Bridging the gap between macro and micro: enhancing students' chemical reasoning: how to use demonstration experiments effectively for the teaching and learning of structure-property reasoning

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Chapter 1:

General Introduction

1.1 Introduction

“Mrs., what am I actually doing now?”, Claire (year 5, age 16) exclaims during an experiment where she prepared salt precipitations. Performing the research proceeded fine, by the way, but she could not explain for herself what those actions had to do with her research question and the associated chemical concepts. James in year 6 (age 17) asked just before his exam “But what are these molecules really?” and later he mentioned: “I wish I could think like you do....”.

In my experience as chemistry teacher abovementioned exemplary student remarks show that it is hard for students in general to achieve a primary goal of our chemistry education: to learn students “to think like a chemist”. Students experience learning chemistry as difficult. For an expert in chemistry, thinking about chemical problems and topics seems quite simple, but for a novice this is quite elusive.

The challenge inherent in chemistry stems from the requirement of engaging in multilevel thought for chemical reasoning. (Johnstone, 1982, 1991). In the realm of macroscopic observations, we perceive the properties exhibited by compounds and duly take note of their transformations. In chemistry, this is called the macro level. If we want to explain and describe these properties and changes, we need to go down into a world invisible for the naked eye, or even with the best microscope. We need to zoom in to the level of the particles, the so-called (sub)micro level. Last, when thinking and talking about both the macroscopic world and the invisible world full of chemical models, we need a language, which is called the symbolic level. Johnstone (1982, 1991) depicted the three levels as a triangle to visualize this multilevel thought. The corners represent the three levels, macro, micro and symbolic (Figure 1.1). Although present in the work of other researchers, the question remains whether this symbolic level can be regarded as a discrete level. The symbolic level helps chemists in representing and communicating about the chemical concepts, both at the micro as the macro level (Taber, 2013). Therefore, in the Dutch chemistry curriculum, we use the term micro-macro thinking, which is restricted to these two levels when referring to chemical reasoning with multilevel thought (Meijer, 2011).

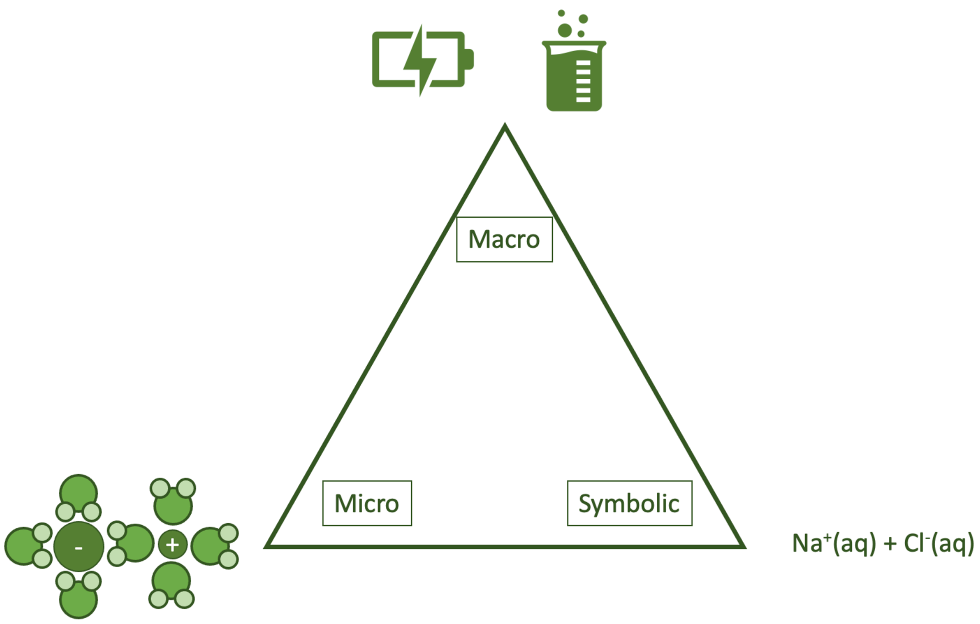

Figure 1.1: *Johnstone’s triangle depicting the multilevel thought of chemistry* (Johnstone, 1991).

Many problems in chemistry are based on the so-called structure-property relations, the relation between the macroscopic properties of a compound and the submicroscopic models like atoms, molecules, and ions. The reasoning about these relations is referred to as structure-property reasoning (Cooper et al., 2013; Talanquer, 2018). The term structure-property reasoning is used in the Anglo-Saxon curricula and chemistry education research (Cooper, 2020; National Research Council, 2013; Stowe et al., 2019; Talanquer, 2018). Structure-property reasoning is also incorporated in the Dutch exam requirement, for example under Subdomain A12: Reasoning in terms of structure properties (*Syllabus Centraal Examen, Scheikunde Vwo*, 2016). Therefore, I will use the term structure-property reasoning in this thesis.

Experts do not experience difficulties with structure-property reasoning, because they easily and unconsciously move back and forth between these levels. Novices in chemistry find it challenging working at the micro level and macro level simultaneously. Their working memory will be overloaded (Johnstone, 1991). Therefore, this multilevel thought needed for structure-property reasoning is very difficult for students.

In the classroom, teachers will experience students' difficulties with reasoning about structure-property relations (Meijer, 2011). First, due to the invisibility of the micro level, chemists use different models to communicate about this level (Cheng & Gilbert, 2017; Chittleborough & Treagust, 2007; Gabel, 1999). Evidently, chemistry teachers want their students to get acquainted with these models. For this reason, chemistry curricula include models of the particulate nature of matter (Harrison & Treagust, 2003). However, students struggle with the needed structure models. They often translate these models one-to-one with reality. Furthermore, students do not know what the boundaries of models are (Adbo & Taber, 2009; de Jong & Taber, 2015). Second, most students have a macroscopic orientation caused by their former experiences (Gabel, 1999; Johnstone, 2000). Third, students have different misconceptions about the particle model and thus the micro level. The main misconception with the particle nature of matter is that students see particles as small portions of the whole substance, with all the properties of this substance (Ben-Zvi et al., 1986; de Jong & Taber, 2015; Talanquer, 2018). Last, teaching is not always matched with students' existing conceptual framework (de Jong & Taber, 2015). Above problems could give rise to misconceptions about the micro level and hinder the acquiring of structure-property reasoning.

Both the importance and general approach to structure-property reasoning are widely endorsed. However, there is little discussion about how to best support students in developing this type of reasoning (Talanquer, 2018). Showing the chemical phenomenon, which students could relate to, to emphasize the three levels and integrate these three levels could make the instruction more effective (Gabel, 1993; Kelly et al., 2010; Kozma et al., 1997). In sum, structure-property reasoning should be taught explicitly (Gilbert & Treagust, 2009; Meijer, 2011) to enable students to learn to switch between the macro and the micro level. Furthermore, teaching should be centered on the core idea of this type of reasoning (Stowe et al., 2019; Talanquer, 2018).

However, previous research shows that teachers do not have sufficient experience in the explicit teaching of structure-property reasoning (Dolfing et al., 2011). Moreover, literature offers little clues to teachers need for this explicit teaching (Talanquer, 2018). Teachers would be helped with an approach and tools for the explicit teaching of structure-property reasoning.

Literature shows that a laboratory activity like a demonstration or practical assignment offers opportunities to promote students' structure-property reasoning (Becker et al., 2015; Gabel, 1993, 1999; Kelly & Jones, 2007; Kozma et al., 1997; Ramsey et al., 2000; Treagust & Tsui, 2014; Tsaparlis, 2009). In these experiments, chemical phenomenon (the macro level) is shown that can be explained with the behavior of and interactions between particles (the micro level). In this way, the teacher starts where students start, namely at the macro level (Johnstone, 2000). Moreover, a laboratory activity provides the opportunity for the teacher to connect to students' macroscopic orientation (Gabel, 1999).

Doing a demonstration experiment in the class instead of a practical assignment has an important benefit for students because a demonstration could reduce the level of noise of a practical assignment (Gunstone & Champagne, 1990; Hodson, 2014; Hofstein, 2017; Pols, 2023). Students make errors in observing and measuring - leading to unreliable results, lose interest or fail to finish the data collection in time. These will lead to the wrong data and/or wrong conclusions that restricts the learning of structure-property reasoning. This problem can be prevented by reducing the noise for example by simplifying the activity. However, this is not possible for every chemical phenomenon with associated model on micro level you want a student to experience. In this case a demonstration experiment is a good solution (Hodson, 2014).

Although demonstrations can be preferred over practical activities, the potential of demonstration experiments for the teaching of structure-property reasoning is often not realized. In many demonstrations the teacher shows, points out observations, and explains and the students passively observes (Figure 1.2). Students' attention is mainly with the external characteristics of the experiment. They fail to explain what they observe by means of the micro level and students have very few possibilities to test their ideas and ask their teacher questions (Treagust & Tsui, 2014). Moreover, if there is a group discussion in response to an experiment, the students mainly discuss about symbolic representations - for example the balancing of a chemical reactions. The crucial connections between the micro and the macro levels are not made by students themselves (Becker et al., 2015). Consequently, they have trouble with developing the right conceptual understanding.

Demonstration experiments, when accompanied by explicit support for structure-property reasoning, have the potential to be effective in enhancing students' structure-property reasoning. However, for these approaches to be successful, it is crucial that teachers actively implement them in the classroom. Innovative teaching practices can further augment the effectiveness of demonstration experiments. Specifically, teachers need to explicitly teach structure-property reasoning during demonstrations. Despite the potential benefits of innovations, teachers often experience a gap between what is considered effective and what is practically applicable in the classroom (Doyle, 2006; Doyle & Ponder, 1977; Janssen et al., 2013; Shavelson et al., 2008).

Practicality theory (Doyle & Ponder, 1977) posits that an innovation, a proposal of change, will only be implemented by teachers when they consider the innovation as practical. Furthermore, teachers will adapt or reconfigured an innovation to increase the practicality. Doyle & Ponder (1977) developed the three dimensions of practicality. The first dimension is instrumentality, which means that the innovation has clear and recognizable procedures. The second dimension is congruence, which means that the innovation is congruent with teachers' goals. The third dimension is cost-effectiveness, which means that the innovation costs less time, energy, and materials then the normal teaching practice. When an innovation is considered instrumental, congruent with teachers' goals, and when it has low costs, the innovation will be considered as practical by teachers.

The dimensions of practicality were further elaborated by Janssen and colleagues into a theory and a methodology to make innovations practical without losing the core of the proposed innovation (Janssen et al., 2014, 2015).

The traditional approach to conductivity of solid salts and salt solutions

The goal of this demonstration is developing the awareness that salt consists of ions (structure/micro level). In the demonstration the teacher shows that a molecular compound such as (pure) water does not conduct electricity using a conductivity meter (property/macro level). Measuring the conductivity of a solid salt shows that it does not conduct either. Then the teacher makes a salt solution of the showed solid salt and water and shows the conductivity of this salt solution. Following the demonstration in teacher-directed explanation, the teacher shows that a molecular compound consists of uncharged particles, named molecules and a salt consists of charged particles, named ions (structure/micro level). Only when the salt is dissolved or molten these charged particles can move freely and there will be conductivity of electricity. (Figure 1.2)

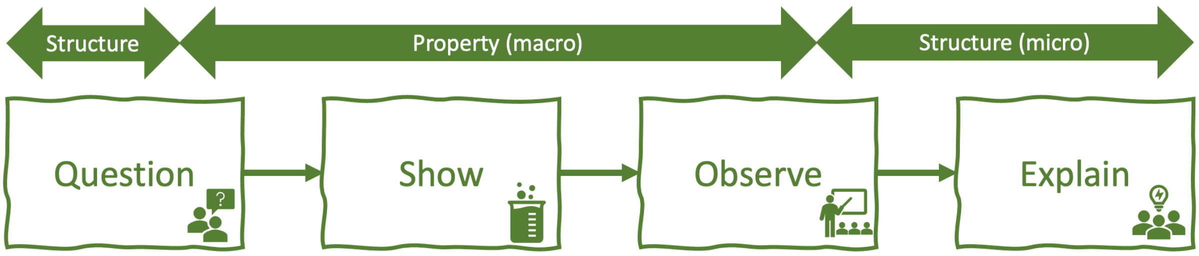

Figure 1.2: Building blocks of a demonstration experiment.

1.2 Research Goals and Overview of the Study

Based on the previous considerations regarding structure-property reasoning and the teaching and learning thereof as well as considerations regarding design of effective chemical demonstrations, we expect that education with regards to structure-property reasoning may benefit from the use of appropriate demonstrations. These demonstrations of the chemical phenomenon should give the students the opportunity to think for themselves. Furthermore, students should be supported in acquiring structure-property reasoning by making the teaching of structure-property reasoning explicit to let students make the crucial connections between the micro and macro level. An essential prerequisite for such an intervention is that teachers perceive the teaching practice as practical. (Janssen et al., 2015; Janssen et al., 2013). Against this background the central research question for this research project is: What are the characteristics of an effective and practical approach that supports chemistry teachers in designing, enacting, and evaluating lessons in which a demonstration experiment is used to enhance students' structure-property reasoning? To answer this research question four studies were conducted. These are described in the next four chapters.

First, explicit teaching of structure-property reasoning presupposes a model by which macro and micro levels are explicitly connected. Chapter 2 describes such a model for structure-property reasoning building on Johnstone's triangle and followers. This model is based on scientific perspectivism (Landa et al., 2020) making it possible to explicitly connect chemical concepts with the big idea of structure-property reasoning. We call this model a perspective for structure-property reasoning. This perspective is designed to support students in structure-property reasoning. Using four chemical cases of increasing complexity, we show how the perspective can be progressively built upon and provide direction in structure-property reasoning.

Because we want to assess the extent to which the desired approach promotes students' structure-property reasoning, we have developed an assessment instrument for this purpose, described in Chapter 3. With this instrument the proficient in structure-property reasoning of secondary school students could be assessed. Proficiency in structure-property reasoning is necessary for a good understanding of many chemical topics. This instrument should meet four criteria: 1) the instrument has to be based on a comprehensive model for structure-property reasoning, 2) the instrument has to be practical for teachers (Janssen et al., 2013), 3) the instrument has to be applicable to large groups, and 4) teachers has to be able to use the instrument repeatedly and adapt the tool to the grade, level, and content they teach. The SPR instrument was administered to two target groups – secondary school students at the pre-university track and first-year university chemistry students – to determine whether it could discriminate between those groups.

In the study presented in Chapter 4, a demonstration-based lesson series aimed at acquiring structure-property reasoning was designed and tested. Two design principles underlie this lesson series: 1) students are encouraged to think for themselves through a predict-observe-explain task; 2) their structure-property reasoning is supported with the perspective for structure-property reasoning. To promote possible practicality, the lesson series was not developed from scratch, but existing demonstration experiments were adapted. Next, the demonstration-based lesson series was tested for the progression of students' structure-property reasoning with the SPR instrument and qualitative data from a case study of one student.

In Chapter 5, teachers' estimated practicality of the teaching approach for teaching structure-property reasoning developed in Chapter 4 was investigated. Eight teachers were interviewed to estimate the practicality (de Graaf et al., 2018) of redesigned demonstration lesson about chemical equilibrium. The teachers were presented the redesign and then asked to score the perceived desirability of the redesign and perceived probability they would use the design in their own teaching practice. To explore their motivational beliefs, the teachers were asked to name advantages and disadvantages of the design. These motivational beliefs give insight into the extent to which a teacher considers the toolbox practical for their own teaching practice.

Chapter 6 discusses the main findings of this thesis. Furthermore, I address the contributions of this research to theory and practice, the practical implications, as well as the limitations and suggestions for further research.