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

Otter, M. den

English Summary

Teaching students chemical reasoning is one of the main goals of chemistry education (Talanquer, 2018). An important part of this chemical reasoning is structure-property reasoning, in Dutch referred to as micro-macro thinking. In the context of chemical reasoning, structure-property reasoning involves the task of elucidating macroscopic properties using the micro level, the level of particles and the interactions between them (Cooper et al., 2013; Meijer, 2011; Talanquer, 2018).

An expert in chemistry smoothly and almost unconsciously moves back and forth between these two levels when thinking about chemical questions and problems. A novice, in this thesis a secondary school student, encounter significant difficulty in achieving this cognitive task (Johnstone, 1991). There are several reasons for this. First, the micro level, the level of particles, cannot be seen by the naked eye. Chemists employ models to describe the micro level, however, students face difficulties in understanding and working with these models. They tend to interpret these models as an exact representation of reality. Furthermore, learners struggle to comprehend the limitations of these models. Second, because of their previous experiences, learners have a macroscopic orientation. Third, students have various misconceptions about particle models. This hinders the learning and development of structure-property reasoning (Adbo & Taber, 2009; Ben-Zvi et al., 1986; Cheng & Gilbert, 2017; de Jong & Taber, 2015; Gabel, 1999; Gilbert & Treagust, 2009; Harrison & Treagust, 2003; Johnstone, 1991).

To facilitate the learning and development of structure-property reasoning among students, teachers require effective and practical teaching approaches. However, educational research provides insufficient guidance in this regard. Several studies have highlighted the significance of demonstrating chemical phenomena (the macro level) and subsequently explaining them at the micro level. This approach enables the explicit teaching of structure-property reasoning (Dolfing et al., 2011; Gabel, 1999; Kelly et al., 2010; Talanquer, 2018).

Practical work in the form of student experiments would be appropriate to demonstrate those chemical phenomena. However, the efficacy and practicality of such experiments for learning are often inadequate. The inherent complexity involved in conducting experiments can result in significant noise, which may hinder the acquisition of conceptual knowledge during practical sessions. This noise can be reduced by using demonstration experiments (Becker et al., 2015; Hodson, 2014; Johnstone, 2000; Kelly & Jones, 2007; Kozma & Russell, 1997; Pols, 2023; Ramsey et al., 2000; Treagust & Tsui, 2014).

A demonstration experiment often consists of two steps: show and explain, both conducted and led by the teacher. The problem is that during the show, students often observe the demonstration passively, and therefore their attention is on the external features of the chemical phenomenon. They find it difficult to explain the phenomenon at the micro level and, in addition, there are few opportunities for students to test their ideas. As a result, students struggle to develop appropriate conceptual knowledge. Therefore, teachers benefit from approaches that overcome the shortcomings of a demonstration experiment (Becker et al., 2015; Treagust & Tsui, 2014).

Doyle and Ponder (1977) suggest that an innovation will not be adopted by teachers until it is perceived as being practically useful. To achieve this, they identified three dimensions that must be considered: instrumental, congruent, and cost-effective. The instrumental dimension refers to the innovation having a clear and recognizable procedure. The congruent dimension pertains to the innovation being aligned with the teacher's teaching goals. Finally, the cost-effective dimension involves the innovation being beneficial to the teacher in terms of time, resources, and energy. If these conditions are met, teachers are more likely to perceive the innovation as being practically useful and therefore implement it (Borko et al., 2010; Doyle, 2006; Doyle & Ponder, 1977; Janssen et al., 2013; Shavelson et al., 2008).

The purpose of this research was to explore an effective and practical approach to teaching and evaluating structure-property reasoning in chemistry classes at the secondary school level. Based on the previous considerations regarding structure-property reasoning and its teaching and learning, as well as considerations regarding the design of effective chemical demonstrations, we anticipated that teaching in structure-property reasoning could benefit from the use of appropriate demonstrations. To test this hypothesis, the following central research question was formulated: "what are the characteristics of an effective and practical approach that supports chemistry teachers in designing, enacting, and evaluating demonstration lessons to increase students' micro-macro thinking? To answer this research question, four studies were conducted, namely 1) the development and use of the perspective for structure-property reasoning to make structure-property reasoning explicit, 2) the design of an evaluation tool to assess students' progress in structure-property reasoning, 3) the design and implementation of a demonstration-based lesson series to explicitly teach structure-property reasoning, and 4) an interview with eight chemistry teachers to estimate the practicality of the approach. The results of the sub studies will be used to offer teachers recommendations on how to evaluate and teach structure-property reasoning to students.

The first study described the development of a model structure-property reasoning (**Chapter 2**). With this model, we aimed to represent the relationship between chemical concepts and the skill of structure-property reasoning. Scientific perspectivism is used for this purpose (Landa et al., 2020). The core idea of structure-property reasoning is: The **properties** of **substances** can be explained by the nature of the **particles** of which they consist, the **bonds and forces** between them, and the **movement** and **organization** of those particles (Smith et al., 2006). From the bold words, six questions can be formulated (Figure 1). The answers to these questions are the chemical concepts you need for structure-property reasoning. This organizes chemical knowledge in coherence.

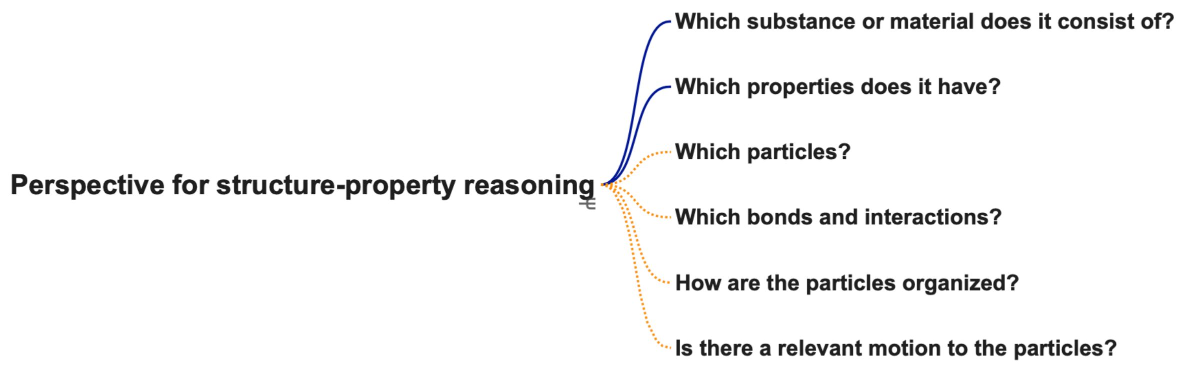

Figure 1: *Perspective for structure-property reasoning used in the studies of this thesis.*

Four cases increasing in difficulty demonstrated how the perspective for structure-property reasoning and its elaborations can stimulate reasoning about these cases. This causes an implicit learning progression as the perspective's questions branch out further and further. With each further differentiation, the strategy becomes increasingly powerful. In addition, the perspective increases horizontal and vertical coherence. Horizontal coherence here refers to the alignment of the chemical concepts and skills within a grade. Vertical coherence refers to the alignment of chemical concepts and skills across grade levels (Jin et al., 2019).

Chapter 3 described the development of an evaluation tool for chemistry teachers to assess students' level of structure-property reasoning. Three criteria were established for this SPR (SPR stands for structure-property reasoning) instrument, namely 1) the instrument must be based on a comprehensive model of structure-property reasoning, 2) the instrument must be cost-effective, and 3) the instrument must be adaptable by teachers to their own teaching goals. To achieve these goals, the SPR instrument combined a sorting task (Irby et al., 2016; Krieter et al., 2016) and a mapping task, both unframed and framed.

Results showed that the SPR instrument can discriminate between pre-university track students (age 15-17) and first-year chemistry students. In addition, it showed that the perspective for structure-property reasoning can serve as a comprehensive model that covers the necessary aspects of structure-property reasoning. The instrument also met the second criteria set, i.e., the instrument is cost-effective. Preparation and implementation of the SPR instrument was not time-consuming and the instrument was suitable for larger groups. However, analyzing the results still took time. Also, the final criterion has been met: the instrument is adaptable to the teacher's own instructional goals.

Chapter 4 described the design and implementation of a demonstration lesson series aimed at teaching students' structure-property reasoning. Two design criteria were established for this purpose, namely 1) using a POE task (Treagust & Tsui, 2014) to encourage students to think for themselves and model the micro-level and 2) supporting POE task with the perspective for structure-property reasoning to guide students in reasoning in the explain phase. Existing demonstrations were redesigned using these two design principles. The lesson series was tested in two cohorts (age 15-16) to determine the effect of the two design principles. The SPR instrument was used to determine the progress in structure-property reasoning of the whole class. The results of this instrument show that the lesson series contributed to the development of structure-property reasoning. The mapping tasks of the SPR instrument showed that students were able to reproduce and understand more chemical concepts necessary for structure-property reasoning. In addition, the sorting tasks of the SPR instrument showed that students were better at applying and evaluating knowledge to problems requiring structure-property reasoning. Following a student, named Sally, and her groupmates, the progression in structure-property reasoning was qualitatively analyzed.

The findings demonstrated that the two design principles yielded the intended outcomes. Specifically, the utilization of the POE task led to a higher level of active participation among students in the process of modeling the structure models during the explain phase. As a result, students will have more knowledge of the required micro-models. In addition, the SPR instrument showed that the perspective for structure-property reasoning was developed in students. This increases the value of perspective as a scaffold for structure-property reasoning. Therefore, one could say that both design principles helped students in developing the skill of structure-property reasoning.

Chapter 5 investigated the estimated practicality (Doyle & Ponder, 1977; Janssen et al., 2013) of the two design principles of Chapter 4. For this purpose, eight chemistry teachers were interviewed and asked to compare the practicality of their own approach with our approach. The results showed that the teachers rated the practicality of the redesigned demonstration as high as that of "traditional" demonstration. As advantages of the redesign, it was mentioned that in this way students are enabled to think for themselves and that the perspective for structure-property reasoning can act as a thinking framework for the students. A frequently mentioned disadvantage is that the perspective consisted of a large number of questions.

Chapter 6 presents a comprehensive description and discussion of the findings from all the sub studies. The results of the four sub studies showed that that perspective is suitable as a model for structure-property reasoning. The perspective consists of questions that can be used to describe and explain the macroscopic properties of a substance using the micro-level. Teachers can use the perspective as a design tool when (re)designing lessons or ear the design of assessment instruments in which the perspective acts as the basis of the instrument.

In addition, the results of the four sub studies showed that the POE task allows the teacher to engage students more during the demonstration. The POE demonstration allows teachers to start at students' macroscopic orientation. Through the predict phase of the POE task, students are actively engaged in the demonstration. The student-centered explain phase of the POE task allows students to think for themselves and model the micro-level so that the demonstrated chemical phenomenon can be described and explained. Using the perspective in the explain phase supports students in formulating micro-level explanations. The perspective questions can be used to describe and question the phenomenon. The chemical concepts that emerge in response to the questions can help students formulate a good answer and micro-model. The POE demonstration combined with the perspective allow the teacher to explicitly teach structure-property reasoning.

The two design principles combined are also perceived by teachers as practical. The practicality of the approach is enhanced by the fact that existing demonstrations can be used for the redesign. The POE task only adds one building block to the approach. The perspective for structure-property reasoning reorganizes the chemical concepts to be taught so that there is more consistency among these concepts. The innovation will be perceived as instrumental due to the minor modifications to usual teaching practice. By giving students more opportunity to think for themselves through the POE task, the innovation will be congruent with the teacher's teaching goals. Lastly, the innovation is cost-effective due to the use of (existing) demonstrations that are less costly in terms of time, resources and energy compared to practical work performed by students.

Every study has inherent limitations, and this study is no exception. First, there was a small group of students who participated in the studies of Chapters 3 and 4. Therefore, it is recommended that this study should be repeated with larger groups. In addition, a lesson series to develop structure-property reasoning in students is obviously not enough. The lesson series from Chapter 4 will have to serve as a starting point to develop a learning progression for structure-property reasoning. A limitation of Chapter 5 is that it concerns the estimated practicality. Follow-up research that includes professional development could examine how teachers implement the innovation and then how they rate the practical usefulness of the approach. Finally, the suitability of the perspective for structure-property reasoning has only been demonstrated through a limited number of examples. This makes the scope of the perspective limited to structure-property reasoning in K-12 chemistry education. Further research should clarify whether the perspective for structure-property reasoning can be expanded to encompass the entire domain of structure-property reasoning and then expanded even further to include all subjects in K-12 chemistry education.

Several theoretical and practical implications follow from this research. First, the perspective for structure-property reasoning appears to be a useful explication of structure-property reasoning. This allows the perspective to be used as a thinking framework, a knowledge organizer, and a scaffold for students. Teachers can use the perspective as a design tool for designing lessons, lesson series and curricula. In addition, the perspective can be used to design evaluation tools. The perspective is part of the overarching chemistry perspective for K-12 chemistry education, which will broaden the scope for both students and teachers. The POE task allows teachers to use demonstrations more effectively and thereby teach structure-property reasoning more explicitly. Such a POE task is not new, but the combination with the perspective structure-property reasoning increases the value and practicality of the demonstration. In addition, the two design principles, the POE task and the perspective are also applicable in other situations where students need to develop structure-property reasoning such as student practices and assignments.