong, uhu…	Makes a chopping movement toward the image. The movement is aimed perpendicularly to the direction of the representation of the polymer chain.
Teacher	I won't even try. You know that you can't chop wood in that direction, don't you?	Holds the axe with the edge toward the long side of the log, perpendicularly to the growth direction.
Student 2	It's possible, but it's not easy.	
Teacher	It's possible, but it's not easy. Furthermore, this one [the axe] is also awfully dull and awfully corroded. So I will chop in the other direction.	Holds the log aligned with the image, so that the length of the log is parallel with the direction of the representation of the polymer chain.
Teacher	Then the question is, the special sound, what kind of sound is it? When I chop now, what bonds will I be breaking?	Placing the log on the floor and holding the axe over the head.
Teacher	Thus, I will chop in this way, I will chop in this way now.	Using the axe to show the chopping direction in the representation of cellulose on the whiteboard, that is, the axe is moved in parallel with the direction of the polymer chain
Student 3	Hydrogen bonds.	

students were shown the animation of dispersion forces (Figure 6a), the teacher stated: "the animation shows dispersion forces, that the substances are uncharged, but it is plus-minus charged during a fraction of a second and then the next molecule can attract in the same way." The students were then told that they could visit this website in their own time if they wanted to find out more about intermolecular forces and "have a peek at the animations." The teacher's partial explanation of the phenomenon of dispersion forces omitted any discussion of the critical aspects visualized in the representation. For instance, the teacher did

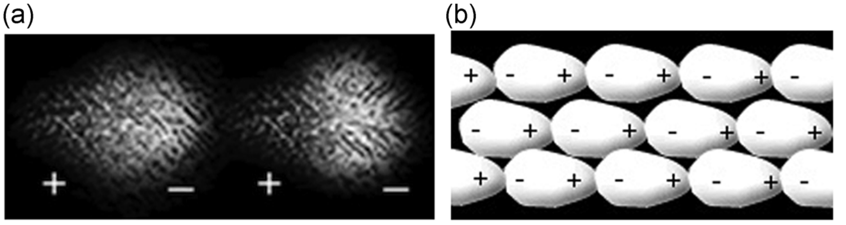


FIGURE 6 (a) A snapshot from the end stage of an animation of dispersion forces is shown. At the beginning of the animation, there was no indication of polarization of the ellipsoid, cloudlike objects. Then the left-hand object changed form—to the one shown in the snapshot—and was assigned plus and minus signs to it, and in the third stage the right-hand object also was assigned plus and minus signs to it. (b) A snapshot of an animation illustrating dipole–dipole interaction is displayed. The parallel linear arrangements of the dipoles moved relative to each other in the animation. Source: http://www4.liber.se/gymnasiekemi/08.html

not mention what the white, cloudlike objects in Figure 6a were supposed to represent, nor in what way (if any) the dispersion forces were being visually represented in the animation.

The ways in which the animations were equivalent or different to the other visualizations employed by the teacher was also not discussed. For example, the representation of dipole–dipole interaction depicted in Figure 1 is markedly different to the way it is represented on the website (see Figure 6b). The teacher appeared to be making the assumption then that the students, on their own, would be able to make sense of the different representations.

Another example of *unpacking by assumption* occurred when one of the teachers showed a movie of dipole–dipole interactions, hydrogen bonding, and dispersion forces. The voice-over in the movie explained the characteristics of the different types of forces, but did not unpack the visual representations being shown, and neither did the teacher. As in the case of the dipole–dipole animation, the visual representations shown in the movie were quite different from the ones the teacher had drawn on the white board earlier in the lesson. Once again, it appears that the teacher assumed that the students would be able to appreciate the relationship between the representations on their own. The different ways in which hydrogen bonding between water molecules were illustrated in the movie and by the teacher, respectively, is shown in Figure 7. In the two representations, the atoms, the molecules, and the bonds between them, are represented in quite different ways.

4 | DISCUSSION

The purpose of this study was to explore the qualitatively different ways that teachers unpack visual representations when teaching intermolecular forces. In our analysis, we establish that there are five qualitatively different ways of unpacking visual representations: by *verbal explanation*, by *adding feature(s)*, by *transformation*, by *transduction* and by *assumption*. Furthermore, we propose that these qualitatively different ways of unpacking visual representations provide different levels of support for making the critical aspects of the phenomenon visible to the students. Based on Marton and Booth (1997) claim that the qualitatively different categories found in a phenomenographic study can typically be arranged hierarchically, we draw on Trigwell and Prosser's (1996) work into teacher-centered and student-centered ways of teaching, to suggest that the categories we established can be arranged into two such groups, which we have termed teacher-centered and student-centered unpacking. The

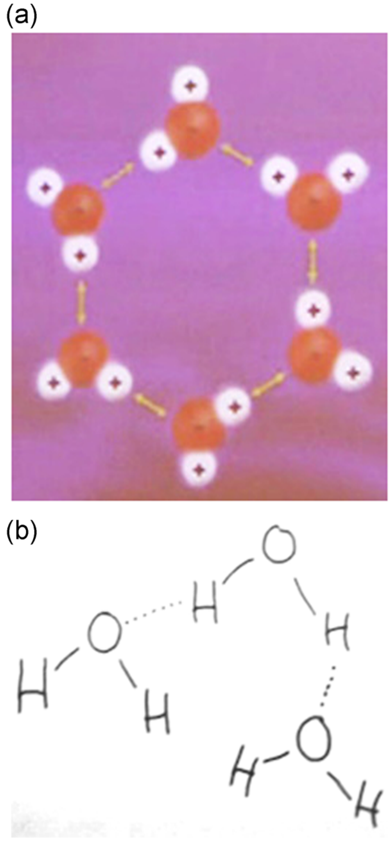


FIGURE 7 Two representations of hydrogen bonding. (a) A representation of water molecules and the hydrogen bonds between them from the movie is shown, and (b) is the representation of hydrogen bonding between water molecules drawn by the same teacher that showed the movie. *Source*: 7(a) is taken from a movie called “Intermolekylära bindningar,” (Eng. Intermolecular forces), from www.kursnavet.se

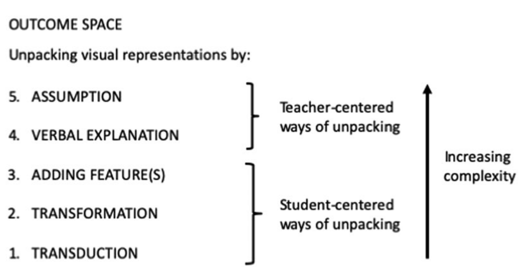


FIGURE 8 An overview of the outcome space illustrating the conceptual hierarchy of the different ways of unpacking visual representations (for details, see text)

categories within each of these two groups can be seen to form, from a students' perspective, a conceptual hierarchy in terms of perceived complexity that are internally related (see the *outcome space* in Figure 8).

4.1 | Teacher-centered and students-centered ways of teaching

Trigwell and Prosser's (1996) phenomenographic study explored university science lecturers' qualitatively different ways of teaching. Their results revealed five qualitatively different teaching strategies that they characterized as being either teacher-centered or student-centered. The teacher-centered strategies involved teaching practices built on transferring knowledge from teacher to student, while student-centered strategies involved teaching practices that focused on helping students to develop their own understanding of the disciplinary content being taught.

4.2 | Teacher-centered ways of unpacking

We regard two of the teaching strategies depicted in Figure 8: unpacking by *assumption* and by *verbal explanation* as being teacher-centered.

Unpacking by *verbal explanation* is arguably an ineffective way of unpacking representations since, as Danielsson (2011) has pointed out, information given only through speech (and gestures) is often regarded as less important by students. Rather, students tend to focus mainly on what the teacher writes or draws on the whiteboard, and copy that material into their notebooks. A similar notion has been reported by Trigwell and Prosser (1996), who argue that teachers who assume that students can make sense of a phenomenon just by telling their students about the concept have a teacher-centered approach to teaching, where the focus is on transmitting information to the students.

When a visual representation is unpacked by *assumption*, it is taken for granted that students will be able to make meaning with the representation on their own. In such instances, teachers may show visual representations to the students but do not bring the critical aspects of the representation into their students' focal awareness. Previous research has highlighted the importance of the teacher's role in assisting students to make meaning with the representations being used to develop students' deeper understanding of the phenomenon being studied (Airey & Linder, 2017; Eilam & Gilbert, 2014b; Hilton & Nichols, 2011; C. Linder, 2013). Therefore, unpacking by assumption is potentially a particularly ineffective teaching strategy. However, those with in-depth knowledge of chemistry do not always appreciate that it can be challenging for students to make meaning with representations without explicit help, since the representations seem self-explanatory to an expert (Baldwin & Orgill, 2019).

4.3 | Students-centered ways of unpacking

Student-centered teaching is, as Trigwell and Shale (2004, p. 534) put it: "an activity that emerges in collaboration with students as partners in learning," and where the focus is on what students are learning, rather than what the teacher is covering (Trigwell & Prosser, 1996). In our analysis, we derive the term student-centered teaching from the phenomenographic modeling of learning which sees teachers' efforts of unpacking representations as being directed at enhancing the possibility of students learning to see things in new ways and learning to see new things.

From this perspective, three of the teaching strategies: unpacking by *adding features*, by *transformation* and by *transduction* are student-centered ways of unpacking.

When critical features are added to a representation, the pedagogical affordance of the representation increases. This helps to bring critical aspects of the phenomenon that were initially appresent in the representation into the students' focal awareness (Ingerman et al., 2009), and in so doing, assists the students to see things in a new way.

Similarly, when a visual representation is unpacked by translation (either *transformation* or *transduction*), the critical aspect(s) may be shown in new ways and critical aspects that were appresent in the first representation may be brought to the students focal awareness, thus helping the students to gain a more holistic understanding of the phenomenon. However, it should be noted that when teachers use this approach, it is essential that they actively assist the students to make the necessary translations between the different representations, since many of the students may struggle to make the translations on their own (Hilton & Nichols, 2011).

4.4 | The hierarchy of the ways of unpacking

The qualitatively different ways of unpacking, together with the way in which we have arranged them hierarchically, make up, from a phenomenographic perspective, the *outcome space* of our analysis. As noted earlier, this arrangement of teaching strategies was derived from a consideration of their complexity from the students' perspective. Referring to Figure 8, the strategies are ranked, from bottom to top (1-5), in order of increasing complexity. The ways of unpacking with high complexity means that the students have limited access to the critical features in the representation and ways of unpacking with low complexity grant students the most access to the appresent critical aspects or features in the representations.

As indicated in Figure 8, teaching strategies 1–3 in the conceptual hierarchy are student-centered. When it comes to their ranking, the unpacking of visual representations by *transduction* is the least complex formulation for the students since the added mode has in itself the potential to show critical aspects in ways that were inaccessible in the other visual mode used. For instance, when one of the teachers in this study added a magnetic whiteboard eraser to illustrate a dipole (see Figure 4) to the drawing symbolizing dipoles, the possibility of illustrating molecular movement and different molecular arrangements was added, and a more holistic understanding was made possible. This is in accordance with Airey and Linder (2009), who argue that a "critical constellation" of modes needs to be used for gaining meaningful holistic access to the disciplinary ways of knowing.

The unpacking of visual representations by *transformation* is marginally more complex and hence is placed second in the hierarchy. According to Fredlund et al. (2014) it is necessary to use multiple representations to acquire a more holistic understanding of the disciplinary knowledge of a phenomenon. In our study, we observed that the teachers unpacked representations with high disciplinary affordance by adding other representations with high pedagogical affordance in the same visual mode. This enabled relevant critical aspects (from the teacher's point of view) being brought into students' focal awareness; while other, irrelevant features (excluded in the second representation) were de-emphasized.

Unpacking of representations by *adding features* to the representation occupies third place in the hierarchy. This way of unpacking is student-centered because critical aspects are made visible, thus lowering the complexity of the representations. However, features in the original version of the representation of lower relevance is still present when critical features are added, which can make it difficult for students to know which parts of the representation to direct their focal awareness towards. Kozma and Russell (1997) have shown that students often focus on surface features in visual representations that are not relevant for making sense of chemical phenomena, rather than attending to the conceptual information being presented. Furthermore, when making changes to a representation, instead of adding a new representation, the students will in all likelihood not have access to the original, disciplinary version of the representations in their notes.

The two categories in the top of the hierarchy are unpacking visual representations by *assumption* and unpacking visual representations by *verbal explanation*, respectively. As discussed earlier, both of these ways of unpacking are teacher-centered. Seeing as representations that are unpacked by *assumption* are not unpacked at all by the teacher, they are considered to provide the least access to the critical aspects of the phenomenon being studied. Consequently, such teaching strategies have the highest level of complexity for the students and this category is placed at the top in the hierarchy.

5 | CONCLUSIONS AND IMPLICATIONS FOR TEACHING

In this article, we have described the variation in teaching strategies employed by teachers as they go about unpacking the visual representations used in the teaching of intermolecular forces. These teaching strategies represent qualitatively different ways of unpacking visual representations that can be arranged hierarchically, ranked according to their complexity from a student's learning perspective. As mentioned previously, Trigwell and Prosser (1996) revealed teaching strategies that are characterized as teacher-centered and student-centered. In a further study, Trigwell et al. (1999) found that when teacher-centered practices were used in the classroom, students were more likely to adopt a "surface approach"[1] to learning, while students who had teachers who used student-centered strategies tended to adopt a "deeper approach"[2] to learning.

As we have described, teaching strategies that involve ways of unpacking with low complexity are more likely to facilitate students' access to those critical aspects and features of the representations, which will allow them to begin to constitute a holistic understanding of the phenomenon at hand (in this instance, intermolecular forces). This carries a clear educational implication: if teachers unpack representations in a teacher-centered way (i.e., by *verbal explanation* or by *assumption*), then, arguably, their students will be more likely to adopt a surface approach[1] to learning. However, if teachers unpack representations in a student-centered way (i.e., by *transduction*, *transformation* and by *adding critical features*), then their students will be more likely to adopt a deep approach[2] to learning. This has, in turn, important implications for teacher training and teacher education programs — for teachers need to be made aware of the most effective ways in which visual representations can be unpacked in their teaching.

Fredlund et al. (2014) propose that teachers should interrogate the representations used by asking two questions. The first question is concerned with which appresent aspects the students need help to "see" to make meaning with the representation in the way the teacher intends. The second question touches upon how aware students are of the appresent information, and if they will be able to use the representation in an efficient and appropriate way. We would add a further question: in what ways could the teacher unpack the representations used to help the students to aim their focal awareness toward the critical aspects of the intended object of learning? For instance, the teacher could reflect upon whether the representation needs to be altered in any way, or if it would be more helpful to add an additional representation, to help the students constitute a more holistic understanding of the intended object of learning.

5.1 | Further research

Since teachers' ways of unpacking visual representations in chemistry have not been explored in this way before, we believe that the categories of unpacking described in the Section 3, and the hierarchy of the outcome space described in the Section 4, present a new tool for researchers wishing to explore how visual representations can be used effectively both in chemistry and more broadly, in other areas in science education.

As a new tool, and knowing that phenomenographic studies have repeatedly shown that the ways of experiencing a phenomenon is limited (Marton & Booth, 1997; Marton, 1986, 2014), it can be argued that our findings become potentially generalizable to other areas of chemistry and even to other disciplines, such as physics, having similar internally related experiences of complexity in their objects of learning.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ENDNOTES

[1]A surface approach to learning is associated with “accepting new facts and ideas uncritically and attempting to store them as isolated, unconnected, items” (Houghton, 2004, p. 11).

[2]A deep approach to learning is associated with “examining new facts and ideas critically, and tying them into existing cognitive structures and making numerous links between ideas” (Houghton, 2004, p. 11).

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REFERENCES

Ainsworth, S., & Newton, L. (2014). Teaching and researching visual representations: Shared vision or divided worlds? In B. Eilam, & J. K. Gilbert (Eds.), *Science teachers´ use of visual representations* (pp. 29–49). Springer.

Airey, J., & Eriksson, U. (2019). Unpacking the Hertzsprung-Russell diagram: A social semiotic analysis of the disciplinary and pedagogical affordances of a central resource in astronomy. *Designs for Learning*, *11*, 99–107. https://doi.org/10.16993/dfl.137

Airey, J., & Linder, C. (2009). A disciplinary discourse perspective on university science learning: Achieving fluency in a critical constellation of modes. *Journal of Research in Science Teaching*, *46*(1), 27–49. https://doi.org/10.1002/tea.20265

Airey, J., & Linder, C. (2017). Social semiotics in university physics education. In D. F. Treagust, H. E. Fischer, & R. Duit (Eds.), *Multiple representations in physics education* (pp. 95–122). Springer. https://doi.org/10.1007/978-3-319-58914-5

Baldwin, N., & Orgill, M. (2019). Relationship between teaching assistants' perceptions of student learning challenges and their use of external representations when teaching acid-base titrations in introductory chemistry laboratory courses. *Chemistry Education Research and Practice*, *20*(4), 821–836. https://doi.org/10.1039/c9rp00013e

Bezemer, J., & Cowan, K. (2020). Exploring reading in social semiotics: Theory and methods. *Education*, *3-13*, 1–12. https://doi.org/10.1080/03004279.2020.1824706

Bezemer, J., & Kress, G. (2008). Writing in multimodal texts–A social semiotic account of designs for learning. *Written Communication*, *25*(2), 166–195. https://doi.org/10.1177/0741088307313177

Booth, S. (1997). On phenomenography,learning and teaching. *Higher Education Research & Development*, *16*(2), 135–158. https://doi.org/10.1080/0729436970160203

Booth, S. (2008). *Researching Learning in Networked Learning – Phenomenography and Variation theory as empirical and theoretical approaches* The 6th International Conference on Networked Learning, Halkidiki, Greece. https://www.lancaster.ac.uk/fss/organisations/netlc/past/nlc2008/abstracts/PDFs/Booth_450-455.pdf

Bowden, J., & Marton, F. (1998). *The university of learning*. Kogan Page

Cahapay, M. (2020). A case study of curriculum unpacking practices of a kindergarten teacher. *Journal of Curriculum and Teaching*, *9*, 1–8. https://doi.org/10.5430/jct.v9n2p1

Cokelez, A., Dumon, A., & Taber, K. S. (2008). Upper secondary French students, chemical transformations and the "register of models": A cross-sectional study. *International Journal of Science Education*, *30*(6), 807–836. https://doi.org/10.1080/09500690701308458

Danielsson, K. (2016). Modes and meaning in the classroom: The role of different semiotic resources to convey meaning in science classrooms. *Linguistics and Education*, *35*, 88–99. https://doi.org/10.1016/j.linged.2016.07.005

Danielsson, K. (2011). Att bli del av en naturvetenskaplig diskurs: text och textanvändning i svenska och finlandssvenska klassrum. In I. Eriksson (Ed.), *Kemiundervisning, text och textbruk i finlandssvenska och svenska skolor – En komparativ tvärvetenskaplig studie* (pp. 161–237). Stockholm university press.

Doll, R. C. (1992). *Curriculum improvement: Decision making and process*. Allyn and Bacon

Eilam, B., & Gilbert, J. K. (2014a). *Science teachers' use of visual representations*. Springer International Publishing. https://doi.org/10.1007/978-3-319-06526-7

Eilam, B., & Gilbert, J. K. (2014b). The significance of visual representations in the teaching of science. In B. Eilam, & J. K. Gilbert (Eds.), *Science teachers´ use of visual representations* (pp. 3–28). Springer. https://doi.org/10.1007/978-3-319-06526-7

Ellis, R. A. (2004). University student approaches to learning science through writing. *International Journal of Science Education*, *26*(15), 1835–1853. https://doi.org/10.1080/0950069042000243772

Entwistle, N. (2018). *Student learning and academic understanding: A research perspective with implications for teaching*. Elsevier Science

Eriksson, M., Eriksson, U., & Linder, C. (2020). Using social semiotics and variation theory to analyse learning challenges in physics: A methodological case study. *European Journal of Physics*, *41*(6), 065705. https://doi.org/10.1088/1361-6404/abb0a2

Eriksson, U. (2014). *Reading the sky: From starspots to spotting stars* (Doctoral thesis, comprehensive summary, Acta Universitatis Upsaliensis). Uppsala.

Euler, E., Radahl, E., & Gregorcic, B. (2019). Embodiment in physics learning: A social-semiotic look. *Physical Review Physics Education Research*, *15*(1), 010134. https://doi.org/10.1103/PhysRevPhysEducRes.15.010134

Fredlund, T. (2015). *Using a social semiotic perspective to inform the teaching and learning of physics* (Doctoral thesis, comprehensive summary, Acta Universitatis Upsaliensis). Uppsala.

Fredlund, T., Linder, C., Airey, J., & Linder, A. (2014). Unpacking physics representations: Towards an appreciation of disciplinary affordance. *Physical Review Special Topics-Physics Education Research*, *10*(2):020129. https://doi.org/10.1103/PhysRevSTPER.10.020129

Gilbert, J. K., Boulter, C. J., & Elmer, R. (2000). Positioning models in science education and in design and technology education. In J. K. Gilbert, & C. J. Boulter (Eds.), *Developing models in science education* (pp. 3–18). Kluwer Academic Publishers. https://doi.org/10.1007/978-94-010-0876-1

Gurwitsch, A. (1964). *The field of consciousness*. Duquesne University Press

Hilton, A., & Nichols, K. (2011). Representational classroom practices that contribute to students' conceptual and representational understanding of chemical bonding. *International Journal of Science Education*, *33*(16), 2215–2246. https://doi.org/10.1080/09500693.2010.543438

Houghton, W. (2004). Engineering subject centre guide: Learning and teaching theory for engineering academics. https://www.advance-he.ac.uk/knowledge-hub/engineering-subject-centre-guide-learning-and-teaching-theory-engineering-academics

Ingerman, A., Linder, C., & Marshall, D. (2009). The learners' experience of variation: Following students' threads of learning physics in computer simulation sessions. *Instructional Science: An International Journal of the Learning Sciences*, *37*(3), 273–292. https://doi.org/10.1007/s11251-007-9044-3

Jaber, L. Z., & BouJaoude, S. (2012). A macro-micro-symbolic teaching to promote relational understanding of chemical reactions. *International Journal of Science Education*, *34*(7), 973–998. https://doi.org/10.1080/09500693.2011.569959

Johansson, B., Marton, F., & Svensson, L. (1985). An approach to describing learning as change between qualitatively different conceptions. In L. West, & A. Pines (Eds.), *Cognitive structure and conceptual change* (pp. 233–258). Academic Press.

Justi, R., & Gilbert, J. K. (2003). Models and modelling in chemical education. In J. K. Gilbert, O. de Jong, R. Justi, D. F. Treagust, & J. H. van Driel (Eds.), *Chemical education: Towards research-based practice* (pp. 47–68). Kluwer Academic Publishers. https://doi.org/10.1007/0-306-47977-X

Knain, E., Fredlund, T., & Furberg, A. (2021). Exploring student reasoning and representation construction in school science through the lenses of social semiotics and interaction analysis. *Research in Science Education*, *51*, 93–111. https://doi.org/10.1007/s11165-020-09975-1

Kozma, R. (2003). The material features of multiple representations and their cognitive and social affordances for science understanding. *Learning and Instruction*, *13*(2), 205–226. https://doi.org/10.1016/S0959-4752(02)00021-X

Kozma, R., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching*, *34*(9), 949–968. https://doi.org/10.1002/(SICI)1098-2736(199711)34:9<949::AID-TEA7>3.0.CO;2-U

Kress, G. (1997). *Before writing: Rethinking the paths to literacy*. Routledge. https://doi.org/10.4324/9780203992692

Kress, G. (2010). *Multimodality: A social semiotic approach to contemporary communication*. Routledge

Kress, G. (2016). What is mode? In C. Jewitt (Ed.), *The Routledge handbook of multimodal analysis* (2 ed., pp. 60–75). Routledge.

Linder, A., Airey, J., Mayaba, N., & Webb, P. (2014). Fostering disciplinary literacy? South African physics lecturers' educational responses to their students' lack of representational competence. *African Journal of Research in Mathematics, Science and Technology Education*, *18*(3), 242–252. https://doi.org/10.1080/10288457.2014.953294

Linder, C. (2013). Disciplinary discourse, representation, and appresentation in the teaching and learning of science. *European Journal of Science and Mathematics Education*, *1*(2), 43–49. https://www.researchgate.net/publication/285596951_Disciplinary_discourse_representation_and_appresentation_in_the_teaching_and_learning_of_science

Linder, C., & Fraser, D. (2009). Higher education science and engineering: Generating interaction with the variation perspective on learning. *Education As Change*, *13*, 277–291. https://doi.org/10.1080/16823200903234802

Lo, M. L. (2012). *Variation theory and the improvement of teaching and learning*. Acta universitatis Gothoburgensis. https://gupea.ub.gu.se/bitstream/2077/29645/5/gupea_2077_29645_5.pdf

Lybeck, L., Marton, F., Stromdahl, H., & Tullberg, A. (1988). The phenomenography of the 'mole concept' in chemistry. In P. Ramsden (Ed.), *Improving learning: new perspectives*. Nichols Publishing Company.

Marton, F. (1981). Phenomenography–describing conceptions of the world around us. *Instructional Science*, *10*(2), 177–200. https://doi.org/10.1007/bf00132516

Marton, F. (1986). Phenomenography—A research approach to investigating different understandings of reality. *Journal of Thought*, *21*(3), 28–49.

Marton, F. (2014). *Necessary conditions of learning*. Taylor & Francis. https://doi.org/10.4324/9781315816876

Marton, F., & Booth, S. (1997). *Learning and awareness*. L. Erlbaum Associates

Marton, F., Dahlgren, L. O., Svensson, L., & Säljö, R. (1977). *Inlärning och omvärldsuppfattning [Learning and conception of the world around us]*. Norstedts

Marton, F., Hounsell, D., & Entwistle, N. J. (1984). *The experience of learning*. Scottish Academic Press

Marton, F., & Morris, P. (2002). *What matters? Discovering critical conditions of classroom learning*. Göteborg Studies in Educational Sciences 181: Acta Universitatis Gothoburgensis

Marton, F. (1988). Describing and Improving Learning. In R. R. Schmeck (Ed.), *Learning strategies and learning styles. Perspectives on individual differences*. Springer. https://doi.org/10.1007/978-1-4899-2118-5_3

Marton, F., & Säljö, R. (1976a). On qualitative differences in learning: I. Outcome and process. *British Journal of Educational Psychology*, *46*(1), 4–11. https://doi.org/10.1111/j.2044-8279.1976.tb02980.x

Marton, F., & Säljö, R. (1976b). On qualitative differences in learning: II—Outcome as a function of the learner's conception of the task. *British Journal of Educational Psychology*, *46*(2), 115–127. https://doi.org/10.1111/j.2044-8279.1976.tb02304.x

Marton, F., & Tsui, A. (2004). *Classroom discourse and the space of learning*, classroom discourse and the space of learning. L. Erlbaum Associates. https://doi.org/10.4324/9781410609762

Moro, L., Mortimer, E. F., & Tiberghien, A. (2020). The use of social semiotic multimodality and joint action theory to describe teaching practices: Two cases studies with experienced teachers. *Classroom Discourse*, *11*(3), 229–251. https://doi.org/10.1080/19463014.2019.1570528

Özmen, H. (2004). Some student misconceptions in chemistry: A literature review of chemical bonding. *Journal of Science Education and Technology*, *13*(2), 147–159. https://doi.org/10.1023/B:JOST.0000031255.92943.6d

Patron, E., Wikman, S., Edfors, I., Johansson-Cederblad, B., & Linder, C. (2017). Teachers' reasoning: Classroom visual representational practices in the context of introductory chemical bonding. *Science Education*, *101*(6), 887–906. https://doi.org/10.1002/sce.21298

Prain, V., & Waldrip, B. (2006). An exploratory study of teachers' and students' use of multi-modal representations of concepts in primary science. *International Journal of Science Education*, *28*(15), 1843–1866. https://doi.org/10.1080/09500690600718294

Rau, M. A. (2017). A framework for educational technologies that support representational competencies. *IEEE Transactions on Learning Technologies*, *10*(3), 290–305. https://doi.org/10.1109/tlt.2016.2623303

Rau, M. A. (2018). Making connections among multiple visual representations: How do sense-making skills and perceptual fluency relate to learning of chemistry knowledge? *Instructional Science*, *46*(2), 209–243. https://doi.org/10.1007/s11251-017-9431-3

Reid, A., & Petocz, P. (2006). University lecturers' understanding of sustainability. *Higher Education*, *51*(1), 105–123. https://doi.org/10.1007/s10734-004-6379-4

Svensson, K., & Eriksson, U. (2020). Concept of a transductive link. *Physical Review Physics Education Research*, *16*(2), 026101. https://doi.org/10.1103/PhysRevPhysEducRes.16.026101

Svensson, K., Eriksson, U., & Pendrill, A. M. (2020). Programming and its affordances for physics education: A social semiotic and variation theory approach to learning physics. *Physical Review Physics Education Research*, *16*(1), 010127. https://doi.org/10.1103/PhysRevPhysEducRes.16.010127

Svensson, L. (1997). Theoretical foundations of phenomenography. *Higher Education Research and Development*, *16*(2), 159–171. https://doi.org/10.1080/0729436970160204

Swedish Research Council. (2017). *Good research practice*. Swedish Reserach Council. https://www.vr.se/analys/rapporter/vara-rapporter/2017-08-29-god-forskningssed.html

Säljö, R. (1988). Learning in education settings: Methods of inquiry. In P. Ramsden (Ed.), *Improving learning: new perspectives* (pp. 32–48). Kogan Page.

Tang, K. S., Won, M., & Treagust, D. (2019). Analytical framework for student-generated drawings. *International Journal of Science Education*, *41*(16), 2296–2322. https://doi.org/10.1080/09500693.2019.1672906

Treagust, D. F., Chittleborough, G., & Mamiala, T. L. (2003). The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education*, *25*(11), 1353–1368. https://doi.org/10.1080/0950069032000070306

Trigwell, K., & Prosser, M. (1996). Congruence between intention and strategy in university science teachers' approaches to teaching. *Higher Education*, *32*(1), 77–87. https://doi.org/10.1007/BF00139219

Trigwell, K., Prosser, M., & Waterhouse, F. (1999). Relations between teachers' approaches to teaching and students' approaches to learning. *Higher Education*, *37*(1), 57–70. https://doi.org/10.1023/A:1003548313194

Trigwell, K., & Shale, S. (2004). Student learning and the scholarship of university teaching. *Studies in Higher Education*, *29*(4), 523–536. https://doi.org/10.1080/0307507042000236407

Uttal, D. H., & O'Doherty, K. (2008). Comprehending and learning from 'visualizations': A developmental perspective. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Models and modeling in science education: Visualization: Theory and practice in science education* (pp. 53–72). Springer. https://doi.org/10.1007/978-1-4020-5267-5

Volkwyn, T. S. (2020). *Learning Physics through Transduction: A Social Semiotic Approach* [Doctoral thesis, comprehensive summary, Acta Universitatis Upsaliensis]. Uppsala.

Volkwyn, T. S., Airey, J., Gregorcic, B., Heijkenskold, F., & Linder, C. (2017). Physics students learning about abstract mathematical tools when engaging with "invisible" phenomena. In L. Ding, A. Traxler, & Y. Cao (Eds.), *2017 Physics Education Research Conference* (pp. 408-411). https://doi.org/10.1119/perc.2017.pr.097

Volkwyn, T. S., Airey, J., Gregorcic, B., & Linder, C. (2020). Developing representational competence: Linking real-world motion to physics concepts through graphs. *Learning: Research and Practice*, *6*(1), 88–107. https://doi.org/10.1080/23735082.2020.1750670

Weliweriya, N., Sayre, E. C., & Zollman, D. (2019). Case study: Coordinating among multiple semiotic resources to solve complex physics problems. *European Journal of Physics*, *40*(2), 025701. https://doi.org/10.1088/1361-6404/aaf5d5

Wu, H. K., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education*, *88*(3), 465–492. https://doi.org/10.1002/sce.10126

Yayon, M., Mamlok-Naaman, R., & Fortus, D. (2012). Characterizing and representing student's conceptual knowledge of chemical bonding [10.1039/C0RP90019B]. *Chemistry Education Research and Practice*, *13*(3), 248–267. https://doi.org/10.1039/c0rp90019b

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