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

Chapter 5:

Estimated Practicality of a Redesigned Demonstration for Teaching Structure-Property Reasoning

Abstract

Acquiring structure-property reasoning is difficult for novice chemistry students. Teachers can help them by explicitly teaching structure-property reasoning and using demonstrations to show the chemical phenomena. However, a traditional demonstration lacks opportunities for students to think for themselves, or teachers do not offer enough scaffolding when students think for themselves. Teachers' usual presentation of demonstrations needs to be redesigned. For such an innovation to be implemented in teachers' own teaching practice, however, the innovation should be experienced as practical, with clear procedures, high congruency with their own teaching goals, and high cost-effectiveness. In this study, the practicality of an innovation with two design principles, i.e., POE task and the perspective for structure-property reasoning, was judged by eight participants. The results show that the redesigned demonstration was perceived to be about as practical as traditional demonstrations. Also, many of the intended benefits were recognized by the teachers. Because the redesign of the demonstration used bridging methodology, a first step towards designing a professional development training course showing teachers how to implement this innovation was taken. This will enable the two design principles for demonstrations to become part of chemistry teachers' teaching practice.

5.1 Introduction

Chemical reasoning is one of the most important, yet challenging, skills chemistry students need to acquire. The main difficulty of chemical reasoning is so-called multilevel thought, i.e., being able to think over multiple levels simultaneously. According to Johnstone (1982, 1991), three levels of thought are important: the micro (the level of particles and their interactions), the macro (the level of the observable), and the symbolic (the level of symbols, equations, etc.) levels. When teaching chemical reasoning, therefore, one important goal of teachers is to teach their students so-called micro-macro thinking, better known as structure-property reasoning: explaining observable properties and changes of compounds (macro) in terms of particles and their interactions (micro) (Meijer et al., 2013; Talanquer, 2018).

Students experience difficulties with structure-property reasoning. First, while experts in chemistry are able to use all the levels simultaneously (Treagust et al., 2003) and unconsciously transfer between levels, students mainly think from a macroscopic point of view (Gabel, 1999). Second, students find it difficult to think using structure models, as these oppose the macroscopic level where things are tangible and visible to the naked eye (de Jong & Taber, 2015). Structure models at the micro level are also often represented using symbolic, microscopic, or mixed features which are sometimes implicit or ambiguous (Gkitzia et al., 2011). Students have difficulties in understanding such representations (Kozma & Russell, 1997).

Earlier studies suggest that showing chemical phenomena and teaching the micro level explicitly aid students in acquiring structure-property reasoning as these provide opportunities to teach at all three levels simultaneously (Gabel, 1993; Kozma et al., 1997; Talanquer, 2018). Consequently, chemical phenomena are often embedded in teachers' daily teaching practice, primarily as practical work (Becker et al., 2015; Hodson, 1993, 2014; Hofstein, 2004). Practical work, however, is often not very effective in teaching structure-property reasoning (Abrahams & Millar, 2008; Hodson, 2014; Hofstein & Lunetta, 2004), among other reasons due to the high cognitive load for students of performing practical work (Hodson, 2014; Paterson, 2019): they must pay attention to various factors, e.g., following instructions (verbal and written), dealing with apparatus and materials, and obtaining and processing the right data.

A demonstration of a chemical phenomenon, on the other hand, lowers distractions, and hence the cognitive load, for students (Logar & Ferk Savec, 2011; McKee et al., 2007; Meyer et al., 2003; Ramsey et al., 2000). As the teacher performs the procedures, students can concentrate on the chemical phenomenon and the underlying micro-level explanation. This enables students to practice structure-property reasoning. However, a demonstration has the disadvantage of lower student engagement and interaction. Students are impressed by the show, but they are not greatly stimulated to think for themselves. The lack of interaction and the low student engagement during a demonstration impedes students in learning to reason explicitly between the various levels (Roth et al., 1997). This indicates the need for a different design of demonstration lessons, to increase their effectiveness in helping students to acquire structure-property reasoning skills. Existing approaches to demonstrations need to be redesigned for this purpose, so students are enabled to think for themselves during the demonstration. As in any innovation, it is critical that is this also done in a way that is practical for teachers.

Practicality theory (Doyle & Ponder, 1977) shows that an innovation will only be accepted and implemented by teachers if it is judged to be practical. Three criteria are important for practicality. First, it should be instrumental. An innovation should comprise clear procedures to enable teachers to quickly implement it in their own teaching practice. Second, it should be congruent with teachers' regular teaching practice. Finally, it should be cost-effective. Innovations should have low costs in both time and resources.

In the present study, we describe a practical method to redesign existing demonstrations, leading to demonstration experiments aimed at promoting students' structure-property reasoning. After redesigning a demonstration, we asked teachers to compare the practicality of our design with that of their delivery of a demonstration. Furthermore, we aimed to gain insight into teachers' motivational beliefs underlying their estimation of practicality. Our research question for this study was, how do teachers assess the practicality of redesigned demonstrations aimed at promoting students' structure-property reasoning?

5.2 Redesigning Demonstrations to Strengthen Structure-Property Reasoning

In a traditional demonstration, a chemical phenomenon is shown by the teacher, while the students observe. During and after the demonstration, the teacher explains the chemical concepts related to the chemical phenomenon. A teacher often starts a traditional demonstration by posing a question as a means of introducing the topic (Hilario, 2015). Such an activating question introduces the students to the subject and the learning objectives. The theory behind the chemical concepts addressed by the demonstration is mostly explained before the demonstration. Sometimes, the teacher uses the demonstration to introduce the theory. In a traditional demonstration, the teacher is lecturing most of the time, and interaction with students is low (Roth et al., 1997). When observing the demonstration, students are impressed by the show, but they are not stimulated enough to think for themselves. This impedes the students in learning to reason over multiple levels. To stimulate students to engage in structure-property reasoning, their interaction in the demonstration should be increased (Bowen & Phelps, 1997; Crouch et al., 2004; Pierce & Pierce, 2007; Ramsey et al., 2000).

Traditional demonstrations should be redesigned to enable students to think for themselves. In an effective demonstration, there should be explicit attention for students' structure-property reasoning. However, an effective demonstration should also be practical for teachers. Both aspects should be accomplished simultaneously, without promoting one at the expense of the other. To make the educational reform practical without losing the essential elements of the innovation, a bridging methodology was developed (Dam et al., 2013; Janssen et al., 2013). In this methodology, the existing and the new teaching practices are described in comparable building blocks (Dam & Janssen, 2021; Janssen et al., 2013). The innovation can then be realized through a stepwise recombination or adaptation of the existing building blocks. Every step in which a building block is adapted or recombined should be experienced by teachers as an improvement of their daily teaching practice.

Teachers typically strive to improve their daily teaching practice, but they find it hard to strive for realization of all their teaching goals. Therefore, for a teacher to consider an innovation or redesign as an improvement, the expected value of the redesign should be estimated to be higher than that of the original teaching practice. This expected value is defined as the product of desirability (the extent to which a person considers the expected outcome of the redesign to be desirable) and probability (the extent to which a person expects that he or she will be able to realize the expected outcome) (Pollock, 2006).

Bridging methodology can help make an innovation practical because it gives teachers access to a procedure which enables them to realize the innovation in their own teaching practice. In addition, this procedure costs little in terms of extra time and resources because it starts with existing building blocks (cost-effectiveness). Furthermore, it explicitly builds on what teachers normally do and what they find important (congruence). Bridging methodology has been applied and tested in multiple settings, such as teacher education (Janssen et al., 2014, 2015; Janssen et al., 2014) and teacher professional development training (Dam & Janssen, 2021) in the fields of biology (de Graaf et al., 2018) and modern foreign languages (de Vrind, et al., 2019). In this study, we applied bridging methodology to the redesign of traditional demonstrations, creating demonstrations aimed at developing structure-property reasoning in chemistry.

When applying bridging methodology to the redesign of existing demonstrations, we first need to define the typical teaching practice in a traditional demonstration lesson in terms of building blocks comparable with those of the intended innovation. Such a lesson typically consists of the following five building blocks: Question, Show, Observe, Explain, and Theory (Figure 5.1, first row). First, teachers ask students a question about a certain chemical phenomenon, in this way introducing them to the subject and the learning objectives of the lesson. Next, the teacher explains the theory behind the concepts addressed by the demonstration. The chemical phenomenon is demonstrated to the students, who observe the show. Last, the teacher explains the demonstrated phenomenon in relation to theory about the associated chemical concepts.

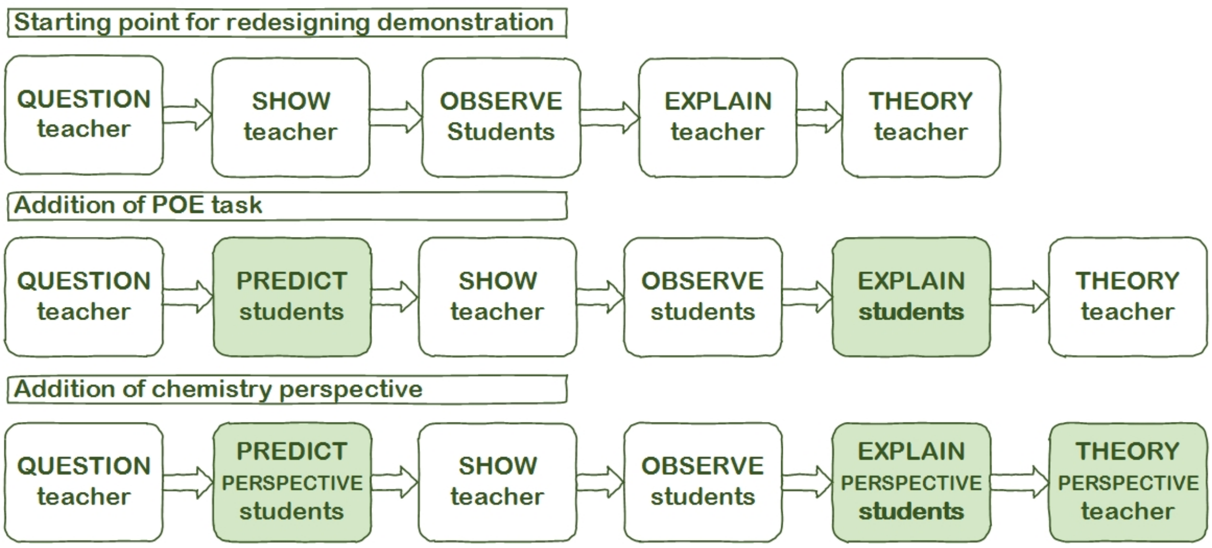

Figure 5.1: *Building blocks for traditional demonstration and steps for redesign.*

The first design principle we introduced was aimed at enabling students to think for themselves (increased student engagement) during the demonstration: the POE task (Crouch et al., 2004; den Otter et al., 2021; Kibirige et al., 2014; Liew & Treagust, 1998; Shiland, 1999; Treagust, 2007). The POE task adds a building block to the teaching practice: namely, the Predict phase. Before the demonstration, the teacher asks the students to predict the outcome of the experiment. Students preferably explain their predictions using reasoning at the micro level. The teacher then performs the demonstration. Afterwards, the students explain their observations, again with help of the micro level. In this way, students are asked to link the outcome of the demonstration to the addressed chemical concepts, making the building block Explain more student-directed. The addition of the POE task is the first step in the bridging methodology (Figure 5.1, second row).

To scaffold students' structure-property reasoning in the Predict and Explain phases, we introduced the second design principle, a domain-specific perspective for structure-property reasoning (Figure 2) (den Otter et al., 2021). Perspectives are a way of looking at, thinking about, and working on complex problems, based on scientific perspectivism (Giere, 2010; Wimsatt, 2007). A hierarchically organized perspective starts with a central core reasoning idea. For structure-property reasoning, the core reasoning scheme could be defined as follows:

"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."

Six basic questions can be formula ted based on the words in bold from the core reasoning scheme (Figure 2) (den Otter et al., 2021, 2022; Janssen et al., 2020; Landa et al., 2020). The answers to these questions are specific chemical concepts such as electrons, protons (particles), or Van der Waals bond, hydrogen bond (forces, interactions). The advantage of such a perspective is that chemical concepts are coherently organized. The domain-specific perspective can act as a scaffold for students' structure-property reasoning and modelling. Students can use the questions of the perspective to consider the problem, and the answers in the form of the applicable chemical concepts can help students to formulate a solution to the problem.

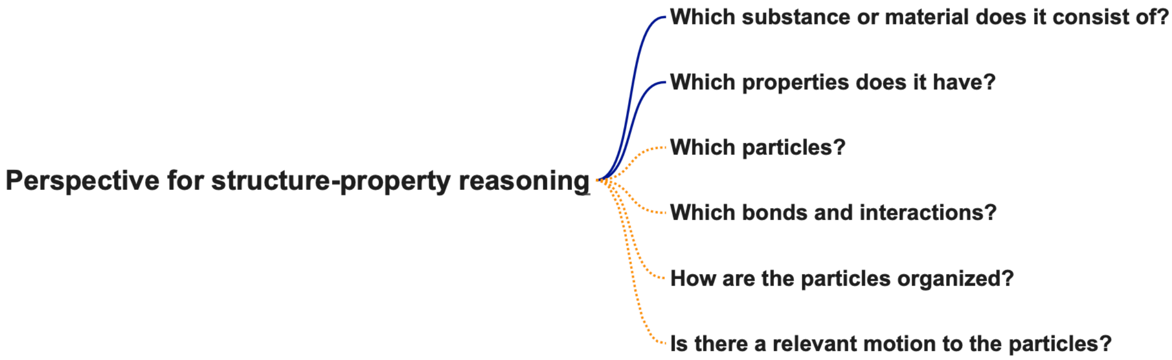

Figure 5.2: *The domain-specific perspective for structure-property reasoning. The blue lines lead to questions at the macro level, the orange lines to questions addressing the micro level.*

The perspective for structure-property reasoning enables the teacher to reorganize the chemical content he or she would normally address. The chemical concepts can also be seen as building blocks, i.e., content building blocks (de Boer et al., 2019). Using a perspective leads to the content building blocks being organized coherently through questions and makes the bigger picture of the demonstrated structure-property relation clear to students. Figure 5.3 shows how the content building blocks addressed in the disturbance of the equilibrium of cobalt (IV) chloride by adding some drops of hydrochloric acid are organized in the perspective. The questions about the macro level describe the macroscopic situation. The questions about the micro level make clear to students which structure models they need to explain the shown phenomenon. In this way, the perspective helps students to develop structure-property reasoning and, therefore, enables teachers to explicitly teach structure-property reasoning.

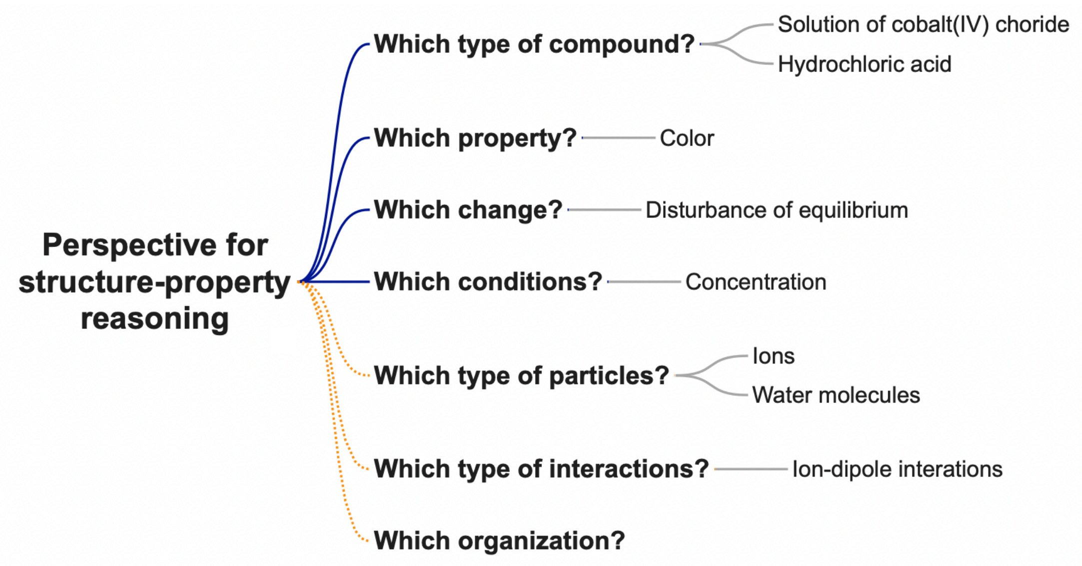

Figure 5.3: *The domain-specific perspective for structure-property reasoning used in this study and elaborated for the disturbance of a cobalt (IV) chloride equilibrium by adding some drops of hydrochloric acid. Because the demonstration concerned the disturbance of an equilibrium, two questions about change and conditions were added to the perspective for structure-property reasoning as depicted in Figure 5.2. The blue lines lead to questions at the macro level, the orange lines to questions addressing the micro level.*

In a previous study, we showed that a redesigned demonstration including a POE task (Predict-Observe-Explain) and the domain-specific perspective for structure-property reasoning aided students in acquiring the skill of structure-property reasoning (den Otter et al., 2021). The POE task and the perspective for structure-property reasoning enabled the teacher to engage students in the demonstration, while providing the students with opportunities to develop structure models of metals, salts, and molecular compounds, and to explain the demonstrated properties using these structure models.

5.3 Redesign of a Demonstration Lesson Using the Two Design Principles

In the present study, an existing demonstration lesson used in the lessons of the first author was redesigned as discussed above. We selected the topic of the disturbance of equilibrium. Normally, the first author would show a video of the disturbance of the $CoCl_4^{2-}$ equilibrium (equation 5.1) as the demonstration.[1] The effect of a change in concentration as well as a change in temperature on the equilibrium would be demonstrated. The teaching practice for this demonstration lesson is depicted in Figure 5.1, row 1. The concept would be introduced with a short description of the demonstration to be shown and an activating question. The video would then be shown and stopped at certain points to ask the students to explain their observations. After the demonstration video, the theory of Le Chatelier's principle would be explained to the students. Finally, the students would work on some assignments related to this principle.

$$\text{Heat} + [Co(H_2O)_6]^{2+} + 4\,Cl^- \rightleftarrows [CoCl_4]^{2-} + 6\,H_2O \qquad \text{(equation 5.1)}$$

[1] This video was found on YouTube: https://youtu.be/dmOif5MUPcE.

In redesigning the demonstration lesson, the building block Predict was added to the original teaching practice (as in Figure 5.1, row 2). Therefore, in the redesigned demonstration, students were asked to predict the color change and other possible observations when (1) hydrochloric acid, and (2) a solution of silver nitrate were added, and (3) the temperature was changed. The questions of the perspective for structure-property reasoning (Figure 5.3) were shown on the screen and used to explore and describe the macroscopic situation. Because the demonstration concerned a disturbance of an equilibrium, two questions about the change and the conditions were added. The questions remained on the screen during the demonstration. Students' predictions were shared, and students were asked to explain their predictions. The teacher used the questions of the perspective for structure-property reasoning to scaffold these explanations. After the demonstration phase, the teacher discussed the observations with the students to check their explanations of their observations. Again, the teacher used the questions of the perspective for structure-property reasoning to scaffold the explanations put forward by the students. This redesign changed the traditional demonstration practice to our target teaching practice, as in Figure 5.1, row 3.

5.4 Methods

5.4.1. Research Design and Participants

First, a demonstration lesson was chosen for this study. The original demonstration lesson was redesigned using the steps described above (see Figure 5.1). The redesigned demonstration lesson was given by the first author of this chapter to a Y4 (aged 15-16 years) pre-university-level class of 18 students, during the COVID-19 period. Therefore, the demonstration was showed to the students using a video from YouTube. The lesson was taught remotely via an MS Teams meeting.

Next, seven teachers and one teacher educator agreed to be interviewed. The teachers taught at seven different secondary schools. Table 5.1 summarizes the participants' characteristics. All names have been anonymized.

5.4.2. Data Collection and Analysis

To investigate the practicality of the demonstration including POE and the perspective for structure-property reasoning, the participants were interviewed. The interviews were semi-structured and lasted about one hour. The interviews were audio-taped, and the interviewer made notes.

We started the interviews with questions to gather information about the teachers' background and experience. We then explained the two design principles we used for the redesign of the demonstration: namely, the POE and the perspective for structure-property reasoning. Next, the lesson demonstration performed by the first author was explained by showing two key sheets of the PowerPoint used in the lesson. After this, the estimated practicality of the demonstration was determined according to a procedure described in previous studies (de Graaf et al., 2018; Janssen et al., 2014). First, we asked the participants to score the estimated desirability and probability on a seven-point Likert scale (1 to 7) for both the traditional demonstration and the redesigned one.

The expected value was calculated by multiplying the scores given for desirability and probability, because the expected value is determined by the extent to which a teacher thinks the expected outcome of a design is desirable and by the extent to which a teacher expects to be able to realize the design in their own teaching practice (Pollock, 2006). Teachers consider a design an improvement if the expected value of the design is higher than the expected value of their original plan (de Graaf et al., 2018).

Next, to get insight into participants' motivational beliefs underlying their scores for desirability and probability, we asked every teacher to name specific advantages and disadvantages of both the traditional and the redesigned demonstrations. The estimated advantages and disadvantages also provided insight into the extent to which the teachers considered the two design principles practical for their own teaching practices.

Next, two researchers analyzed these beliefs and clustered them into groups based on their content, without losing too many of the original words. When the two researchers disagreed, they reached consensus through discussion. Five participants mentioned disadvantages of giving assignments for home experiments. These disadvantages were removed from the list.

Table 5.1: *Characteristics of interviewed teachers*

	Felix	Imani	Anna	Julia	Jason*	Isabel	Alissa#	Simon
Teaching experience (years)	8	23	1	8	1	8	1[b]	12
Grade level[a]	PUE	PUE	PUE	PUE	PUE	PUE	PUE	PUE
Upper/lower secondary education	Both	Upper	Both	Upper	Upper	Both	-	Both
School	A	B	C	D	E	F	-	G
Performed online demonstrations	Yes	Yes	Yes	Yes	No	Yes	-	Yes
Made practical assignments for students at home	Yes	Yes	No	No	No	Yes	-	No

*Note. * Jason is a student teacher; # Alissa is a teacher educator*
a PUE = pre-university education, GSE = general secondary education
b Experience in teacher education

5.5. Results

5.5.1. Estimation of the Expected Value

The average estimated desirability and probability of the traditional demonstration and the redesigned demonstration are shown in Table 5.2, together with the calculated expected value of both the traditional demonstration and our design.

The participants found a demonstration desirable for their lessons, whether taught remotely or not, as can be seen in the rather high average scores (5.5 and 6.1) for the desirability of both the traditional demonstration and the redesigned demonstration. In addition, it was clear from the scores that participants found the redesigned demonstration more desirable than a traditional design, as can be seen in the increased value (+0.6) for desirability (Table 5.2). However, Table 5.2 also shows a decrease (-0.5) in the average score for probability of the redesigned demonstration, including POE and perspective, compared with the traditional demonstration. On average, the expected value of our redesigned demonstration is slightly higher than that of the traditional demonstration.

Table 5.2: *Participants' estimated desirability and probability scored on a seven-point Likert scale (1-7) for a) Traditional Demonstration, b) Redesigned demonstration (n=8). Expected Value = Desirability x Probability*

	Desirability	**Probability**	**Expected value (DxP)**
	Mean	Mean	Mean
Traditional demonstration	5.5	5.9	32.5
Redesigned demonstration	6.1	5.4	32.9
Difference	+ 0.6	- 0.5	+ 0.4

The individual scores for desirability, probability, and expected value are shown separately in Table 5.3 for the eight participants.

Table 5.3: *Participants' estimated desirability and probability scored on a seven-point Likert scale (1-7) for a) Traditional Demonstration, b) Demonstration with POE and Perspective*

	Felix	**Imani**	**Anna**	**Julia**	**Jason***	**Isabel**	**Alissa#**	**Simon**
Traditional Demonstration								
Desirability	7	4	5	3	5	6	7	7
Probability	7	6	7	4	4	7	6	6
Expected Value (DxP)	49	24	35	12	20	42	42	42
Demonstration with POE and Perspective								
Desirability	5,5	7	6	5	6	6	7	6
Probability	6	6	5	2	6	6	7	5
Expected Value (DxP)	33	42	30	10	36	36	49	30
Difference Expected Value	- 16	+ 18	- 5	- 2	+ 16	- 6	+ 7	- 12

*Note. * Jason is a student teacher; # Alissa is a teacher educator*

5.5.2. Motivational Beliefs Underlying the Scores for the Expected Values

The results show that the average expected value (=desirability x probability) increased by a marginal difference of 0.4 points (Table 5.2). This means that the eight participants found the redesigned demonstration including the two design principles to be approximately as practical as traditional demonstrations. Table 5.4 shows the perceived advantages and disadvantages of the traditional demonstration (Table 5.4a) and of the redesigned demonstration (Table 5.4b), giving insight into the participants' motivational beliefs; these beliefs explain the scores for both the desirability component and the probability component of the expected value. We discuss the advantages and disadvantages mentioned by the participants below and relate these motivational beliefs to the aims of the two design principles.

Four participants named as advantages of a traditional demonstration that students learn more and understand better when observing a demonstration in the lesson compared with instruction without a demonstration. Four participants mentioned that a demonstration makes a concept, a procedure, and the micro level more visible compared with instruction without a demonstration. A disadvantage of a traditional demonstration that was mentioned is that students only must observe; they are less stimulated to think for themselves.

Table 5.4a: *Participants' estimated advantages and disadvantages of the traditional demonstration with the design principles POE and Perspective (n=8)*

Advantages	Number	Disadvantages	Number
It is timesaving, efficient, cost-effective	2	Students don't have to think, only to watch	3
Video gives opportunity to pause and watch again*	1	Learning effect is less compared with doing it yourself in a student experiment	1
Nice to do, motivating for the students	3	Difficult to differentiate between students	1
Students will learn more, understand better, students are challenged to think for themselves compared with instruction without demonstration	4	Lack of guidance, scaffold options, and check while watching an asynchronous demonstration video*	3
Demonstration makes procedure / concept / micro level more visible, illustrates better compared with instruction without demonstration	4	Demonstration on screen is less impressive, students cannot smell, feel, etc., compared with demonstration in the classroom*	3
Students have same starting point	1	Interaction with students is poor and demonstration is teacher-directed	2
		Selecting correct demonstration video and timing of video in online lesson design is difficult*	1

*Note. * Statement concerns online demonstration*

Table 5.4b: *Participants' estimated advantages and disadvantages of the demonstration with the design principles POE and Perspective (n=8)*

Advantages	**Number**	**Disadvantages**	**Number**
Students are challenged to think for themselves (before seeing it)	7	Difficult to engage every student in class, difficult to let every student predict, not only the ones asked. Students must learn to work with this method.	4
Students will remember better or learn more when thinking for themselves or when they create their own knowledge (compared with a traditional demonstration)	3	Less interaction due to online environment*	2
Perspective gives thinking frame, gives coherence, and is a toolbox for students to solve problems	5	Many questions in perspective. (Open) perspective is uncomfortable, students do not know which direction. Perspective is difficult to use, especially when pre-knowledge is poor	5
Predict and perspective give opportunities for thinking for themselves and increase engagement of students	5	Demonstration is a complex elaboration of theory, maybe too complex for students	1
Internal conflict helps with learning the concepts	1	Students create their own knowledge, so misconceptions could arise	2
Students learn micro aspects better; perspective helps them learn structure-property reasoning	2		
Opportunities for formative assessment	3	Students are forced into a certain thinking frame	2
Perspective connects to pre-knowledge	1	Other domain-specific perspectives are also needed	1
Engagement of students by predicting the outcome	3		
Perspective offers structure for the teacher to discuss and teach chemical concepts	1		

Seven participants named as advantages of the redesigned demonstration including the two design principles that students are challenged to think for themselves. Five participants mentioned that the perspective for structure-property reasoning gives students a thinking frame. Another advantage that was named five times is that the two design principles give students the opportunity to think for themselves, the opposite of a mentioned disadvantage of the traditional demonstration. Five participants said there were too many questions in the perspective and that they, therefore, found the perspective difficult to use.

5.6 Discussion

Teaching students to engage in structure-property reasoning is an important goal of chemistry education in secondary schools. This can be achieved by performing practical work with chemical phenomena, which should be explained through the structure models underlying them (Gabel, 1993; Kozma et al., 1997; Talanquer, 2018). However, when students perform practical work themselves, cognitive overload may impair their learning (Hodson, 2014; Paterson, 2019). Furthermore, practical work is time-consuming for teachers. Performing a demonstration can solve these problems (Logar & Ferk Savec, 2011; McKee et al., 2007; Meyer et al., 2003; Ramsey et al., 2000), but students' learning of structure-property reasoning is less well facilitated by the way a demonstration is typically taught.

The abovementioned indicates the need to redesign existing demonstration lessons. Therefore, we introduced two design principles: the POE task and the perspective for structure-property reasoning. We demonstrated the effectiveness of these design principles for teaching structure-property reasoning in a previous study (den Otter et al., 2021). In the current study, we examined the extent to which teachers considered the redesigned demonstration to be practical. This is not a given: many innovations fail to make it to the classroom because they are rejected as impractical. Bridging methodology (Dam et al., 2013; Dam & Janssen, 2021; Janssen et al., 2013), the recombination and adaptation of existing building blocks, was applied to a regular demonstration to design a demonstration which could improve students' structure-property reasoning. Eight participants were asked to score the estimated probability and desirability of using this approach in their own teaching practice.

The findings show that the redesigned demonstration was perceived to be about as practical as traditional demonstrations. Also, many of the intended benefits were recognized by the teachers. The redesigned demonstration enables students to think for themselves; consequently, they will remember and learn better. The participants estimated that student engagement would increase as a result of using the redesigned demonstration. In addition, the perspective for structure-property reasoning was recognized as a thinking tool for students.

Some disadvantages were also mentioned: for example, that the perspective for structure-property reasoning might be difficult to use due to the large number of questions. When starting with structure-property reasoning, novices have only a limited set of simple main questions at their disposal. When progressing in structure-property reasoning, students expand the perspective step-by-step by adding sub-questions to the main questions, and later sub-questions to the sub-questions. In this way, a perspective branches out into a coherent set of questions. Using this step-by-step construction of the questions in the perspective, the teacher can have the students practice structure-property reasoning gradually, and the perspective will develop into a growing thinking frame for them. In this way, a perspective-based learning progression (Duschl et al., 2011) will appear. A more branched out perspective with too many questions at once would cause an excessive increase in cognitive load for novices (Jin et al., 2019). So, for novices starting to acquire structure-property reasoning, the perspective should consist of a limited number of questions. This step-by-step construction of the perspective should be investigated in future research.

Some disadvantages of the redesigned demonstration point to a limitation of the study as a whole: namely, the context in which we performed the research. The interviews were conducted at the end of the first Covid-19 lockdown in the Netherlands (June 2020). The participants were at the end of a rough period in which they had had to acquire a completely new teaching practice, giving lessons in an online setting. The participants were tired and overwhelmed by all the changes. The prognosis at that time was that normal teaching at school would resume after the summer holidays. This possibly gave the participants a distorted view and influenced their estimations of the practicality, especially the cost-effectiveness, of an online demonstration with or without the two design principles. This view could also be seen in the disadvantages mentioned of both the traditional demonstration and the redesigned demonstration. It is clear from the participants' naming of these disadvantages that this online setting lacked opportunities for much-needed student-teacher interactions. Nevertheless, the scores and the advantages mentioned of the two design principles are promising regarding the practicality of the innovation, suggesting that there is a place for the redesigned demonstration in the teaching practices of the participants.

Another limitation of this study is that it concerns teachers' estimated practicality of the demonstration. It is not based on teachers' personal experience. However, the scores for the estimated desirability and probability of the redesigned demonstration look promising. In addition, the current study described a small trajectory in which teachers could expand their repertoire step by step. This bridging trajectory could be used in a professional development program. Further research may reveal how teachers estimate the practicality of the redesigned demonstration compared with their traditional demonstrations.

The results of this study have some practical implications. For successful implementation of the two design principles, it may be important to introduce the participants to the approach. This might reduce feelings of uncertainty caused by the unfamiliarity of the approach. This can be done by designing a professional development course for participants who wish to use the two design principles. In this training, the incorporation of modularity enables participants to incrementally modify their teaching practice, facilitating the development of a personalized and customized bridging trajectory, as illustrated in Figure 2. (Dam & Janssen, 2021). In further research, therefore, a professional development training course should be designed to investigate the actual use of the two design principles by participants. A personal bridging trajectory should be deployed in this. In addition, it could be useful to refine the procedures of both design principles, adding a design template and examples of good practice. In this way, the two design principles may become part of a teaching approach that enables participants to (re)design their demonstration lessons to increase students' proficiency in structure-property reasoning.